AEROGELS: A Novel Material for Improving the Functional Properties of Textiles

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Abstract:
Aerogels are extremely flexible and porous materials. Aerogels are low-density solids with a low optical index of refraction, low thermal conductivity, high surface area, low dielectric constant, and a low speed of sound through the material. Properties of the aerogel-treated textiles can be suitably modified depending on the end user's requirements. Various functional properties of textiles such as mechanical properties, water repellence, permeability to air and water vapour, acoustic properties, reflection and blocking of electromagnetic radiation and fire resistance can be modified by aerogels. This paper discusses the structural features of aerogels and the functional applications of aerogel-treated fabrics.

Keywords: *Aerogels, Acoustic properties, Air permeability, Fire resistance, Water repellence*

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1. Introduction

Aerogels are highly porous materials with extreme properties [1]. In 1930, Kistler invented the first process for making such a highly porous inorganic silica product which is considered to be 'Material of the Twenty-First Century' [2]. Aerogels are also known as frozen smoke, solid smoke, solid air or blue smoke [3]. Aerogels are characterized as low-density solids with a low optical index of refraction, low thermal conductivity, and low speed of sound through the material, a high surface area, and a low dielectric constant. According to IUPAC, an aerogel is defined as a gel comprising a microporous solid in which the dispersed phase is a gas [4]. Aegerter et al defined aerogels as gels in which the liquid has been replaced with air, with very moderate shrinkage of the solid network [5].

The pores in the aerogels can occupy 90% of the material's volume. Their high porosities and low densities make them lightweight insulators of heat, sound, and electricity [6]. Aerogels made of materials such as silica or aluminium oxide have a strong resistance to fire and chemicals. Aerogels can be used to impart many useful properties to textiles. The typical structure of aerogel is shown in Figure 1.

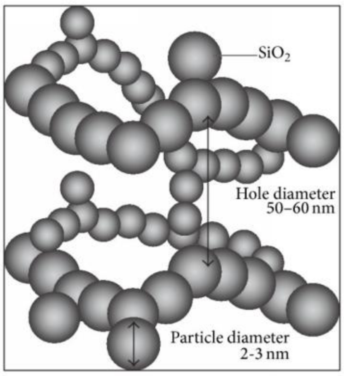

Figure 1 - Nanometre scale particles and pores in an aerogel [7, 8]

2. History and Evolution

The first study on aerogels was published in 1931 but received little attention from researchers [9]. Kistler found a way to remove the fluid from a wet silica gel, leaving behind its solid structure. Around 1920s, he had been working with high-pressure fluids on the point of boiling called supercritical fluids. In the early 1930s, he continued his experiments with aerogels, studying some of their thermal and catalytic properties [10]. In 1942, the first commercial aerogel was produced by the Monsanto Corporation, under the trade name Santocel. The process involved soaking a sodium silicate solution in sulphuric acid, then washing it in alcohol repeatedly and drying it at high pressure [11]. In 1970, Monsanto discontinued aerogel production because of its high manufacturing cost. However, interest in aerogels has grown exponentially over the last 40 years.

Aerogels have been most widely investigated for their applications in aerospace, building materials, catalysts, absorption media, food, controlled release of active materials, energy storage devices, solar-steam generation and medicine [12-14]. The attention to aerogels in textiles started only in this century. The first application of aerogel in textiles appears to have been in protective clothing for space exploration [15]. Aerogels can be classified in a variety of ways as shown in Figure 2.

