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Terms and definitions

Acronym	Description
AKD	Alkyl Ketene Dimer
ASA	Alkenyl Succinic Acid
FEM	Finite Element Method
EVA	(Expanded) Ethylene-Vinyl Acetate
BHKP	Bleached Hardwood Kraft Pulp
BSKP	Bleached Softwood Kraft Pulp
BRC	BreadCell Foam
CMC	Carboxymethylcellulose
CNC	Cellulose Nanocrystals
CNF	Cellulose Nanofibrils
FOG	Condensable Emissions
EV	Electric Vehicle
EPDM	Ethylene Propylene Diene Monomer
EPP	Expanded Polypropylene
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
EPS	Expanded Polystyrene
HMF	Hydrophobic Melamine Foam
HVAC	Heating Ventilation and Air Conditioning
HR	High Resilience
IFD	Indentation Force Deflection
LDPE	Low Density Polyethylene
NFC	Nanofibrillated Cellulose
NBR	Nitrile Butadiene Rubber
PCM	Phase Change Material
PA	Polyamide
PUR (or PU)	Poly(ester) or Poly(ether)-Urethane
PE	Polyethylene
PFA	Polyurethane Foam Adhesive
PLA	Polylactic Acid
PP	Polypropylene
PVC	Polyvinyl Chloride
RPUR	Rigid Polyurethane Foam

TIM	Thermal Interface Material
VOC	Volatile Organic Compounds

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Executive summary

This report presents consideration and potential of BreadCell foam, a cellulose fiber-based network structure, for automotive applications. The study begins by examining the terminology used to describe these structures, comparing them to traditional foams. It then provides a comprehensive overview of foam usage in various automobile components, highlighting their functional purposes. The report includes existing applications of fiber networks, particularly cellulose-based ones, in vehicle construction. Additionally, it briefly outlines methods for modifying pulp fiber-based network structures to enhance their properties and expand their applicability in the automotive industry.

Four potential automotive applications for pulp fiber-based network structures are outlined, focusing on leveraging their strengths while addressing potential weaknesses through fiber or bulk structure modifications.

The report concludes that BreadCell foam is best suited for multifunctional applications that capitalize on its unique properties, such as high sorptivity, acoustic and thermal insulation, porosity, biocompatibility, and low volatile organic compound (VOC) emissions.

Specifically, the study suggests that BreadCell foam could be ideal for roof, floor, or door liners, where it can simultaneously provide thermal insulation, phase change material harnessing, impact energy management, and acoustic insulation. This multifunctional approach maximizes the material's potential in automotive design and construction.

Project overview

The major challenge to reduce consequences of climate change, microplastic pollution and raw material shortages is to convert our economic system. We need to replace fossil-based resources by renewable ones, replace persistent materials by biodegradables while developing and employing environmentally friendly processing technologies to create safe products with minimum impact on the environment. A real impact on economy, society and ecology is only generated if the materials, processes and products to be replaced are in large scale.

In BreadCell, we develop a radically new technology to produce **porous lightweight low-density materials** which are currently used in large scale industries and mainly consist of synthetic non-degradable polymers. BreadCell technology comprises a **foaming process** to create products relying on existing and new raw materials from pulping (cellulose, xylan), and to convert them to high value, lightweight, energy-absorbing and load-transferring composites such as in sports and safety components of cars. The whole process chain will be guided by a safe-and-sustainable-by-design approach to ensure the production of sustainable and inherently safe products. Today, the innovation capacity of European scientists and industry in renewable materials makes them already the leading global players in the field. We will provide a scalable technology that will further support the European technological leadership in the area by cross-fertilization of different fields (pulp and paper, biotechnology, polymer technology, toxicity) while addressing needs of future materials.

Consortium:

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1. Introduction

This report summarizes the applicability of the BreadCell foam for automotive applications. The material or, more precisely, the structure studied in the BreadCell project is a fibrous network structure formed by mechanical or (bio)chemical foaming and consisting of cellulose fibres. In scientific and popular literature, these structures are often referred to as foams. In Chapter 1, we explore the question of whether this terminology is correct by first outlining the key properties and manufacturing processes of foams and fibre network structures, and by concluding on the differences between foams and fibre network structures. Chapter 2 provides an overview of the components and assemblies of an automobile in which foams are used - and for what functional purpose. Chapter 3 gives examples of fibre networks and in particular cellulose-based fibre networks that are already being used in vehicle construction. Chapter 4 outlines possible approaches for modifying or enhancing the properties of pulp fibre-based fibre network structures with the aim of expanding their field of application. Finally, Chapter 5 outlines three possible applications for pulp fibre-based fibre network structures in automotive engineering. The question of which requirements the respective application case poses and which upgrades are necessary to meet these requirements is addressed.

1.1. Foams

Foams are materials characterized by the presence of a gas dispersed within a liquid or solid matrix, resulting in a structure that is both lightweight and capable of providing various functional properties. The fundamental definition of a foam involves the formation of bubbles, which are gas-filled cavities surrounded by a thin film of liquid or solid material. This unique structure imparts a range of mechanical, thermal, and acoustic properties that make foams suitable for diverse applications across multiple industries, including automotive, construction, and consumer goods.

Depending on the phase of the matrix, one can distinguish between:

- Liquid foams: These have a liquid continuous phase, like soap bubbles or whipped cream.
- Solid foams: These have a solid continuous phase, such as styrofoam or memory foam mattresses

Depending on the morphology of the pores, one can distinguish between:

- Open-cell foams have interconnected pores that allow air and liquids to flow through, while
- Closed-cell foams consist of isolated gas pockets that provide superior insulation and buoyancy [2].

The choice between these types of foams depends on the intended application, as each type offers distinct advantages and disadvantages: Open-cell foams are often used in applications requiring sound absorption and cushioning, while closed-cell foams are preferred for insulation and structural support due to their higher strength and lower thermal conductivity [3].

1.1.1 Properties

The ability to tailor the properties of foams through adjustments in processing conditions and material selection allows for the development of specialized foams that meet specific performance criteria for various applications [4]. In addition to their mechanical properties, foams are also valued for their

- thermal insulation capabilities. The gas trapped within the foam structure significantly reduces heat transfer, making foams effective insulators in applications ranging from building materials to automotive components [5]. The low thermal conductivity of foams is particularly beneficial in energy-efficient designs, where minimizing heat loss is critical for maintaining comfortable temperatures and reducing energy consumption [6].

- Acoustic properties are another important aspect of foam materials. Foams can effectively absorb sound waves, making them ideal for applications requiring noise reduction, such as in automotive interiors and soundproofing materials [7]. The porous structure of foams allows them to dissipate sound energy, thereby reducing the transmission of noise through walls, ceilings, and other surfaces [8]. This property is especially valuable in environments where noise control is essential for comfort and productivity.

Key Properties

- Low density: Foams are significantly lighter than their base materials due to the large volume of gas they contain.
- Insulation: The trapped gas bubbles in foams provide excellent thermal and acoustic insulation properties.
- Compressibility: Many foams can be easily compressed and may return to their original shape when the pressure is released, especially in the case of flexible foams.
- Surface area: Foams have a high surface area to volume ratio, which can be advantageous in applications like catalysis or filtration.
- Buoyancy: Due to their low density, many foams are highly buoyant in liquids.
- Stability: The stability of foams varies depending on their composition: Liquid foams are generally less stable and will eventually collapse as liquid drains from the bubble walls. Solid foams are more stable and maintain their structure over long periods.

In summary, foams are multifaceted materials that consist of gas bubbles dispersed within a liquid or solid matrix, providing a unique combination of mechanical, thermal, and acoustic properties. Their classification into open-cell and closed-cell types, along with the ability to tailor their characteristics through processing techniques, makes foams suitable for a wide range of applications across various industries

- Construction: As insulation materials
- Packaging: For cushioning and protection
- Furniture: In mattresses and cushions
- Food industry: In products like whipped cream and bread
- Firefighting: As fire-suppressing agents

Applications

The versatility of foams stems from their ability to combine low weight with desirable mechanical, thermal, and acoustic properties, making them valuable in numerous applications across different fields

- Foams are also utilized in various industrial processes, including the synthesis of advanced materials with controlled porosity. For example, foams can serve as templates for creating porous ceramics or composites, allowing for the fabrication of materials with specific mechanical and thermal properties [9].
- The versatility of foams in material science extends to their use in biomedical applications, where they can be engineered to support cell growth and tissue regeneration [10].

1.1.2 Production

The formation of foams can be achieved through various methods, including mechanical agitation, chemical reactions, or the introduction of gas into a liquid or solid matrix. For instance, in the case of polymer foams, the process often involves the incorporation of a foaming agent that generates gas bubbles during the curing or hardening of the polymer matrix [11]. The stability and characteristics of the resulting foam depend on several factors, including the properties of the liquid or solid matrix, the type of gas used, and the presence of surfactants that can stabilize the foam by reducing the surface tension of the liquid film [6].

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1.2. Fibrous networks

1.2.1 Structures

A fibrous network structure is an arrangement of interconnected fibers that form a three-dimensional framework. This type of structure is prevalent in both natural and synthetic materials, playing crucial roles in various biological systems and industrial applications. In biological systems they are abundant in nature, forming critical components of many biological materials, like cellular cytoskeleton, connective tissue and collagen and fibrin networks in the extracellular matrix. In industrial, man-made products, fibrous networks are found in paper, non-woven fabrics, tissue paper and synthetic scaffolds for tissue engineering.

The material under study in the project BreadCell is a fibrous network formed created from pulp fibres. Fibrous network structures are characterised by:

- Microstructure: Fibrous networks are characterized by their intricate microstructure, consisting of intertwined fibres. This arrangement creates a porous structure with high surface area-to-volume ratios.
- Stochastic Nature: The organization of fibers within these networks is often stochastic, meaning it exhibits random or probabilistic patterns. This randomness contributes to the unique properties of fibrous materials.
- Hierarchical organization: Many fibrous networks display a hierarchical structure, with organization occurring at multiple scales from the nanoscale to the macroscale. This hierarchical arrangement can significantly influence the material's overall properties and performance.

1.2.2 Properties

Fibrous networks exhibit unique mechanical behaviors that are influenced by their structural characteristics:

- Strength and stiffness: The overall strength and stiffness of the network depend on factors such as fiber properties, network density, and interconnections [12].
- Deformation behavior: Fibrous networks can undergo complex deformations, including stretching, bending, and reorganization of fibers [12].
- Porosity: The spaces between fibers contribute to the network's porosity, which affects properties like fluid flow and material density [13].
- Transport properties (functional properties): The structure of fibrous networks influences their ability to transport fluids or particles, which is crucial in applications like filtration.
- Basis weight uniformity: This property affects various characteristics of fibrous porous networks, including their porosity and mechanical behavior [13].

The morphological characteristics – in terms of fibres, and not pores – can be described by following parameters [14]. (Remark: For the morphologic characterisation of fibrous networks, a fibre-based analysis prevails, while this is not the case with foams, where a pore-based analysis is common).

- Number of nodes: Nodes are the points where fibers intersect or connect within the network [14].
- Persistence length: This property describes the stiffness of individual fibers, indicating how straight or curved they tend to be [14].
- Mesh size: The mesh size represents the average space between fibers in the network [14].
- Fractal dimension: This characteristic describes the complexity and self-similarity of the network structure [14].
- Fiber diameter: The thickness of individual fibers in the network is an important structural feature [15].