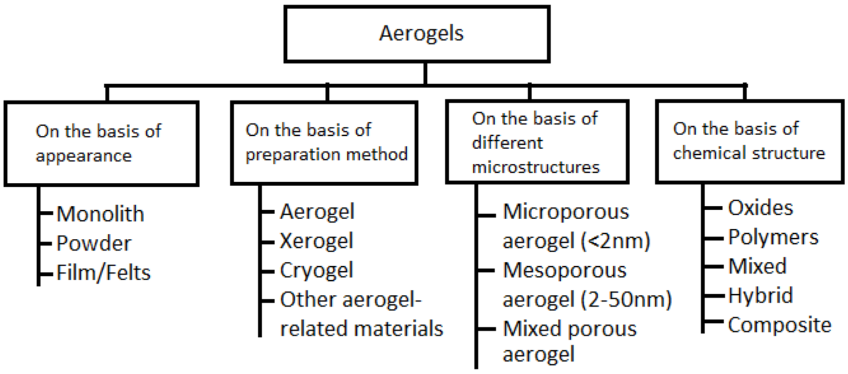

Figure 2 - Classification of aerogels [17]

3. Structural Features

By tailoring the production process, many of the properties of aerogel can be adjusted. For example, bulk density and thermal conductivity can be adjusted simply by making a more or less concentrated precursor gel [18, 19]. Properties such as transparency, colour, mechanical strength and susceptibility to water depend primarily on the composition of the aerogel. The properties of aerogels are given in Table 1.

Table 1 - Properties of aerogel [17]

Property	Value
Apparent density	0.03-0.35 g/cm^3
Internal surface area	600-1000 m^2/g
% Solids	0.13%–15%
Mean pore diameter	~20 nm
Primary particle diameter	2-5 nm
Index of refraction	1.0-1.05
Thermal tolerance	to 500 °C
Coefficient of thermal expansion	2.0-4.0 $\times 10^{-6}$
Poisson's ratio	0.2
Young's modulus	10^6-10^7 N/m^2
Tensile strength	16 kPa
Fracture toughness	~0.8 kPa m$^{1/2}$
Dielectric constant	~1.1
Sound velocity through the medium	100 m/s

4. Properties of Textiles that can be modified by Aerogels

4.1 Mechanical Properties

Acidic hydrolysis of silane followed by an alkaline gelation process gives silica gel which is then applied to fabrics by dip coating. Before oven drying, the coated fabric was washed with ethanol and n-hexane. In three-layered weft-knitted spacer fabrics (92% polyester & 8% spandex), the application of silica gel improved the mechanical properties like an increase in initial moduli from 2.4 to 3.9 MPa and an increase in work of compression from 35 to 39 Pa m [20]. In nonwoven fabrics, the application of silica gel resulted in the reduction of compressibility and maintenance of thermal insulation [21]. This benefited protective clothing and building insulation applications. Silica aerogel monolithic synthesized at atmospheric pressure with isocyanate crosslinking inserted into an assembly of 30 layers of aramid fabric significantly reduced the penetration of handgun bullets. The insertion was done at a level of 1-7% of the mass of the fabric [22]. In melt-bonded polyester nonwoven fabrics and polyurethane open-cell foam, voids are made by laser which represented around three-quarters of the volume of the original material. The voids are filled with hydrophobic silica aerogel with 5×5mm pillars of polyester or polyurethane. Additional fabrics were applied to keep the aerogel in place. In polyester fabric assembly with air-filled voids or aerogel-filled voids, the resistance is lower to compression than in control assembly. The foam assembly with air-filled voids has no effect on resistance to compression but with aerogel-filled voids, it increased slightly. The aerogel-filled voids increased thermal resistance significantly [23]. The aerogel precursor [20] like silica aerogel when applied to textiles produced inter-fibre bonding which lead to the increase in initial moduli and resistance to compression [24]. This bonding contributes to observed changes in mechanical properties which are acceptable for technical textiles rather than apparel [25].