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- Fiber Alignment: The orientation and arrangement of fibers within the network can vary, affecting its overall properties [15]

1.3. Similarities and dissimilarities of foams and fibrous networks

1.3.1 Constituents

The hierarchical structure of foams is simple, consisting of a primary level (the gas-filled cells) and a secondary level (the solid matrix). The arrangement of these cells can lead to complex behaviors, but the overall hierarchy is less pronounced compared to fibrous networks. The mechanical properties of foams are primarily determined by the size and distribution of the pores and the properties of the matrix material [16]. Fibrous networks exhibit a more complex hierarchical structure, often characterized by multiple levels of organization. At the molecular level, individual fibers are composed of polymer chains, which can further aggregate into microfibrils and macrofibrils. This hierarchical organization allows for a wide range of mechanical properties, as the interactions between different levels of structure can significantly influence the overall performance of the material [17]. The hierarchical nature of fibrous networks enables them to exhibit unique mechanical behaviors, such as strain-stiffening and energy absorption, which are critical for applications in biomedical and structural materials [18]. Further, while there are also liquid foams, no liquid fibre-networks exist.

1.3.2 Anistropy

Most foams exhibit isotropic properties, meaning that their mechanical characteristics are uniform in all directions, particularly in the case of open-cell foams. This isotropy is due to the random arrangement of gas bubbles within the matrix, which allows for consistent performance regardless of the direction of applied stress [19]. However, closed-cell foams may exhibit some anisotropic behavior depending on the manufacturing process and the orientation of the cells.

Fibrous networks are typically (more) anisotropic, as their mechanical properties can vary significantly depending on the orientation of the fibers. For example, the tensile strength of a fibrous networks (e.g. paper) is often greater along the direction of the fibers compared to perpendicular directions. This anisotropic behavior is a result of the alignment and distribution of fibers within the network, which can be influenced by the manufacturing process [20]. This is also the case with bulky network structures, like the BreadCell structure, which shows transerval-isotropic or orthotropic behaviour: In-plane anisotropies occur due to the pouring process into the mould, while out-of-plane anisotropies result from collapsing in foaming and drying.

1.3.3 Strength and stiffness

Strength and Stiffness: The matrix of foams can be made from plastics/polymers, metals, or ceramics. These matrices can in most cases be considered isotropic. The foam's mechanical properties are therefore primarily influenced by the size, distribution, and connectivity of the pores [21]. In particular for closed cell foams constitutive models exist, that can estimate the mechanical behaviour of foams under compression accurately with the knowledge of the elastic modulus of the unfoamed solid material and the porosity of the foamed material [22].

The fibers in fibre networks can be made from various materials, including natural fibers (like cellulose) or synthetic polymers. In particular the cell walls of natural fibres are anisotropic theirselves. The mechanical properties of fibrous networks depend on factors such as fiber diameter, length, orientation, the degree of entanglement between fibers [23], and the strength of interaction of the fibres.

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1.3.4 Deformation Behaviour and Densification

Foams typically exhibit a non-linear stress-strain response. They show three distinct regimes during compression: linear elasticity, plateau, and densification. The underlying mechanisms are linear elasticity: (1) cell wall bend and stretch at low strains. With increasing stress, (2) the cell wall buckle and collapse. As a result, a plateau is found in the stress-strain behaviour of foams at intermediate strains. Eventually (3) densification occurs, where cell walls contact each other, leading to rapid stress increase at high strains.

Fibrous networks often display a strain-stiffening response. They show a transition from bending-dominated to stretching-dominated behavior. The underlying mechanisms are governed primarily by fiber bending and rotation (at low strains), fiber alignment and stretching, which becomes more dominate at higher strains. In any stage, the network connectivity and fiber properties significantly influence the overall response: fibers can bend, stretch, or break – and so can their bonds at the entanglement points [20] [23].

Practically this means, that most foams show a higher primary stiffness, and a higher crush strength (or strength at strains lower than 5%) than fibrous networks. Due to the formation of skins during drying of fibre networks, the buckling of these skins when loaded parallel to the skin plane results in a behaviour similar to that observed in foams. However, in fibre networks these buckling mechanisms are on a higher length scale (macroscopic) than in foams (mesocopic).

In summary, foams generally exhibit strain-softening at intermediate strains (plateau region), while fibrous networks often display strain-stiffening behavior. The micro-mechanical models of fibrous networks, established within the project BreadCell, indicate that buckling induced strain softening would be – theoretically – observable, when more control over fibre orientation would be possible.

1.3.5 Morphology and its characterisation

In order to achieve comparability with foams, fibre networks are also often described in terms of the morphology of their pores (size, orientation, shape). However, due to the geometry of the fibres, which can be assumed to be slender or 1-dimensional (linear expansion significantly exceeds the other dimensions), the fibre-based morphological characterisation is more characteristic and accurate. Only when additives such as carboxymethyl cellulose (CMC) or nanofibrillated cellulose (NFC) lead to the formation of flat, surface like structures in the sense of pore walls does morphological characterisation based on pore formation appear appropriate. In the case of the BreadCell project, both characterisations were carried out [24]. However, it is worth mentioning that characterisation at fibre level is technically much more complex.

In terms of morphology foams exhibit with well-defined, more regular shaped pores, and more homogenous porosity, while fibrous networks exhibit variable porosity with irregular pore shapes. Further the base structural elements of foams and fibrous networks are considerably different: The structural elements of foams on mesoscopic level consist of cell walls and struts, while that of fibrous networks are individual fibers and filaments.

1.3.6 Strain-rate behaviour

The strain-rate effects in foams are influenced by the base material properties, microstructural effects and macroscopic effects:

- Base material properties: The viscoelastic nature of most polymers contributes to rate sensitivity in polymeric foams [25], like polyvinyl chloride (PVC) [26].
- Micro-inertial effects are induced be the cell wall deformation: At higher strain rates, there is a delay in cell wall buckling due to micro-inertia effects, which prolongs uniaxial compression of cell walls [26]. This also means, that the initial orientation of cell walls affects the micro-inertial response [26].

- Macro-inertial effects: At high impact velocities, shock wave (propagation) effects become significant and contribute to the overall strain rate sensitivity [26]. The relative density of the foam influences its strain rate sensitivity and energy absorption characteristics [25][27].
- Fluid dynamic effects: Entrapped gas within closed-cell foams influences the velocity field and strain distribution under impact [26]. In some foams, gas can be effectively retained within cells during high-speed impact, affecting the mechanical response [26].

The dominant mechanisms can vary depending on the strain rate regime: At low to intermediate strain rates, micro-inertial effects may be more prominent [26]. In the shock regime (very high strain rates), macro-inertial effects become more significant [26], though their relative contribution is debated [14]. The same mechanisms come into play in fibrous networks, i.e.,

- Viscosity: One of the primary sources of strain-rate effects in cellulose networks is the viscoelastic nature of cellulose itself.
- Micro-inertial effects: At very high strain rates, inertial effects become significant. Some studies have observed that curled cellulose nanofibers within network structures do not have enough time to uncurl before failure at high strain rates [28].
- Fluid dynamic effects: As opposed to closed pore foams, fluid dynamic and entrapment effects are likely less relevant, due to the fibrous networks' open cell morphology.

Within the project BreadCell, high-strain rate compression experiments have been conducted, which showed a surprisingly strong strain rate amplification, exceeding that of many synthetic foams, in particular when density is low. This should put our focus on other (speculated) strain-rate mechanisms for cellulose-based fibrous networks:

- Strain-induced crystallization: In some cases, rapid straining can induce crystallization in amorphous regions of cellulose, affecting the mechanical properties [28].
- Structural rearrangement: The rate of loading affects how quickly the cellulose network can rearrange its structure to accommodate stress. Slower rates allow more time for structural adaptation [29].
- Rate-dependent failure mechanisms: The mode of failure in cellulose networks can change with strain rate. At higher rates, there may be less time for gradual damage accumulation, e.g. in hydrogen bonds, leading to more sudden failure [30].

Random fibre network models indicate that stress variations increase with decreasing density, i.e. stress-concentrations become more pronounced in lower density structures. These stress-concentrations can lead to sudden fibre movements, where already slight movements can lead to significant stress redistributions [31]. Assuming that this sudden fibre movement stems also from failure, one could speculate, that the load-redistribution and stress-relaxation is delayed upon rapid loading, due to a delay in damage accumulation and failure. This would also explain, why strain rate amplification increases with decreasing density.

1.3.7 Buoyancy

Closed-cell foam generally provides superior buoyancy compared to open-cell foams and generally open-cell structures, which includes fibre networks. This is due to its structure of sealed, air-filled cells that prevent liquids from entering the foam. The closed cell structure makes this type of foam water-resistant and allows it to maintain its buoyancy even when submerged for extended periods [32]. Due to these differences, closed-cell foam is the preferred choice for marine flotation applications, such as life jackets and buoyancy aids, barges and docks [33]. Open-cell foam, while less suitable for direct water contact, still has uses in marine environments, such as cushioning for boat seating.

1.3.8 Acoustic properties/sound absorption

Foams are widely recognized for their sound-absorbing capabilities. The porous structure of foams allows for the dissipation of sound energy through multiple reflections and interactions with the foam material. The air-flow resistivity (e.g. of polyurethane foams) was found to significantly influence their sound absorption characteristics, with higher resistivity leading to better sound absorption properties [34]. The sound absorption foams varies with frequency, and depends on cell morphology and pore size, indicating that foams can be optimized for specific sound frequencies [35]. Foams absorb sound through air trapped in interconnected pores, viscous and thermal losses within the cellular structure and resonance of the foam structure.

Fibrous networks absorb sound primarily through viscous and thermal losses as sound waves pass through the interstitial spaces between fibers. Voronina noted that the acoustic properties of fibrous materials are influenced by factors such as fiber diameter, density, and orientation, which affect the material's ability to dissipate sound energy [36]. The directional arrangement of fibers, i.e. this anisotropy can lead to variations in sound absorption depending on the direction of the sound wave relative to the fiber orientation. This characteristic can be advantageous in applications where specific directional sound absorption is required [37].

The acoustic properties of fibre networks are influenced by: Fibre dimensions (length and width), fibre flexibility, chemical composition and surface properties, fibre volume fraction and network density and porosity. Natural fibre-based composites often outperform synthetic materials in sound absorption [38]. Smaller fibre diameters generally provide better sound absorption [39].

Natural fibre composites (e.g., jute, flax) [40] and fibre networks, such as wood-based pulp fibre foams, provide absorption comparable to conventional porous materials [39]. Fibre networks often perform well in mid to high frequency ranges. Foams can be tailored to absorb sound across a wide frequency spectrum. In both materials the acoustic properties can be affected by moisture [41].

1.3.9 Thermal properties/insulation

The gas trapped in the pores of foams has a very low thermal conductivity, providing excellent insulation [42]. The solid matrix of the foam also contributes to insulation, but to a lesser extent than the trapped gas. Typical foam insulation materials like polyurethane have thermal conductivity values around 0.023-0.026 W/m·K [42]. Wood pulp foams typically have thermal conductivity values in the range of 0.040-0.050 W/m·K. Nanocellulose-based foams have shown thermal conductivity values between 0.020-0.040 W/m·K [43] [44].

Network structures rely on the low thermal conductivity of the solid material itself. They also trap air within their structure, but less effectively than foams. Heat transfer is impeded by the tortuous path through the material. As a consequence, the thermal conductivity varies depending on the material and structure.

In conclusion, foams generally offer superior thermal insulation properties due to their ability to trap gases with extremely low thermal conductivity [42] [45] (The latter might be a 'surprising' reference, but provides a great comparison on the thermal insulations of various materials: Fishermen's guide to insulation). However, network structures can be engineered to approach foam performance.

1.3.10 Transport behaviour

Foams and fibrous network structures exhibit distinct transport behaviors due to their unique structural characteristics. Fluid transport in foams occurs primarily through the interconnected channels between pores. As foam drains, the liquid flows through these channels, leading to coarsening of the foam structure over time [46]. The pores size distribution and foam stability significantly influence the transport behavior. Fluid transport in fibrous networks occurs through the pore spaces between fibers. The orientation and density of fibers greatly affect the

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flow paths and transport properties [47]. Fibrous networks can exhibit anisotropic transport behavior due to preferential fiber alignment [48,46].