4.2 Water Repellency

Depending on starting materials, aerogels can be prepared with hydrophobic, hydrophilic or oleophilic characteristics [26, 27]. Hydrophobic silica aerogels are prepared using methyltrimethoxysilane (hydrophobic starting material). It was possible to employ ambient pressure drying by using this starting material and a volatile/ nonaqueous solvent (methanol). In cotton fabric, the application of aerogel in conjunction with polydimethylsiloxane imparted superhydrophobicity with a 155.4° water contact angle and a very low (6.8°) water shedding angle. The low surface energy of polydimethylsiloxane and the formation of micro-rough coating (lotus effect) on the fabric attributed to the water repellency [26, 28]. In polyethylene fabric, the application of silica aerogel in a polyvinylidene fluoride coating of a ratio of 1:1.5 rendered the fabric hydrophobic with a 157.8° water contact angle and a 3° water shedding angle [29]. To increase the water resistance of knitted polyester fabric (outerwear), a hydrophobic silica aerogel has been used. It was applied by padding with a binder where there is no change in appearance or tensile strength of the fabric. But it greatly increased the resistance to water spray and water droplets which raised the water contact angle to 170°. This coating increased the amount of oily soil removed during washing and the water-repellency effect was resistant to multiple launderings [30].

The aerogels have lesser abrasion resistance on textiles because of their fragility. To enhance this, silica aerogel and a fluorocarbon chemical were mixed and electro-sprayed onto a polyester woven fabric which showed higher abrasion resistance and increased hydrophobicity considerably more than fluorocarbon alone [31]. Hydrophobic silica aerogels have been dispersed in polyester solution which was then electrospun into webs of fibre resulting in an increased water contact angle up to 130° and the fibres without aerogel had a 103° water contact angle [32, 33]. Even hydrophilic aerogels can increase water repellency via the lotus effect.

To enhance the water repellence of textiles with aerogels, following the combination of three mechanisms worked.

- Micro-roughness of the aerogels
- Low surface energies of some aerogels and siloxane
- Employment of fluorochemical polymers to bind aerogels to textiles

Alternatives for the water-repellent coatings for textiles are needed because of the growing realization of the dangers posed by fluorochemicals [34].

4.3 Permeability to air and water vapour

Permeability is an important property of textiles especially apparel, as it has a large effect on human comfort [35]. In polyester fabric, the application of silica aerogel at levels from 1.25 to 6.25 GSM with hot melt adhesive particles and on top of a polyacrylonitrile fibre web was applied [36]. The assembly was heat bonded and testing resulted that the aerogel had limited effect on air and water permeability of the laminated fabric and increased the thermal insulation. The application of silica aerogel-phase change material to fabric in form of coating resulted in reduced air permeability [37]. The application of hydrophobic silica aerogels up to 4% levels of fibre mass in electrospun polyester fibre did not change the water vapour permeability [33]. But it affected fibre diameter. At 2% & 4% aerogel, the air permeability is higher than at 0.5% & 1% aerogel or fibres without aerogel. The increased level of aerogel in silica and fluorochemical application by electro-spraying resulted in a greater reduction of air permeability [31]. To enhance water vapour permeability, a hydrophilic silica aerogel was included in a polyurethane membrane. In cotton fabric, this membrane was laminated which imparted excellent air permeability, water-evaporative ability and emission of thermal radiation properties very desirable for comfortable clothing in hot environments [38]. The methods of incorporating aerogels into textiles play an important role in the air and water permeability of textiles. The permeability is reduced when aerogels are applied to textiles by low permeability polymer coating or incorporated inside the fibre and increase fibre diameter. These findings suggest that aerogels cannot enhance the permeability of textiles. A check on permeability should be done when aerogels are applied to textiles to impart desirable properties like hydrophobicity or resistance to projectiles.

4.4 Acoustic properties

The high porosities and high specific surface areas of aerogels and textile assemblies make them a good combination for absorbing sound [39]. The acoustics of silica aerogel/polyethylene fabrics have been studied [40]. In one preparation, 5 mm thick nonwoven fabric was dipped in a solution of aerogel precursors. In other preparation, before the fabric was placed in the dispersion, the silane progressed through hydrolysis and gelation followed by ultrasonication. In both cases, before drying at room temperature, the surface of the silica on the fabric was rendered more hydrophobic by trimethylchlorosilane. When the aerogel was formed on the fabric, the fibres became well coated with an aerogel network. When the fabric was dipped into the hydrogel dispersion, discrete particles of silica aerogels were deposited on the fibres. Some aerogel applications significantly increased sound absorption at 1000-6000 Hz. But no application enhanced the absorption at lower frequencies. In a study of sound-absorbing textiles for buildings, both hydrophobic and hydrophilic silica aerogels were investigated on polyester fabrics [41]. The fabrics were treated with silica sol in a mixture of ethanol and n-hexane followed by drying under ambient pressure, at temperatures up to 120°C. Oh et al followed the procedure of treating the sol with chlorosilane which rendered the fabric hydrophobic before drying [40]. This approach leads to preparing aerogel particles with a range of pores. When the silica aerogels were tested, they showed the results of increased sound absorption at all frequencies (50-1600Hz), lower bulk densities, larger pore sizes and higher porosities [41]. The hydrophobic silica aerogels having greater porosity gave greater sound absorption than hydrophilic ones. In building, a hydrophobic material is preferable as it is less susceptible to deterioration from moisture and condensation. In another study, silica aerogel increased the sound absorption of a nonwoven polyester/polyethylene thermal fabric [42].

By soaking the cotton fabric in hydrophobic silica aerogel precursors, the sound absorption was improved between 250 and 2500Hz but reduced for higher frequencies [43]. Because the aerogels had been prepared with a range of reagent concentrations, ageing times, surface areas, pore sizes and densities, the effects of these on sound absorption could be investigated. Aerogels having lower densities gave greater sound absorption whereas surface area and pore size had only minor effects. The application of hydrophobic silica aerogel on polyester/polyethylene nonwoven by thermal bonding found that the sound absorption decreased with increasing amounts of aerogel [44]. The authors proposed two possible reasons for this reduced sound absorption as irregular shapes of aerogel particles and because of increased fabric porosity by applying aerogels reduced airflow resistance [45]. The studies reviewed here demonstrated that sound absorption properties of textiles increased with lower-density aerogels. Density appeared to be more important than pore sizes and surface areas. The relatively low importance of pore size is due to wavelengths of audible sounds to humans (17mm-17m) greater than the pores of aerogel's diameters. The aerogels can be detrimental to sound absorption which increases the porosity of textiles. When aerogels are applied to dense, low-porosity fabric, the aerogels increase the average separation of fibres from each other assisting sound propagation through textiles and through themselves [46].

4.5 Reflection and blocking of electromagnetic radiation

Textiles are important for moderating our exposure to electromagnetic radiation from visible light to thermal radiation to microwaves. The following studies have reported on how aerogels can affect the interactions between textiles and electromagnetic radiation. In some types of clothing, especially outdoor wear, polymer membranes which are used for water resistance contributed to comfort by reducing radiative heat loss from the wearer [47]. The effect on heat transmission in a polyurethane membrane with silica aerogel, quartz sand, carbon black and tungsten oxide has been evaluated under conditions of radiation and convection. These conditions were chosen as in outdoor wear, the membranes were not in direct contact with skin and so were unable to conduct heat from the skin. Silica aerogel (particle size 2-10µm) showed little effectiveness at blocking irradiated heat. In contrast, a blanket of silica aerogel in fire-fighter protective clothing which absorbed infrared radiation showed a 7% reduction in heat transfer [48].

The lasers used in industries pose to health and safety to be managed. The ability of silica aerogel to increase the protection afforded by the fabric has been investigated [49]. The silica aerogel particles held between Kevlar and glass fabrics reduced the temperature of the non-irradiated face of the fabric when a beam of industrial carbon dioxide laser (wavelength-10.6µm, average output power-150/250W) used for cutting and marking textiles was applied. This reduction is proportional to the amount of aerogels in the fabric. Aerogels have been investigated for blocking low-frequency microwaves (2.91-5.1 GHz). In nonwoven fabric, by co-applying a high dielectric loss material (reduced graphene oxide aerogel) and a high magnetic loss material (carbonyl iron), high absorption has been achieved [50]. In cotton fabric, the application of graphene aerogel imparted high shielding of microwave radiation (8-12.5 GHz) [51].