Foam permeability is generally lower than that of fibrous networks due to the more tortuous flow paths created by the bubble structure. Fibrous networks often have higher permeability compared to foams, especially in the direction of fiber alignment. The permeability of fibrous networks can be more easily tailored by adjusting fiber properties and arrangement [49].

Pressure drop in foams is generally higher due to the complex flow paths through the bubble network. The pressure drop can vary significantly with foam density and bubble size distribution [50]. Pressure drop in fibrous networks is typically lower than in foams, especially for low-density structures. The pressure drop can be optimized by adjusting fiber orientation and network density [51].

Foams can exhibit excellent absorption properties, especially for liquids. The absorption capacity is influenced by the foam's porosity and surface properties of the bubble walls [52]. Fibrous networks can be designed for high absorption capacity, particularly when using materials like nanocellulose. The absorption and retention properties can be tailored by adjusting fiber surface chemistry and network structure [52,47].

Under compression, foams can experience significant changes in transport properties due to the collapse of bubble structures. The recovery of transport properties after deformation depends on the foam's elasticity and structural integrity [53]. Fibrous networks can maintain better transport properties under compression, especially when using resilient fibers. The mechanical response of fibrous networks can be tailored to maintain porosity and transport functionality under load [53,47].

In summary, while both foams and fibrous networks can be engineered for specific transport behaviors, fibrous networks generally offer greater flexibility in tailoring properties and often exhibit superior permeability and pressure drop characteristics. Foams, on the other hand, can provide unique absorption properties and structural stability in certain applications.

1.3.11 Specific surface area

Foams, particularly ceramic and metallic foams, are known for their high porosity and specific surface areas: Metal foams like copper foam can have specific surface areas ranging from about 100 to 600 cm^2/cm^3, depending on porosity and pore size [54]. Ceramic foams can achieve even higher specific surface areas, with some reaching over 1000 cm^2/cm^3 [55]. Huo et al. reported that silica foams can achieve specific surface areas ranging from 400 to 1200 m^2/g, depending on their structural characteristics and synthesis conditions [56]. The specific surface area of foams is heavily influenced by factors such as porosity, pore size, material composition and manufacturing method. A high specific surface area is advantageous for applications such as catalysis and adsorption, where increased surface area facilitates enhanced interaction with reactants or adsorbates.

In fiber networks, particularly those reinforced with natural fibers, an increased specific surface area can improve the mechanical properties due to the increased interfacial contact between fibers and the matrix material, but also between fibre and fibre. For instance, alkali treatment of wood fibers has been shown to enhance their surface area and roughness, leading to better adhesion and stress transfer in composites [57]. The specific surface area of wood pulp fibers can vary depending on several factors, but typically falls within a certain range, 30-300 m^2/g [58]. However, the exact value depends on factors like pulp type (softwood vs hardwood), processing method (mechanical vs chemical pulping), degree of refining/beating and drying conditions [59].

The beating process increases the specific surface area by fibrillating the fiber surface and creating fines [59]. This can significantly increase the surface area accessible for bonding. Harsh drying conditions can cause hornification, reducing the surface area. Gentler drying methods help preserve a higher surface area [60]. Chemical pulps tend to have higher specific surface areas compared to mechanical pulps due to the removal of lignin and hemicellulose [61].

The specific surface area is an important property that influences: Fiber bonding potential, water retention, chemical reactivity and strength properties A higher specific surface area generally correlates with increased bonding ability and paper strength [61] [58]. This difference in specific surface area makes foams more suitable for applications requiring high surface area, such as catalysis, Filtration, heat exchange and adsorption of gases or liquids.

1.3.12 Production

Foam production involves creating a dispersion of gas bubbles in a liquid or solid medium [62–64]. The production methods can be categorized in

- Gas dispersion methods
    - Mechanical agitation: One of the most common methods for producing foams is through mechanical agitation. This process involves rapidly mixing air or another gas into a liquid containing a surfactant. The surfactant helps stabilize the foam by reducing surface tension at the gas-liquid interface.
    - Gas injection: In this method, gas is directly injected into a liquid or molten material. The gas forms bubbles, which are then stabilized by surfactants or other additives. This technique is often used in the production of polymer foams.
- Chemical reactions
    - Chemical blowing agents: Foams can be produced by incorporating chemical blowing agents into a material. When heated or subjected to specific conditions, these agents decompose, releasing gas that forms bubbles within the material. This method is commonly used in the production of plastic foams.
- Physical processes
    - Supersaturation: Foams can also be created by suddenly reducing the pressure of a liquid saturated with dissolved gas. This causes the gas to come out of solution, forming bubbles. This principle is used in the production of carbonated beverages and some types of foam materials.
    - Freeze-drying: Certain types of solid foams, particularly in food applications, are produced through freeze-drying. This process involves freezing a liquid mixture and then sublimating the ice under vacuum, leaving behind a porous foam structure.

With fibrous networks other routes can come into play, like electrospinning, wet spinning, melt spinning, and self-assembly processes. Here, we focus on the production of pulp fibre networks only: Processes summarized for foams, like mechanical (e.g. whipping) or chemical (e.g. fermentation) are applied as well, however, this foaming can be rather considered a vehicle to achieve a porous structure. The foaming helps achieve desired bulk and porosity in the final product [65].

1.3.13 Concluding Remarks

Based on the differences identified in Chapter 1.3, it is clear that the terms 'foam' and 'fibrous network' are not synonymous - even though these terms are often used interchangeably in the literature. This synonymous use is due to the

- overlapping fields of application,
- production process, where foam forming of fiber networks is common,
- overlapping properties,
- conciseness and handiness of the word 'foam', as well as due to the

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- easier discoverability in digital searches.

In the following chapters, the distinction between the terms is recognised and therefore are not used synonymously or interchangeably.

2. Applications of foams in automotive engineering

2.1. Overview of use areas

Foams are extensively used in automotive engineering for various applications, enhancing comfort, safety, and performance, mostly using polyurethane (PUR), expanded polystyrene (EPS), expanded polypropylene (EPP) and ethylene-vinyl acetate (EVA).

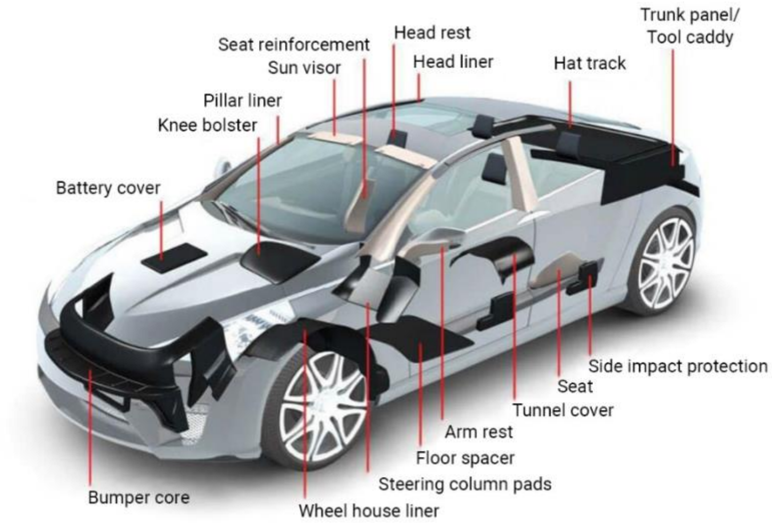

Figure 1: Applications of foam in the car, mainly for impact energy management [66]

Interior applications:

- Seating: Foams are widely used in car seats, providing cushioning and support [67,68]. Polyurethane foam is commonly employed, with different densities, providing i.e. different firmness.
- Headliners: The car's headliner, which covers the internal roof, incorporates foam underneath the fabric covering [67].
- Armrests and door Panels: Foam is used to pad armrests and door panels, enhancing comfort and providing an extra layer of protection.
- Dashboard and Instrument Panels: Polyurethane foam is often used in dashboards and door panels for insulation and noise reduction. [69]
- Airbag systems: Polyurethane foam plays a crucial role in modern airbag systems, expanding upon impact to provide additional cushioning and protection [70].
- Trunk system: EPP or EPS foam is used to create various molded components in the trunk systems [68].
- Floor mats and carpet underlay: EVA foam is widely utilized in automotive floor mats and carpet underlay due to its excellent cushioning, insulation, and protective qualities. It effectively safeguards against dirt, debris, and spills, contributing to the cleanliness and durability of a vehicle's interior flooring. Additionally, EVA foam plays a key role in anti-fatigue and comfort solutions, such as footwell mats [71].

Exterior Applications

- Bumpers: Foam is used in bumper systems for impact absorption. EVA foam is utilized in bumper and grille inserts to improve impact resistance and safeguard the vehicle's exterior against minor collisions. It effectively absorbs energy, minimizing damage during low-speed impacts. [71]
- Roof racks and cargo carriers: EVA foam provides padding and protection for items transported on the vehicle's roof. By utilizing various types of foam in these applications, automotive engineers can enhance vehicle safety, comfort, and performance while often reducing overall weight and improving fuel efficiency.
- "Gaskets and seals: EVA foam is employed as gaskets and seals in automotive settings to ensure a snug and secure fit. This application effectively prevents the entry of water, dust, and noise, helping to preserve the integrity of various components and minimizing the likelihood of leaks." [71]

There they take up various functional roles, like

- Impact absorption: Foam components are used for shock absorption in various parts of the vehicle.
- Noise and vibration reduction: Polyurethane foam is applied in engine compartments, door panels, and underbody areas to reduce noise and vibrations, creating a quieter and more comfortable cabin environment.
- Structural reinforcement: Polyurethane foam can be injected into hollow cavities within a vehicle's body to increase overall strength and rigidity.
- Automotive adhesives and bonding: Polyurethan foams are used as gap filling adhesives, providing flexibility and damping – e.g. between side-impact beam and door metal sheet.

2.2. Impact energy management

Foams are widely used in various components of cars for impact energy management and safety purposes:

- Bumper system: Foam absorbers are integrated behind the bumper fascia, ahead of the bumper cross-beam, to absorb low-speed impact energy [72], but also to provide protection to vulnerable road users, e.g. pedestrians. EPP foam is commonly used in bumper systems for its excellent energy absorption and resilience [73].
- Dashboard: Foam padding is used in the dashboard area, including knee bolsters, to protect occupants during frontal impacts [73]. PUR foams are the primary type of foam used in car dashboards. Semi-open Ethylene Propylene Diene Monomer (EPDM) foams (e.g. NITTO) are also common.
- Door panels: Side-impact foam padding is integrated into door panels for occupant protection in side collisions. PUR foam is one of the most common materials used in door panels: Flexible PUR foam is used to create soft, cushioned surfaces for armrests and other touchpoints, while rigid PUR foam may be used for structural components or insulation within the door panel. EVA Foam is another popular choice for door panel components, as it provides cushioning and impact absorption, offers good sound and vibration dampening and is resistant to water, UV rays, and chemicals. EVA foam is often used in areas requiring softer touch or additional padding within the door panel structure.
- Headliner: Impact absorbers made of foam are incorporated into the headliner for head protection [74]. The headliner foam is typically constructed as a multi-layer sandwich [75], consisting of a foam core, usually made from semi-rigid polyurethane or less common from polyethylene (PE) foam [67], backing material (e.g. fiberglass), and a decorative fabric or vinyl cover.

Figure 2: Foam cushions give the seat its form and function [1]

- Seats: Seats do not only contain comfort foams, but also for impact energy management, like the in headrests or in the seat-pan [74,73].

Figure 3: Anti-Submarining Ramp and Headrest Core made from EPP [76]

- Floor pan: Impact absorbers made of foam can be integrated into the floor structure.
- Roof rails: EPP foam is used in roof rail components for energy absorption and lightweight design [73].

The use of foam materials, particularly EPP and PUR foams, in these areas helps to enhance vehicle safety by absorbing and dissipating impact energy, while also contributing to lightweight design and improved comfort [75]. The specific density, thickness, and composition of the foam can be tailored to meet the required energy absorption characteristics for different areas of the vehicle [75].

In impact energy management, various properties need to be considered:

- Crush depth: The distance to bring an impactor (be it another roaduser or the occupant) to an halt is limited due to design constraints. Assuming a triangular acceleration-time response for decelerating the impactor, ideally the peak acceleration must be in the first phase, to limit crush depth. This means, that structures that buckle are somewhat ideal, because they tend to produce high accelerations in the very first phase of impact – before the crush force levels off. Additionally high initial stiffness of the structure is preferred too, in order to gain the maximum deceleration early.
- Densification Strain: If the base material has a higher density, the densification strain tends to increase for a given foam density. A higher densification strain means also that the structure provides more exploitable crush depth. By definition the energy absorption efficiency is maximum at the densification strain. Then the energy absorption efficiency is degrading again.
- Strain rate dependency: Materials and structures that become stiffer and stronger upon rapid loading, allow for a degree of load-severity adaption, i.e. provide low forces at low impact speed, high forces/decelerations at high impact speed.
- Resilience: In some applications, e.g. in bumper foams, the foam shall regain its initial shape after deformation – such that it provides energy absorption in repeated impacts.

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- Hysteretic unloading: While regaining its initial shape appear beneficial in the first place (multi-impact ability), there is also a drawback to this behaviour. In the impact phase, the kinetic energy of an impactor is converted to internal energy, stored in the (foam) material. In the restitution phase, i.e. in the unloading phase, the internal energy is partly reconverted to kinetic energy. However, this increases the velocity change of the impactor and the time span of loading. In some cases this means an additional injury risk. Therefore, a restitution should occur at a much lower rate, i.e. the foam should show hysteretic unloading.

As outlined earlier, pulp fibre network structures have a low primary stiffness. They also lack a pronounced strain-softening observed with foams, where this is induced by cell-wall buckling. However, cellulose and wood pulp fibres have a high density, which means, they provide higher densification strains than most synthetic polymers. Also wood-pulp fibre structures show a pronounced load-rate amplification.

2.3. Thermal insulation

Door panels and headliners in the automotive interior do not only provide acoustic insulation, and provide protection against injury by mitigating hard contacts against structural parts of the vehicle cabin, but they also provide thermal insulation. The firewall physically separates the engine compartment from the passenger compartment of the vehicle [77]. This creates a barrier between the mechanical components and the occupants. The firewall insulates the passenger compartment from the heat generated by the engine, improving comfort for the vehicle's occupants. Additionally, the firewall acts as a sound-deadening barrier, reducing engine noise that enters the passenger cabin. As its name suggests, the firewall is designed to resist fire breakthrough from the engine compartment to the passenger area [78].

Several types of foam materials are commonly used in vehicle firewalls for heat and sound insulation, e.g. melamine foam combined with a foil heat shield (MegaBlock™) [79], which reflects up to 98% of radiant heat

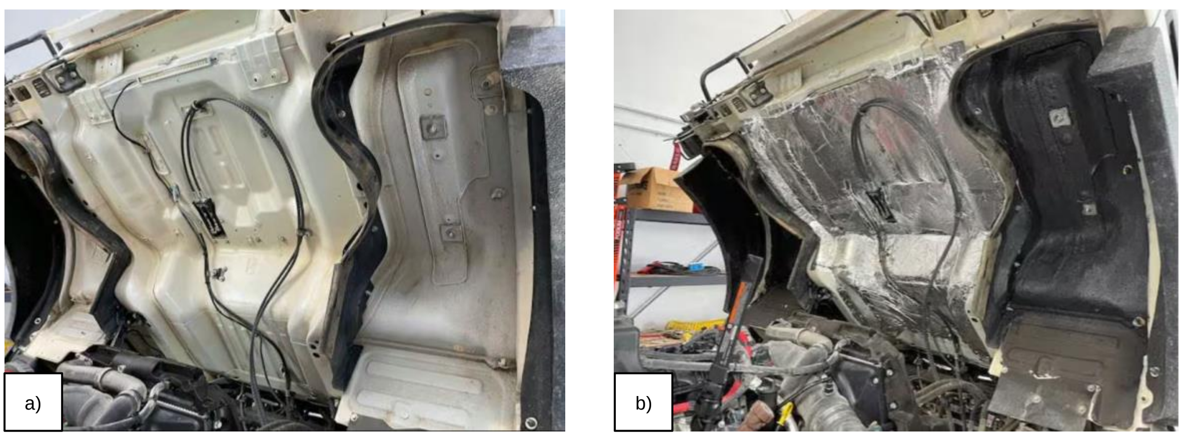

Figure 4: Firewall of heavy-duty vehicle: a) before and b) after thermal insulation by MegaBlock™ foam [79]

energy [80]. This lightweight and flexible foam is water-resistant and can withstand high temperatures, making it ideal for use in engine compartments.

Firewalls may incorporate glass-fiber reinforced materials, which can include foam components. For instance, some firewalls use hot-pressed glass-fiber reinforced polypropylene with a 40% glass fiber content [78]. This material offers a good balance of strength, fire resistance, and insulation properties. In some cases, a polymer foam is used to join layers of a firewall laminate. This can consist of a sheet metal layer combined with a plastic layer, with the foam providing additional insulation and bonding properties.

Besides melamin foams, PUR foams are widely employed in automotive firewalls. The thickness of the PUR foam can be optimized to achieve the desired sound absorption and insulation characteristics, making it a versatile choice for automotive applications [81,82]. Banka introduced a dual-layered lightweight fire-resistant PUR foam composite specifically designed for acoustical insulation in automotive firewalls. This composite enhances sound absorption while providing fire resistance [83]. The synergistic effect of the dual foam layers improves the overall performance of the firewall in terms of noise reduction and thermal management.

Figure 5: Tailor-made PUR-insulation panels for bonnet [82]

Ghasemi investigated the effect of cellulose nanofillers [84] on the morphology, mechanical, and thermal properties of flexible PUR foam, namely cellulose nanocrystals (CNC), CNF, and cellulose filaments with a relative weight content of 0.025–0.8 wt% and compared those with inorganic nanofillers including nanosilica (nSi), reduced graphene oxide, and halloysite nanotubes. The compound with 0.1wt% CNF performed best, resulting in a 44% increase in the compressive modulus – but led to a loss in thermal stability (temperature at 50% weight loss decreased from 350 to 325 °C).

Besides foams, fibre network structures are employed, for combining insulation and fire resistance in the firewall, e.g. glass wool [85], mineral wood and ceramic wool [86]. In an attempt, to replace these by more renewable materials, advanced composites are investigated for their applicability in the vehicle's firewall, like rice husk ash reinforced calabash-epoxy composite [87].

In any case the material must meet strict fire resistance and safety standards while providing effective heat and sound insulation.

A very demanding application for foams is the mitigation of thermal propagation, that is, that the failure of cell is not propagating to the next cell. These foams are called "Thermal barrier shields" or "Compression pads" and "Battery encapsulation". In any case, silicone foams prevail in this application field, for its excellent thermal stability (from -60 to 250 °C) and, because they do no produce gases upon burning, but ceramify (form ceramics) temperatures exceeding 300 °C. Silicon foams can be tailored in terms of compressibility and provides low density (10-50 g/l), high water resistance, excellent dielectric strength, high thermal stability, low flammability, fast curing, very low thermal conductivity (0.1 W/mK) and high electric and thermal insulation [88].

- "Cell Encapsulations / pottings" [88,89]: Liquid dispensable silicones are excellent candidates for electric vehicle (EV) battery cell encapsulation. They offer several advantages for this application:
    - Easy dispensing and filling into dense battery modules due to good flowability
    - Room temperature curing while generating negligible heat, ensuring cell safety
    - Final product form can be a gel, elastomer or foam encapsulant
    - Good electrical isolation, mechanical protection, and stability during battery operation

The liquid precursors of gels and encapsulants are easily dispensed with standard two-part dispensing systems using a static mixer. For foams, static-dynamic or dynamic mix heads are suggested for optimum foaming results. These silicone encapsulants provide crucial thermal management and protection for EV battery cells [90]. Their ability to cure at room temperature with minimal heat generation is particularly important for maintaining cell safety during the encapsulation process. The resulting encapsulant, whether in gel, elastomer, or foam form, offers excellent electrical isolation and mechanical protection, helping to ensure long-term stability and performance of the battery pack.

Figure 6: Example of silicone-foam (cyan) encapsulation of Tesla battery pack after dismatling for examination [90]

- "Thermal barriers / compression pads": While cell encapsulations are the way to go with cyclindrical cells, in prismatic and pouch cells so called sheet-like compression pads are used in between the cells. As opposed to cylindrical cells, considerable swelling and breathing is observed in pouch cells. This means that the cells get thicker at higher states-of-charge (breathing), but also as the grow older (swelling). Additionally, it was found, that aging of cells can be reduced, when the cells are prestrained. To allow for a (nearly) constant prestraining, at various breath and swell states, foam pads are placed in between the cells. Liquid silicone foam products can be converted into foam sheets that offer several advantages for battery pack applications. These sheets can be easily placed or adhered between battery cells, battery modules, or in other areas of the pack, providing versatile protection and insulation. Silicone foam sheets are low-density materials that function effectively as compression pads with low compression set (less than 10%). This property allows them to maintain their shape and performance over time, even under constant pressure. One of the key benefits of silicone foam sheets is their excellent thermal insulation properties. This characteristic is crucial for maintaining optimal battery temperature and preventing thermal propagation in the event of a thermal runaway

  The minimal hysteresis ensures rapid recovery after compression, maintaining consistent performance. The pads can withstand over 1000 cycles, providing long-lasting reliability – and unlike some materials that may degrade over time, silicone foams do not produce powder or debris. These properties combine to create a durable, efficient, and safe solution for battery pack insulation and protection.

2.4. Acoustic insulation

Acoustic insulation in automotive applications utilizes several types of foams, each with specific properties suited for different areas of the vehicle. Again, PUR is "leading the gang" due to its versatility and excellent sound-absorbing properties [91]. This includes the widely used high resilience (HR) flexible foams, but also densified flexible PUR foams, which are harder with a smaller internal pore, used for small filler and acoustic protection parts. The polyurethane can contain also non-woven material inserts – and are often formed as a laminate, where the PUR foam is used on a EPDM blanket and joined with a fabric carpet [91] or a sound permeable film [85].

Both open cell and closed cell foams are used in automotive acoustic insulation: Open cell foams are excellent for sound absorption, especially for mid to high-frequency sound waves. It is often used in door cavities and cargo areas of commercial vans [92], while closed cell foam are more durable and resistant to (cyclic) compression. It is effective as a sound isolator and insulator, often used behind rattling plastic panels.

Hydrophobic melamine foam (HMF), which considered one of the best materials for improving automotive acoustics, can be found in door cavities and cargo areas [92] – but is less common than PUR based foams. When selecting foams for acoustic insulation in automotive applications, factors such as sound absorption, durability, heat resistance, and space constraints must be considered. The choice often depends on the specific area of the vehicle and the particular acoustic challenges it presents.