In most of the reported studies with textiles, aerogels had a positive effect. Graphene and graphene oxide aerogels increased the shielding from microwaves. Silica aerogels improved the blocking of visible laser light and were beneficial for thermal radiation protection in fire-fighter clothing not as additives to a membrane intended for outdoor wear. The most important factor for changing the electromagnetic properties of textiles is their inherent properties like dielectric polarization and emissivity rather than particular properties of aerogels like low density and high surface area. When the material is porous, aerogel-form textile could receive significant coverage of additive with less increase in overall weight than would be the case with non-porous material [46].

4.6 Resistance to chemicals

Aerogels can be envisaged to prevent or reduce the passage of chemicals through textiles. It would also be beneficial for textiles used for the containment of chemical spills. In viscose/polyester nonwoven interlining fabric, the incorporation of silica aerogel and the determination of absorption capacity for seven solvents of different surface tensions from n-hexane (18 dyne/cm) to dimethylformamide (37 dyne/cm) were investigated on detail [52]. The chemical resistance of the fabric was evaluated with respect to the repellency, retention and penetration of the solvents, along with organic acids and a solution of sodium hydroxide. The silica aerogel improved chemical resistance by increasing the amount of chemicals absorbed by the fabric and because of aerogel's porosity, this would be more effective than activated carbon used in protective clothing systems. The chemical resistance of a nonwoven viscose fabric was enhanced by a membrane made by electrospinning of a mixture of polyacrylonitrile, dimethylformamide and a commercial hydrophobic silica aerogel [53]. The results were similar when silica aerogel was applied to cotton fabric in a polyurethane coating [54]. In both studies, it was found that the aerogel's enhancements of chemical protection were not at the cost of reduced breathability/comfort [54, 55]. Aerogel's utility in this application derives from its very high specific surface areas and the chemical inertness of materials like silica.

4.7 Resistance to fire

The high porosity and excellent thermoregulatory properties of polar bear hair inspired a study of some of the properties of polyimide aerogel fibre, including fire retardancy [55]. The fibre was prepared by extrusion of poly (amic acid) hydrogel followed by controlled freezing to form fibres with porous interiors, then freeze-dried and imidised by heating in argon or nitrogen. The resulting fibres had a low density (0.2 g/m^3) and high porosity (up to 88%). The fabrics woven from these fibres proved to be fire retardant, self-extinguishing and thermally insulating with high modulus and elasticity. By applying a phase change material, the thermoregulation of the fabric was further enhanced. The fire resistance of a poly (sulphonamide) fabric has been increased by applying aluminium hydroxide aerogel [56]. The greatest enhancement was imparted when the aerogel's density was 0.645g/cm^3, the specific surface area was 293m^2/g and the mean pore diameter was 10.9nm which reduced the length of vertical burning damage from 4.9-1.3cm. A silica aerogel was prepared on an aramid nonwoven fabric to increase fire resistance, raising the limited oxygen index from 27% to 31% [57]. Phase change materials which are generally hydrocarbons and flammable are increasingly being studied to reduce heat transfer in fire fighter's protective clothing. When silica aerogel was incorporated into a phase change material coating of fabric, it reduced flammability, imparted greater resistance to heat, higher ignition temperature and slower propagation of flame. This is due to the melting of phase change material staying on aerogel particles with very high specific surface area [58-61].

5. Conclusions

This paper examines how aerogels affect a number of textile properties. Researchers are just beginning to pay attention to the numerous applications described in this review. Aerogels are likely to play a larger role in textiles. These innovations include combining various materials with complementary properties to create high-performance composite aerogels, lowering production costs, and making greater use of carbon and biopolymers. This review should hopefully motivate aerogel researchers to think about the qualities they can bring to textiles and seek out experts in textile materials to start productive multidisciplinary research.

References

[1] A. Taher, Scientists Hail 'Frozen Smoke' as Material that Will Change World, Sunday Times, Timesonline, 19 August 2007

[2] S.S. Kistler, J. Phys. Chem. 39 (1) (1935) p.79

[3] K. Higa, Illumin 14 (3) (2014) p.1

[4] A.D. McNaught and A. Wilkinson, Compendium of Chemical Terminology, IUPAC Goldbook, PAC, 2nd ed., Blackwell Science, Cambridge, 2007

[5] M.A.Aegerter, N.Leventis and M.M.Koebel, Aerogel Handbook. Springer, New York, 2011

[6] A.C. Pierre, G.M. Pajonk, Chemistry of aerogels and their applications, Chem. Rev. 102 (2020) 4243–4266, https://doi.org/10.1021/cr0101306

[7] http://www.aerogel.com/

[8] http://www.chem-eng.kyushu-u.ac.jp/e/research.html

[9] S.S. Kistler, Coherent expanded aerogels and jellies, Nature 127 (3211) (1931) 741, https://doi.org/10.1038/127741a0

[10] M. Schmidt and F. Schwertfeger, J. Non-Crystalline Solids 225 (1_3) (1998) p.364

[11] The Annual Review of Heat Transfer, Vol. 14, University of Iowa, 2005

[12] K. Lee, L. Shabnam, S.N. Faisal, V.G. Gomes, Aerogel from fruit biowaste produces ultracapacitors with high energy density and stability, J. Energy Storage 27 (2020), 101152, https://doi.org/10.1016/j.est.2019.101152

[13] D.P. Storer, J.L. Phelps, X. Wu, G. Owens, N.I. Khan, H. Xu, Graphene and rice straw fibre based 3D photothermal aerogels for highly efficient solar evaporation, ACS Appl. Mater. Interfaces 12 (2020) 15279–15287, https://doi.org/10.1021/ acsami.0c01707

[14] F. Zhu, Starch based aerogels: production, properties and applications, Trends Food Sci. Technol. 89 (2019) 1–10, https://doi.org/10.1016/j.tifs.2019.05.001

[15] L. Corazza, Space is fashionable/`E di moda lo spazio, Tessili per Impieghi Tecnici 10 (9) (2003) 12–14

[16] Aerogels: Their History, Structure, and Applications. Copyright 2001 by George Beckingham. Available at http://geobeck.tripod.com/frontier/aerogels.html#link

[17] M. Venkataraman, R. Mishra, T. M. Kotresh, J. Militky & H. Jamshaid (2016), Aerogels for thermal insulation in highperformancetextiles, Textile Progress, 48:2, 55-118, DOI:10.1080/00405167.2016.1179477

[18] Y.C. Kwon, J. Civil Eng. Arch. 7 (12) (2013) p.1494

[19] A. Du, B. Zhou, Z. Zhang and J. Shen, Materials 6 (3) (2013) p.941

[20] S.R. Islam, M.A.N. Rakib, Mechanical properties of weft-knitted spacer fabrics integrated with silica aerogels, J. Donghua Univ. 36 (6) (2019) 559–563

[21] L. Wang, X. Ding, X. Xia, H. Wang, X. Zhou, Protective function of SiO2 aerogel hybrid/aramid nonwovens fabric, Fangzhi Xuebao/J. Textil. Res. 40 (10) (2019) 79–84, https://doi.org/10.13475/j.fzxb.20181002306

[22] A.ÿI. Aytena, M.A. Tas¸delena, B. Ekici, An experimental investigation on ballistic efficiency of silica-based crosslinked aerogels in aramid fabric, Ceram. Int. 46 (2020) 26724–26730, https://doi.org/10.1016/j.ceramint.2020.07.147

[23] X. Xiong, T. Yang, R. Mishra, H. Kanai, J. Militky, Thermal and compression characteristics of aerogel-encapsulated textiles, J. Ind. Textil. 47 (8) (2018) 1998–2013, https://doi.org/10.1177/1528083717716167