2.5. Sealing

Typical applications of cellular sealing solutions are for the Interior cabin systems, HVAC (Heating ventilation and air conditioning), Fuel tank systems, Li-ion and electric battery, and boot and tailgate systems [93] [94] [95]

Figure 7: Aftermarket noise insulation PE foam mats from "Standartplast" applied to interior floor [95]

- Interior cabin systems [96,97]:
  - Closed cell EPDM foam is one of the most popular choices for automotive sealing solutions. It offers excellent sealing properties against air, dust, and water migration, making it ideal for weatherstripping vehicle interior cabins and cockpits. EPDM foam also provides resistance to aging, UV radiation, ozone, and oxidation, good thermal stability across a wide temperature range, excellent compression set resistance. EPDM foam is used in various automotive applications, including gaskets, strips, washers, and pads.
  - Semi-closed EPDM foam are used in the car interior, e.g. for watertight seals in interior trims (at 50-80% compression) [98,99].

- Water repellant open cell flexible PUR foams ("Superseal") provide good water sealing properties, low water absorption, low air permeability, low compression hardness and very low weight (30-50 kg/m³). A good seal is gained when compressed at 80%. it is also more price competitive when compared to other high-performance sealing materials/product.

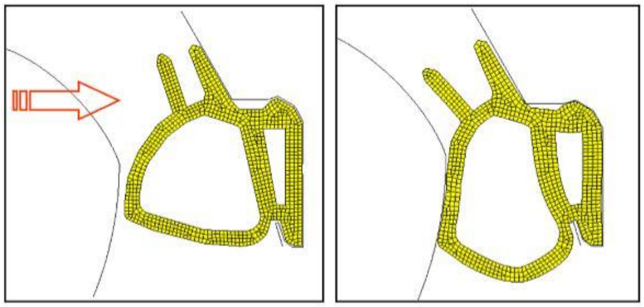

Figure 8: Undeformed and deformed geometry of a complex seal [98]

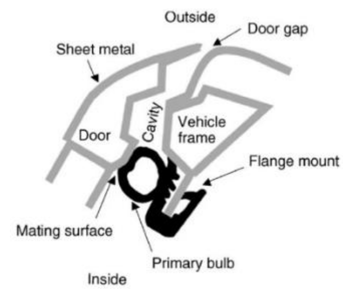

Figure 9: Cross-section of weather-stripping of vehicle doors [99]

- HVAC:
  - Closed cell polyethylene foam (PE and LDPE foam) is cost effective and rigid, providing excellent HVAC seals under little compression, high durability, high strength, at comparatively low weight. The foams provide a smooth surface, excellent consistency, gauge control and low water absorption and vapour transmission. They are exceptionally ozone, UV, chemical and weather resistant. Polyethylene foam gaskets and sealing are mainly used for evaporator units and air-condition heater controller modules. The smooth surface offers which provide acoustic, NVH, thermal and high-performance sealing properties.
  - Open cell PUR foam seal against air, dust and water migration and can be found as foams strips and gaskets can in many HVAC components, including ducts, ducting, evaporator units, hoses, wiring harness and A/C heater controller module. It can be tailored to be conductive, static dissipative and flame-retardant.
  - Closed cell PVC [100] foam is another popular choice for automotive sealing applications. It offers durability and flexibility, resistance to UV radiation, petroleum, and cleaning solutions, low VOC emissions and complies with various automotive material specifications. PVC foam is used in HVAC ducting (seal joints, reduce vibration), but also in applications such as bodyside mirror attachment, quarter window seals and tail lights and headlamps. It is relatively strong and remains pliable at temperatures of -40°C to 80 °C.
- Tank systems
  - Closed cell neoprene-EPDM foam blends are resistant against oil and petrochemical substances, ageing, UV, ozone and oxidation, while providing excellent seal capability under compression as well as thermal conductivity. These blends are not only used for sealing, but for noise-vibration-harshness requirements and anti-rattle, and are used or fuel tanks, tank harnesses, hoses and piping.
  - Closed cell nitrile butadiene rubber (NBR) is a synthetic rubber copolymer of butadiene and acrylonitrile and provides high resistant to oils and fuels, and is thermally stable across a wide range of temperatures ranging from -20 to +100 ˚C. But it is not resistant against UV/ozone attack. NBR is used as O-rings, fuel tank gaskets and seals.
- Battery housings:
  - Closed cell silicone rubber foam is valued in automotive applications for its ability to maintain physical properties over a wide temperature range [101,102]. Key characteristics include wide service temperature range (approximately -50 to 200 °C), high ignition resistance and excellent resistance to environmental factors.

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- Closed cell polyamide foam – Polyamide NB foam provides excellent sealing properties over an extremely wide temperature range from 70 to +200°C. The densities range from 30 – 100 kg/m³.

Figure 10: Automated application of rubber sealant on battery pack housing (and close-up) [102]

So, as opposed to other foam material choices in the automotive industry, where PUR and EPP prevail, in sealing the material choice is more diverse, and the choice of foam depends on the specific requirements of each application, considering factors such as temperature resistance, chemical compatibility, and durability.

Surprisingly not only closed pore foams are applied in sealing, but also waterproof semi- and open-cell foams.

2.6. Load distribution and comfort

The most important characteristics of comfort foams are [103,104]:

- Density and firmness
  - Higher polymer density generally leads to better retention of original properties.
  - Firmness is measured by Indentation Force Deflection (IFD) and is independent of density.
- Support factor
  - Measures foam's ability to support weight.
  - Higher support factors (1.5 to 2.6) indicate better support and prevent "bottoming out."
- Durability tests
  - Flex fatigue: Measures IFD loss after repeated compressions.
  - Roller shear: Severe test combining compression and abrasion.
  - Tear strength: Assesses resistance to tearing or shredding.
- Hysteresis: Measures foam's ability to retain original firmness.
- Resilience: Indicates surface elasticity or "springiness." Comfort foams, especially flexible PUR foams, exhibit high resilience and a favorable strength-to-weight ratio [105]. The mechanical properties are crucial for ensuring that the foam can withstand repeated use while maintaining its shape and comfort. It's typically measured by dropping a steel ball onto the foam and measuring the rebound height. Higher resilience often translates to a better "hand" or surface feel.
- Vibration damping: The ability of comfort foams to dampen vibrations is another critical property – not only for tactile comfort, but also for acoustic comfort: Seat foams can minimizing indoor noise, especially in electric vehicles where even slight noises can be perceptible [106]. Mixing with fibrous or rubbery materials (e.g. with short treated coir fibers and recycled tire particles) enhance damping and improve the vibrational characteristics, by minimizing the amplitude of resonance. Testing is for example done by exciting the foam specimens at 1 and 1.5 mm peak amplitude in the frequency range of 2–20 Hz [105]. The incorporation of natural fillers, can also improve other comfort factors like hysteresis, hardness, resilience, and support factor [107].

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- Wettability and moisture management: The wettability of comfort foams is an important factor that affects their performance, especially in applications where they are in close contact with the skin. Kan et al. emphasized that the wetting characteristics of fabric-foam-fabric plied materials significantly influence comfort properties, particularly during sweating [108]. Foams that manage moisture effectively can enhance comfort by preventing the accumulation of sweat and maintaining a dry surface.
- Air flow: This indicates that cells are open and as flexible as they should be. A minimum 2.0 cfm (cubic feet per minute) is recommended [62]:
- Flame retardancy: Safety is a crucial consideration in the automotive industry: The incorporation of flame retardants is vital for meeting safety standards and ensuring passenger safety. Okrasa et al. discussed the development of viscoelastic PUR foams with reduced flammability, ensure the and cytotoxicity which enhances their suitability for use in safety-critical applications such as automotive interiors [109] (though in this case, the manuscript was focusing on respiratory devices).
- Environmental considerations: It was shown that regenerated PUR foam (RPUF), attained from depolymerization of polyurethane waste scrap, showed similar cell-size morphology and foaming properties to that derived from the virgin polyol. The comfort properties of the RPUF with respect to sag factor, hardness, and hysteresis loss displayed comparable values to that of virgin foam. [110].

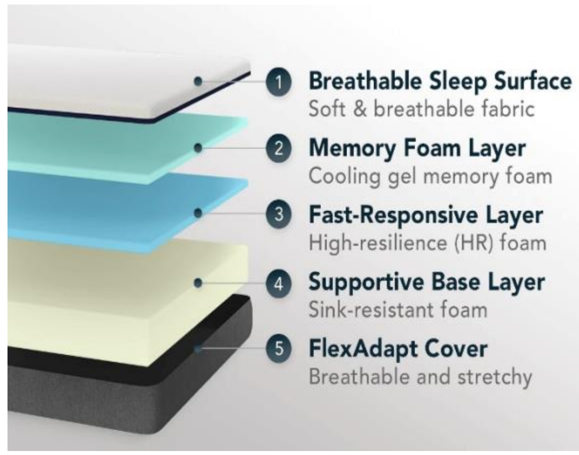

Figure 11: Foam properties example shown on foam layers of a mattress as an example of need for comfort and longevity [104]

2.7. Joining and cavity filling

PUR foam adhesives are widely utilized in the automotive industry and provide strong adhesion between dissimilar materials, such as metal and plastic, which is crucial for modern vehicle design [111]. Akkoyun and Suvacı emphasized that polyurethane is a preferred polymeric material for various applications, including automotive, due to its low manpower costs and ease of processing [112]. Polyurethane foam adhesive (PFA) is a high-performance material that develops through an exothermic chemical process. This process involves the polymerization of diisocyanate and polyol monomers, resulting in a closed-cell structure characterized by exceptional strength and rigidity [113,114]. PFAs are used as gap fillers in the automotive industry. Mostly these are 2 component urethane foams, – for anti-flutter applications such as intrusion beams, roof bows, hood webbing, etc. It expands to 10 times its original volume to fill large cavities with a small amount of material [115].

Figure 12: Applying the PUR-adhesive on a windshield frame [111]

A sort of cavity filling is also used in batteries, in the form of compression pads: These allow the cells to breath and swell (thickening due to charging and aging), while maintain a predefined compression pressure. The compression pads are made of silicone foams, mainly because they should also act as thermal barrier, and

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mitigate the propagation of cell failure due to thermal runaway. Compression pads are more closely described in the chapter on thermal insulation.

2.8. Lightweighting

Clearly porous structures have a huge potential for lightweighting in structures. This in particular applies to cores of beam- or plate-like structures. Similar to biological load bearing structures, like bones, which consist of a solid cortical outer shell and spongious trabecular core. The spongious core provides the function of a shear web, transferring loads between the outher shells.

In automotive engineering this can be achieved through multi-chamber extrusion profiles (aluminium), or roll-profiled sheet metal (steel) [116] {Claar, 2009} {Neu, 2024}.

Alternatively metallic profiles can be filled with metallic foams. This beam like structures can be used in body panels, pillars, and frame components to reduce weight while maintaining strength. They provide excellent energy-absoprtion, e.g. in crash boxes (located between the bumper and the longitudinal beams).

Aluminum foam can be integrated into vehicles through various methods, either by direct foaming or by joining through welding, bonding or mechanical fastening. While aluminum foam as cores in beams and plates offer significant benefits, there are some challenges, related to costs, design and manufacturing complexity.

2.9. Moisture and condensation management

In automotive engineering moisture control is important to mitigate condensation. Manufacturers use moisture-absorbing materials in various parts of the vehicle, such as desiccant packets placed in headlights and taillights, moisture-absorbing fabrics in upholstery and carpets, and silica gel-based products in storage compartments.

To avoid fogging in headlamps hydrophilic polymer composites, consisting of hydrogels (e.g. polyacrylamide-based) and desiccants are used. As desiccants various compoumds are considered, like calcium chloride, silica gel or lithium bromide. In that way 70-80 % water can be absorbed within 24 h [117].

Cellulose-based materials can absorb huge amounts of water, namely 25% of the dry mass from ambient vapor, in the form of bound water confined at a nanoscale in the amorphous regions of the cellulose [118]. Therefore cellulose-based materials have been considered for condensation management, particularly due to their inherent hydrophilicity and structural properties. Cellulose network structures can effectively manage moisture through various mechanisms, including adsorption, capillary action, and the formation of hydrophilic networks. Zhang et al. demonstrated that cellulose fibers enhance water adsorption by reducing the nucleation energy barrier for condensation. The cross-linked polymer chains within the cellulose structure create cages that retain adsorbed water, facilitating dew condensation when the surface temperature drops below the dew point [119]. In the given publication, this property was suggested for applications aimed at atmospheric water harvesting, where maximizing water collection efficiency is crucial – but can perhaps also be transferred to smaller scale applications, like in vehicles.

Figure 13: Reusable silica-gel pouch for moisture absorption in vehicle interior [122]

Cellulose fiber insulation made from recycled paper products can absorb up to 15% of its weight in water without losing its insulating properties [120]. It helps prevent condensation by absorbing excess moisture and redistributing it [121].

An important observation was noted by Zou et al. [118]: "bound water is transported along a network of fibers in contact, even when immersed in a liquid. This effect has important practical consequences, since it shows that in various

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materials such as paper […] in which the cellulose fibers are in direct contact the sorption and desorption processes may rely on a transport of bound water throughout the fiber network. […] this effect starts occurring once critical compression is produced […] [which] places the fibers in contact […]. These close contacts will then also allow for the transport of bound water from one fiber to another […] [Hence] changing the surface properties of the cellulose might induce changes in the diffusion throughout the network, if this can affect the characteristics of the contacts between fibers."

In summary, cellulose-based materials can be used as desiccants in industrial processes to absorb moisture from the air, preventing condensation on sensitive equipment or products [118,122].

2.10. Filtration

Foam filters play a crucial role in automotive engineering, providing effective filtration for various systems in vehicles. Here are some key aspects of foam filters used in automotive applications [123,124]:

- Air filtration: Foam filters are widely used in automotive air intake systems to prevent dust, dirt, and debris from entering the engine.
- Cabin Air Filters: Foam filters are also used in vehicle HVAC systems to purify the air entering the passenger compartment, improving air quality for occupants.

Filter foams in the context of automative applications are made from [125–128]:

- PUR, open-cell, that allows for excellent air and fluid flow while trapping contaminants. It is useful for air and water filtration in HVAC systems
- Reticulated foam, open-cell: This type of foam has a highly open cell structure, providing excellent air and fluid flow. Reticulated foam is durable and resistant to mildew and chemicals, making it suitable for demanding automotive filtration applications. It is used as pre-filter in HVAC systems. Reticulated foams can be made from various materials, and are extremely open foams, with very few to none intact cell windows. Due to its high porosity it is also used as fuel tank insert, as anti-slosh fuel tank foam
- Ceramic foam, open-cell: Ceramic foam is a porous material with high thermal resistance. It is suitable for high-temperature applications. In vehicles it is used as catalyst carrier.

However, fuel filters and oil filters rather rely on fibrous structures made from cellulose or nylon.

Figure 14: Various foam based air-filters for automotive use [129]

3. Applications of pulp fibre foams and network structures in automotive engineering

The review of scientific literature showed, that wood pulp fibres and structures made thereof are considered for applications in the automotive industry. However, pulp fibres are only considered as a composite constituent, i.e. as a fiber-reinforcement of matrix [130–135]. Examples are:

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- Wood pulp fibres are used as an reinforcement for melt-blending with extruded thermoplastics, like PA-6 [136]
- Regenerated cellulose is used in combination with polylactic acid (PLA) to form a composite for an interior floor-well panel, in the sense of a longfibre reinforced structure [137].
- Short vegetable fibres are added to PP for injection-moulding or thermoforming in trim panel production as a reinforcement [138].
- Wood pulp is mixed with phenolic resin as a binder, to form a slurry, which can be formed in a compression moulding process [138].

In summary, no example of a bulky wood pulp fibre network structure (without a matrix) currently used or considered in automotive engineering was found in the literature.

Based on the literature review on the application of foams in the automotive industry, it appears that PUR foams are likely the most common and most often used foam. Therefore, the BreadCell structure must challenge the properties of the PUR. The table below summarizes how a bulky wood pulp fibre network structure would compete against an open cell PUR foam. As the network structure is open, also an open-cell foam was considered as a direct competitor. Both, PUR foam and wood pulp fibre network structure can be modified, e.g. equipped with fire-retardants, water-repellents to improve their properties. In the present case it was assumed that both materials or structures are not modified.

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Unmodified bulky wood pulp fibre structures	compared to rigid open cell PUR	
Insulation, acoustic	o	Insulation is worse; but: due to the inhomogeneity of the BreadCell structure, the targeted frequency range is wider
Insulation, thermal	-	Less cell walls in BreadCell means also more convective mass transport
Thermal conductivity	-	PUR: 0.020-0.028 W/mK; Wood pulp fibre structure: 0.038-0.045 W/mK
Resilience, mechanic	-	Fractures in the fibre-to-fibre bonding, and fiber fracture lead to larger permanent deformation after moderate to severe compression
Stiffness, Mechanic	--	The underlying mechanics (bending and littel buckling) lead to lower stiffness
Strength - compression, Mechanic	--	The weak buckling mechanisms results in little primary stiffness
Strength- tension, mechanic	-	Cellulose fibres themselves are strong; weak point is the fibre-fibre-bond
Bend formability	+	Is the radius divided by thickness (r/t) to rupture upon bending loading:
Strain rate amplification, Mechanic	+	Strong strain-rate induced strength amplification in pulp fibre structures
Densification strain, mechanic	+	Pulp fibres have a density of 1.5 g/cm³, as opposed to 1.0 g/cm³ of unfoamed polyurethan.
Adsorbtivity	+	Sorptivity in general: PUR: 8% Water uptake in 96 h; Pulp fibre foam: 9.5-18x times own dry weight; Wood pulp fibre: Water absorption Ccapacity: 300%; Water retention value: 1.2g/g
Absorbtivity	++	Cellulose fibres provide surface adsorption / desorption, bulk absorption, hydration / dehydration; No absorption in PUR
Recyclability	+	No thermal or chemical treatment needed for recycling
Compostability	++	Pulp fibre structure is compostable
Specific surface	+	PUR (Standard): 0.1-30 m²/g; PUR (modified): 2000+ m²/g; Spruce and pine kraft pulp fibres: 32-35 m²/g; Nanofibres: 400 m²/g
Isotropy, mechanic	--	Producing a fully isotropic pulp fibre foam appears very challenging
Buoyancy	--	Higher ad- and absorptivity of cellulose fibre; open cell structures
Smoke production	-	PUR: 0.01 m²/s; pulp fibre foam: 0.01 - 0.016 m²/kg
Heat storage capacity	o	Specific heat capacity - PUR:1.4.-1.5 kJ/kg K; Pulp fibre: 1-1.4 kJ/kg K
Biocompatibility/ cytotoxicity	++	PUR: IC50: 4.3 mg/ml; BreadCell: IC50: ~50 mg/ml

4. Upgrading and modification of pulp fibre foams

For wood pulp fibre structures to be considered in the application in the context of automotive engineering, they have to be modified, in order to meet requirements particular in terms of strength, fire resistance and hydrophobicity. Below a very short overview on possible modification methods is outlined.

4.1. Mechanical strength and performance

To improve the mechanical strength of wood-pulp fibre structure, several key methods can be employed:

Choosing the right type of pulp is crucial for enhancing strength. Chemical wood pulp typically offers the highest fiber adhesion, followed by cotton pulp, while mechanical wood pulp has the lowest adhesion [139]. The cellulose content and molecular chain length in the pulp also play important roles, as longer cellulose chains contribute to stronger fibers [3].

Adding chemical additives, e.g. wet strength agents, like polyamide epichlorohydrin (PAE) resin, to the pulp slurry can significantly improve both dry and wet strength of pulp fibre structures. Clearly this limits the ecologic benefit of such structures, but already small amounts (0.2%) of PAE can increase dry strength by nearly three times [140]. Also other polymeric retention agents to the pulp can improve mechanical properties by holding fibers together more effectively, resulting in a stronger structure [141]. But also coatings, e.g. such as those derived from modified camelina oil, can improve both mechanical and barrier properties [142].

As dry strength agents, hydrophilic substances can be added, such as starch, protein, or vegetable gum, which can increase interfibral adhesion. These additives form hydrogen bonds with cellulose fibers, strengthening the connections between them [139].

Proper refining of the pulp is crucial. It increases the specific surface area of fibers and promotes better bonding. However, over-beating can lead to fiber damage and reduced strength. Controlling the drying process is important too as it affects the formation of hydrogen bonds between fibers. Drying helps maintain the strength developed during the wet stages of papermaking[139].

A comprehensive overview on possible methods to improve the extensibility potential of fibrous networks is given by Vishtal and Retulainen [143]. Their review focuses on paper and its extensibility, but can, of course be considered valid for any wood-pulp fibre network and its mechanical performance in general.

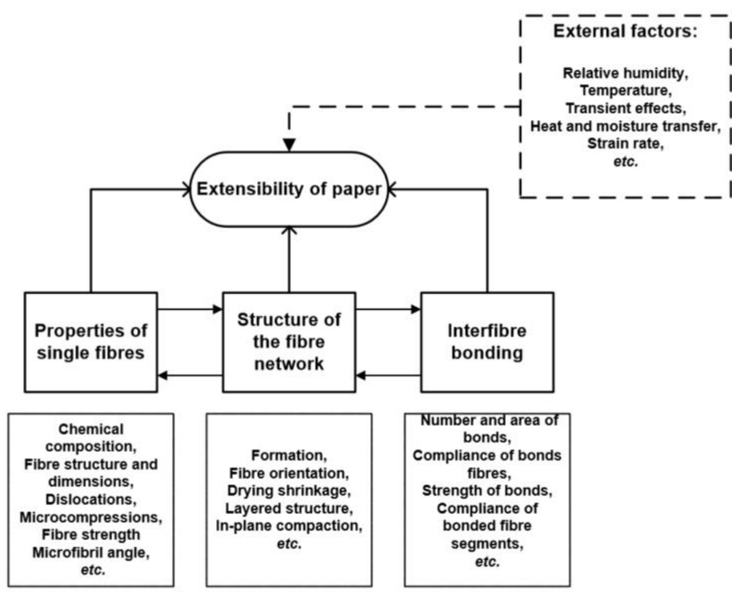

Figure 15: Factors affecting the extensibilty of fibre networks (here: paper) [143]

4.2. Fire resistance

Within the project BreadCell the fire related properties of the wood-pulp fibre structure have been explored using a cone calorimeter and a propagation test according to UL94 and EN 11925-2. Two fire retardants were studied: Citric acid and phytic acid, where the later was proven to be a good fire retardant, especially when it comes to heat release. If applied to the BreadCell structure, the would be classified as (B-s, d0) according to EN 13501.

Fire retardants can be classified into four main categories based on their mechanism of action ([144] citing [145]):

- Gas-phase dilution retardants: These compounds decompose thermally within the temperature range of flammable gas generation from the combustible material. They release non-flammable gases, effectively diluting the concentration of combustible gases and inhibiting ignition
- Heat-absorbing retardants: These materials function by absorbing thermal energy from the heat source, thereby cooling the system and impeding the combustion process
- Intumescent retardants: These operate through a dual-phase mechanism:
    - a) Physical phase: Upon exposure to heat, they form a thick insulating foam layer (several centimeters) on the material surface, creating a barrier between the flammable substrate and the heat source.
    - b) Chemical phase: As the material slowly heats, subsequent chemical reactions occur, further retarding the combustion process
- Mechanical barrier retardants: This category includes non-flammable films, coatings, and claddings that physically shield the combustible material from heat and flame

Flame-retardant treatments can significantly improve fire resistance. For example, one study showed an 84.2% improvement in flame-retardant performance for treated recycled paper materials compared to untreated samples [146]. Fire retardants are either inorganic or organic compounds [147]. The most common organic flame retardants are bromine-based, chlorine-based or phosphate-based.

There are growing concerns about the environmental and health impacts of some flame retardants. Many traditional flame retardants are persistent organic pollutants (POPs) with toxic effects [147]. Halogenated flame retardants (containing bromine or chlorine) are being phased out due to health and environmental risks [148]. Research is focusing on developing more sustainable alternatives with reduced toxicity [149].

Fire retardants work through various mechanisms to inhibit or suppress flame production and prevent fire spread in materials. Phosphorus-containing compounds are increasingly used due to their effectiveness and lower environmental impact [147,150].

Recent research has explored sustainable and environmentally-friendly fire retardant options for natural fibre composites [151] and pulp fibre structures, like paper: Bio-based flame retardants derived from natural sources, nanocomposite materials incorporating flame retardant nanoparticles or e.g. nanowires to create fire-resistant paper [152,153]

Environmental-friendly fire retardants can be made from egg shells: Eggshells contain fire-retardant minerals such as calcium carbonate, phosphorous, nitrogen, potassium, and zinc [154]. The high calcium carbonate content, in particular, contributes to their flame-retardant properties. When added to intumescent flame retardant coatings, eggshells dramatically decreased heat release and smoke formation [155]. Fabrics (e.g. cotton) treated with eggshell-based fire retardants showed improved flame resistance [154]. Eggshell additives in polymer composites enhanced their flame-retardant properties [156]. The addition of eggshells to intumescent flame retardant coatings significantly reduced peak heat release rates [155]. And eggshell additives improved char formation, enhancing the protective barrier against fire [4] [157].

4.3. Hydrophobization

Hydrophobizers play an important role in the paper industry [158], particularly for enhancing the water resistance and printability of packaging papers. Alkyl Ketene Dimer (AKD) is one of the most widely used hydrophobic agents in the papermaking industry. It increases hydrophobicity of paper, its dimensional stability while improving the printability. Other hydrophobic agents are also utilized in paper production are rosin-based sizing agents, Alkenyl succinic anhydride (ASA) and silicone-based compounds.

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Hydrophobizers can be applied to paper through internal sizing (added directly to the paper pulp during manufacturing), surface sizing (applied to the surface of formed paper sheets) and coating (incorporated into specialized coating formulations).

Most industrial hydrophobization techniques rely on internal or surface sizing of paper products – however, surface modifications for individual cellulose fibres or papers is another route.

An extensive overview on internal sizing, surface sizing and surface engineering routes was summarized extensively and comprehensively by Samyn (see Figure 16) [158]. More sustainable, i.e. environmental benign hydrophobization methods are highlighted in green – as opposed to fluorine based hydrophobization (in red).

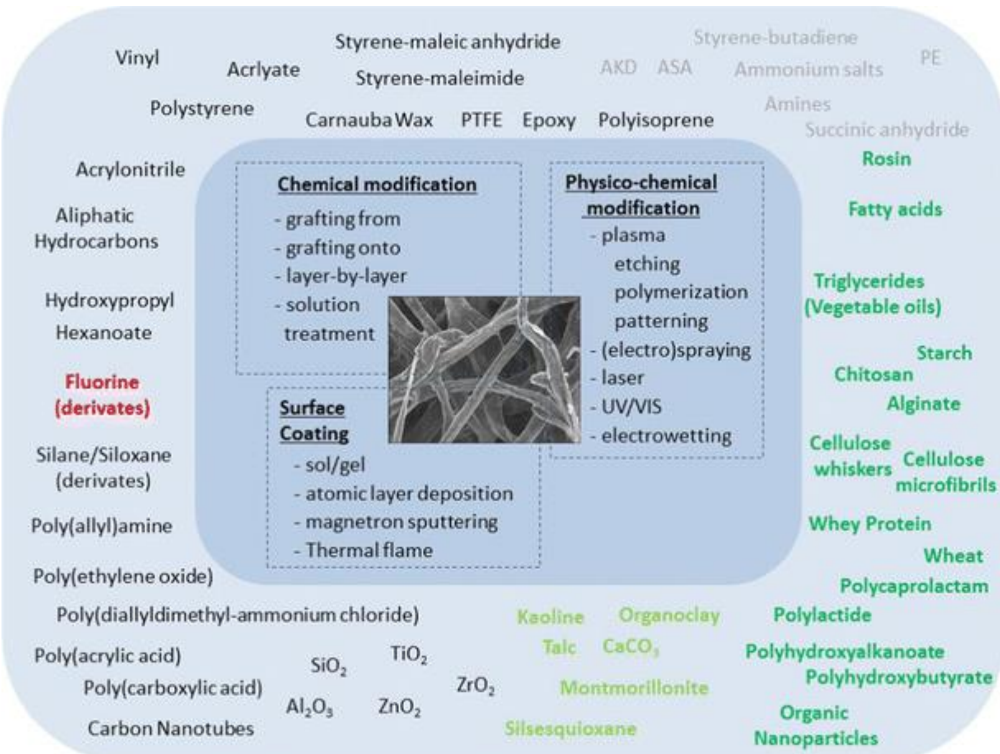

Figure 16: Overview of surface engineering for hydrophobic cellulose fibres: methods and common products [158]

5. Possible applications of BreadCell foam in automotive engineering

5.1. Child seat impact liner

5.1.1 State-of-the-art solutions

Child seats consist of hard-plastic outer shell, made from polycarbonate (PC) or Acrylnitril-Butadien-Styrol (ABS). The seat is lined with foam pads in the pelvic, thoracic and head section. These impact liners are mostly made from low density EPS, with a density of 15-30 kg/m^3.

The liners shall reduce head accelerations, ribcage loading and deflection and pelvic accelerations. Other foams on the seatback and the seatpan are viscous, soft comfort foams. These foams (impact liners, comfort foams and shell) is covered with a fabric cover. The impact liners frequently fail during seat installation or removal, or when the child seat's fabric cover is removed for cleaning and maintenance. From a user and consument perspective less brittle, but energy absorbing foams, which at the same time allow for moisture and sweat management are needed.

Figure 17: Foam impact liner ripped off (fabric cover removed); Source: [159,160]

5.1.2 Potential application

Motivation for BreadCell Foam as impact liner in child seats:

- Experiments show that the BreadCell foam can ad/absorb significant amounts of impact energy, however, it is prone to bottoming out upon localized loading. Due to the design of a child seat, punctual loading is unlikely (outer hardshell is protecting against localised loading). Additionally, the current foam pads are very thin. Increasing the thickness of the foam pads appear feasible (+ 30-50%).
- Design space requirements are strict: A combination of comfort and impact absorbing liner appears feasible.
- The BreadCell foam offers high sorptivity, and can be used for moisture and sweat management
- The production process of BreadCell potentially offers the possibility of create foam-fabric laminates
- The BreadCell foam is comparatively flexible and is less brittle than EPS: therefore, failure due to excessive bending of headrest-wings and when removing the fabric cover is less likely.

Strengths	Weaknesses
• More flexible, less brittle than EPS • Biobased (perception by parents important) • Biodegradable • Biocompatible • Sweat sorption / moisture management • Combination of impact and comfort liner possible • Option to combine with Phase Change Materials (PCM) (for thermal management → see below)	• Water sorptivity overly strong (e.g. spills of drinks)

• High strain rate amplification (load-rate adapting behaviour)	

5.2. Roofliner / head liner

5.2.1 State-of-the-art solutions

Roof or head liners in the car are multi-material laminates, consisting of an outer fabric layer, a first layer of foam, providing the soft-touch, and another three-layered laminate providing mechanical strength, vibration damping and also a limited amount of thermal insulation. This laminate consists of fibre or fabric mats, with a foam in between.

The first foam layer is made of polyester foams (polyester based PUR), as they provide very regular, fault-free and fine cell structure. This foam layer is soft. The second foam layer, located between the fabric or fibre mats, is rigid – and mostly made from PUR foams (polyether based), because they are easy to handle, chemically stable and offer good aging properties [161].

These laminates and their constituents shall provide low compression set (<7% @50% compression), low density (30 kg/m³), limited hardness loss after hydrolysis (<50%), or after aging (<20%). In particular, the terms of emissions - VOC, FOG, odor, formaldehyde and acetaldehyde - the requirements are challenging to meet, when combined with halogen-free flame retardants (e.g. <200 ppm VOC). The laminate is supplied in planar shape, and moulded to shape in a hotforming process.

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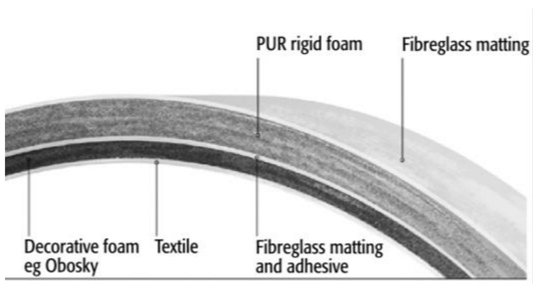

Figure 18: Cross-section of a automotive head liner. [94]

5.2.2 Potential application

Motivation for BreadCell Foam as structural foam in automotive head liner:

- BreadCell combines reasonable mechanical strength, with good acoustic and thermal insulation properties
- BreadCell has a high sorptivity, which assumingly provides good moisture management
- BreadCell assumingly has low VOC and FOG emissions [162]

Strengths	Weaknesses
• Reasonable mechanical strength • Good acoustic insulation • NVH (Noise-Vibration-Harshness) Behaviour • Good thermal insulation	• Bread-like odor emissions • No thermoforming capabilities

• Low VOC and FOG* • Sorptivity might support moisture management in car interior	

(*) Not tested; Assumptions based on receipt and on literature on paper

5.3. Phase change material harness

5.3.1 State-of-the-art solutions

Phase change materials (PCMs) are substances that absorb or release large amounts of thermal energy during their phase transition, typically between solid and liquid states. Phase Change Materials (PCMs) are revolutionizing thermal management in the automotive industry. This unique characteristic makes PCMs invaluable for maintaining temperature stability in vehicles.

PCMs function as thermal batteries, storing and releasing heat energy as needed: (1) Heat absorption: When temperatures rise, PCMs melt, absorbing excess heat and preventing critical components from overheating. (2) Heat release: As temperatures drop, PCMs solidify, releasing stored heat to maintain optimal operating conditions [163,164]. This cyclical process allows PCMs to effectively manage heat fluctuations, ensuring a more stable thermal environment within vehicles.

Battery thermal management: PCMs play a crucial role in managing the temperature of EV and hybrid vehicle batteries. PCMs help maintain optimal operating temperatures for lithium-ion battery packs, improving performance and longevity [165–167]. They absorb excess heat during charging and discharging, preventing overheating [166].They are crucial for fast charging, as higher charging rates lead to significant heating of the cells and power electronics.

Thermal propagation mitigation: PCM also provide safety by mitigating thermal propagation. This phenomenon occurs when a single cell malfunctions and overheats, potentially triggering a domino effect. In such cases, the heat from the compromised cell can spread to adjacent cells, causing them to overheat as well. This chain reaction may escalate to a catastrophic battery pack fire.

Cabin climate control: PCMs can enhance passenger comfort and reduce energy consumption: When placed under a car's roof, PCMs absorb heat and maintain lower interior temperatures when parked in the sun [168]. In one study, 4 kg of PCM (0.22% of cabin volume) reduced interior air temperature by 2 °C. PCMs in the steering wheel can improve thermal comfort and safety by maintaining lower surface temperatures. In many vehicles equipped with start-stop systems, PCMs effectively maintain cabin comfort when the engine is switched off. While driving, the PCM storage is charged by the vehicle's air conditioning system. The PCM stores cold energy at temperatures below its melting point. During idle periods, such as at traffic lights, a ventilator releases this stored cold from the PCM, maintaining a comfortable cabin temperature while conserving fuel.

Engine heat storage for cold starts: Another application of PCMs is the storage of engine heat for use during subsequent cold starts. This approach significantly reduces the warm-up phase, minimizing engine wear and reducing fuel consumption associated with cold starts.

Due to the wide variety of PCM materials available, with corresponding melting points, a tailored solution can be offered for almost any desired temperature between -20 °C and 100 °C.

To overcome the low thermal conductivity of most PCMs, like paraffin and fatty acids, graphite, graphene or metals are added [165], increasing their weight and their environmental footprint. As a passive system, it also offers more safety and reliability, and higher energy efficiency as compared to active cooling, as there are less moving parts.

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Due to the phase change, i.e. the change from solid to liquid, other heat transfer mechanism can be exploited: In the solid phase only conductive heat transfer is possible, but with liquification (also forced) convective heat transfer becomes available.

While PCMs offer significant benefits, their implementation requires careful engineering to address challenges such as containment, thermal conductivity, and integration with existing automotive systems.

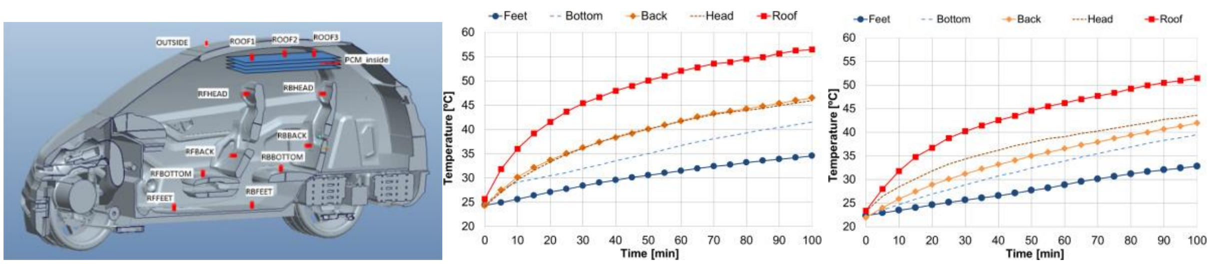

Figure 19: PCM placed in roof liner (left); Temperature-time without PCM (middle) and with PCM (right) [168]

In two-phase immersion cooling technology for EV batteries and components [169], the battery cells and components are submerged in a dielectric cooling fluid with a low boiling point. The fluid boils on the surface of heat-generating components, with rising vapor passively transferring heat. The system dynamically adjusts heat dissipation based on external conditions to maintain constant battery temperature [170]. Vapor is condensed back to liquid in a condenser and recirculated [169]. It is said to extend battery lifetime by up to 3x by preventing heat spikes [170]. It provides uniform cooling with only a 1.5-2°C thermal gradient across the pack [169].

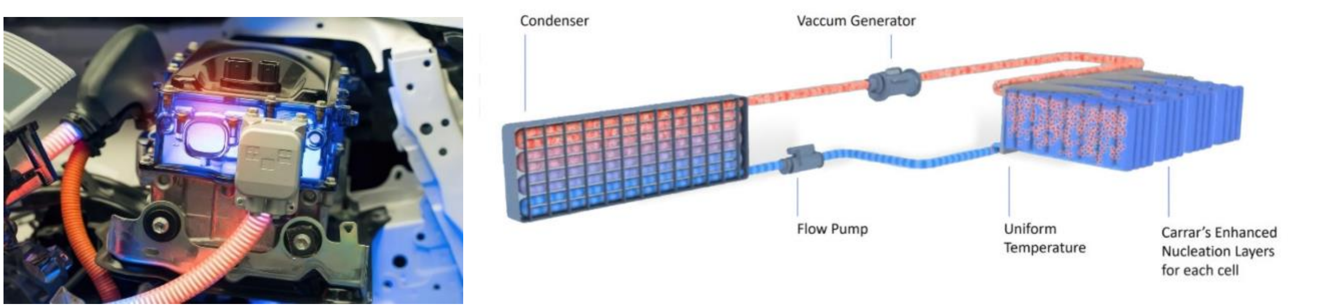

Figure 20: Dual phase liquid cooling for battery packs (Image courtesy of Carrar) [169,171]

Electrically insulating, thermally-conductive (1.5 W/mK) phase change material, with low thermal impedance (0.2°C in²/W) are used as thermal interface material, e.g. between a heat-sink and a heat-source such as electronic circuit units or power electronics. In this case a polyamide film is impregnated with PCM, for ease in handling and high dielectric strength and mechanical resistance. (Remark: Thermal impedance is the sum of thermal resistance and thermal contact resistance of a material.)

Figure 21: Solid phase change materials in thermal interface materials (Image courtesy of Henkel)[171]

An investigation used cylindrical paraffin PCM cells, identical in size to battery cells, placed in various patterns within a battery pack: Three PCM cylinder placements among twenty 18650 battery cells under different discharge rates were investigated. All configurations maintained average temperatures below 40 °C and 55 °C for 1C and 2C rates (Remark: C is the ratio between the charge or discharge-current and the nominal capacity of the battery. At a rate of 1C, the fully charged battery is emptied within 1 hour, at 2C within 1/2h). At 4C, only two configurations kept temperatures below 70 °C. For higher rates, a spread-out PCM tube placement is recommended to prevent heat accumulation (configuration (b) and (c)).

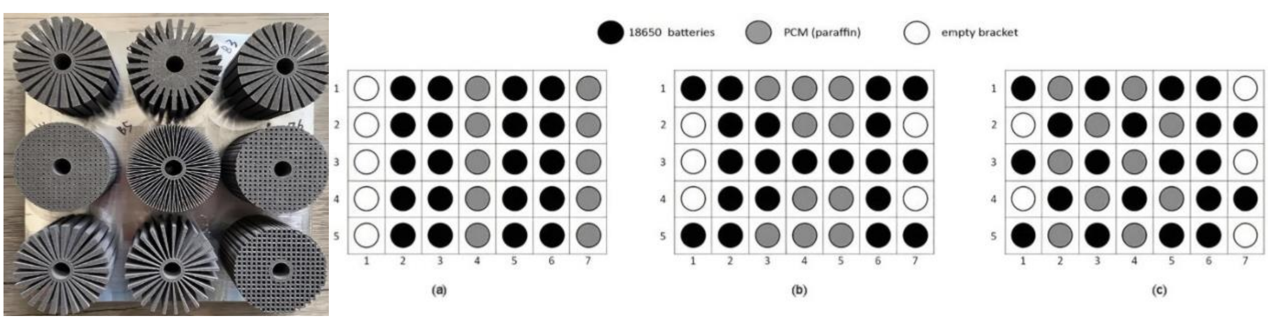

Figure 22: The layout of battery cells and paraffin cells for cooling (Image courtesy of Research Center for Transportation Technology) [171]

5.3.2 Potential application

Motivation for BreadCell foam as thermal phase change material harness:

- Experiments show that the BreadCell foam can ad/absorb and harness huge amounts of waxy paraffin
- Due to the high sorptivity the structure takes up the liquid paraffin an does not release it
- PCMs have a low thermal conductivity. Large surfaces are needed to allow for heat exchange
- The BreadCell structure combines the function of PCM harness and heat exchanger: Through its large surface area – and the porous structure, that allows air to flow through the structure – it can act as heat exchanger, providing large areas of accessible PCM.

Possible technical application: The structure is placed into the ducts of the HVAC. When the vehicle AC is not running (e.g. when the engine is turned off), simple ventilation through the BreadCell impregnated with PCM can maintain the cooling action of the AC. Alternatively the impregnated BreadCell foams can find application in the door panels, roof panels, seat substructures, dashboard, armrests – as combined acoustic, thermal insulation and thermal inertia. With plant based oils and waxes, also biobased and biodegrable alternatives to paraffin would be available.

Figure 23: Frothed BreadCell foam saturated with liquid Paraffin, in solid state (transition temperature 60°C): 3g of Paraffin per gramm foam

Strengths	Weaknesses
• Harnessing the PCM in liquid and solid state • Re-ad/absorbing excess liquid PCM • Providing large surface area for heat exchange • BreadCell is harness and heat exchanger • Additional effects as acoustic insulator may persist (it is assumed, that the acoustic insulation improves, due to viscoelasticity of PCM and additional added mass) • As thermal conductivity of PCM is low, the BreadCell structure might still act thermal insulator • Wax based PCM will also increase the biotic durability of BreadCell	• None (however, change in strength due to multiple phase change cycles unknown)

5.4. Automotive transport protection

5.4.1 State-of-the-art solutions

Automotive transport protection foams are preventing denting and scratching of the vehicle upon transport from the manufacturing plant to the car-dealership. Current state of the art foams are recyclable, and made from biobased resources, but are not compostable or biodegradable. The foam blocks are manufactured in an extrusion process, including co-extrusion processes where two or more compatible feed materials are merged in one single extrusion process. Alternatively thermoforming allows for shaping to a mould, allowing to meet complex design criteria. In a lamination process the foams can be joined with aluminium foils, hooks or loop fasteners.

The pads provide shock absorbance, do not absorb water, and are equipped with a special adhesive, that is compatible with freshly painted cars. The adhesive, however, is strong enough to prevent the foam from falling of in car wash facilities.

These pads are available for

- Door edge protection
- Door handle protection (guards against scratches from finger nails)
- Doorstep protection (protects chrome plated doorstep during transport and handling)

Figure 24: Automotive transport protection (Source: NomaPack ®)

5.4.2 Potential Application

Motivation for BreadCell Foam as automotive transport protection:

- During transport these foam blocks often fall off, or become loose, e.g. on rail tracks …
- Current pads are not biodegradeable.
- Blocks are not reused and therefore have a very limited lifetime.

Strengths	Weaknesses
• Biodegradable	• Water-sorptivity

For the described application case the BreadCell foam must show lower water sorptivity. This can be achieved two folds: (1) by using hydrophobized pulp fibres in the foaming process and (2) by encapsulating, i.e. foiling the foam, e.g. with a film or foil.

6. Conclusions

This study has demonstrated the significant potential of BreadCell foam, a cellulose fiber-based network structure, for automotive applications. The comprehensive analysis of foam usage in various automobile components and the examination of existing fiber network applications in vehicle construction have provided valuable insights into the material's possible integration into automotive design.

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The research has identified four promising automotive applications for BreadCell foam, leveraging its unique properties while addressing potential limitations through strategic modifications7

The material's exceptional characteristics, including high sorptivity, acoustic and thermal insulation, porosity, biocompatibility, and low VOC emissions, position it as an ideal candidate for multifunctional applications in the automotive industry. Particularly noteworthy is the potential use of BreadCell foam in roof, floor, or door liners, where it can simultaneously provide thermal insulation, phase change material harnessing, i.e. providing thermal regulation, impact energy management, and acoustic insulation.

This multifunctional approach not only maximizes the material's utility but also aligns with the automotive industry's growing focus on sustainable and efficient, multi-functional design solutions.

However also the weaknesses of the material must be highlighted, in particular when it comes to the low mechanical strength. In particular the weak fibre-to-fibre bonding limits the exploitable strength. Therefore, combinations with non-fibrous biobased materials appear a feasible avenue – e.g. by combining with tannin or lignin based matrix foams. This natural fibre reinforced foam would widen the application spectrum.

As the automotive sector continues to prioritize lightweight, eco-friendly materials that enhance vehicle performance and comfort, BreadCell foam presents a promising avenue for future development and integration. Further research and real-world testing will be crucial in fully realizing the potential of this innovative material and its applications in next-generation vehicle design.

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