[24] P.E. Ingham, M.R. Sunderland, S.J. McNeil, R. Marazzi, N.C.F. Lanasan, Nanoparticles enhance carpet performance, Int. Dyer 191 (1) (2006) 23–25

[25] S.J. McNeil, O.C. Standard, Increased bending rigidity of wool fabric imparted by hybrid organic-inorganic sol–gel coatings, Textil. Res. J. 87 (5) (2017) 607–616, https://doi.org/10.1177/0040517516635990

[26] X. Zhang, L. Xu, Y. Shen, L. Wang, Preparation of hydrophobic silica aerogel and its application in cotton fabrics, J. Funct. Mater./Gongneng Cailiao 49 (3) (2018) 3118–3123, https://doi.org/10.3969/j.issn.1001-9731.2018.03.019

[27] L. Zou, A.D. Phule, Y. Sun, T.Y. Zhu, S. Wen, Z.X. Zhang, Superhydrophobic and superoleophilic polyethylene aerogel coated natural rubber latex foam for oil-water separation application, Polym. Test. 85 (2020), 106451, https://doi.org/ 10.1016/j.polymertesting.2020.106451

[28] X. Zhang, L. Xu, Y. Shen, L. Wang, Y. Ding, One-step fabrication of self-healing and durable superhydrophobic cotton fabrics based on silica aerogel, J. Nanosci. Nanotechnol. 18 (11) (2018) 7721–7731, https://doi.org/10.1166/ jnn.2018.15548

[29] H. Du, Z. Zheng, S. Ca, F. Chen, Preparation and characterization of super hydrophobic aerogel coated ultra-high molecular weight polyethylene fabric, Fangzhi Xuebao/J. Text. Res. 39 (4) (2018) 93–99, https://doi.org/10.13475/j. fzxb.20160802507

[30] P. Altay, R. Atakan, G. ¨Ozcan, G. Silica Aerogel, Application to polyester fabric for outdoor clothing, Fibres Polym. 22 (4) (2021) 1025–1032, https://doi.org/ 10.1007/s12221-021-0420-4

[31] F. Shams-Ghahfarokhi, A. Khoddami, Z. Mazrouei-Sebdani, J. Rahmatinejad, H. Mohammadi, A new technique to prepare a hydrophobic and thermal insulating polyester woven fabric using electro-spraying of nano-porous silica powder, Surf. Coating. Technol. 366 (2019) 97–105, https://doi.org/10.1016/j. surfcoat.2019.03.025

[32] Z. Mazrouei-Sebdani, A. Khoddami, H. Hadadzadeh, M. Zarrebini, Synthesis and performance evaluation of the aerogel-filled PET nanofibre assemblies prepared by electro-spinning, RSC Adv. 5 (17) (2015) 12830–12842, https://doi.org/ 10.1039/C4RA15297B

[33] Z. Mazrouei-Sebdani, A. Khoddami, H. Hadadzadeh, M. Zarrebini, A. Karimi, F. Shams-Ghahfarokhi, The effect of the nano-structured aerogel powder on the structural parameters, water repellency, and water vapor/air permeability of a fibrous polyester material, Mater. Chem. Phys. 177 (2016) 99–111, https://doi. org/10.1016/j.matchemphys.2016.04.002

[34] L. Ahrens, M. Bundschuh, Fate and effects of poly-and perfluoroalkyl substances in the aquatic environment: a review, Environ. Toxicol. Chem. 33 (9) (2014) 1921–1929, https://doi.org/10.1002/etc.2663

[35] H. Gu, Research on cotton waterproof and water vapour-permeable fabric, Mater. Des. 15 (6) (1994) 371–374, https://doi.org/10.1016/0261-3069(94)90031-0

[36] X. Xiong, T. Yang, R. Mishra, J. Militky, Transport properties of aerogel-based nanofibrous nonwoven fabrics, Fibres Polym. 17 (10) (2016) 1709–1714, https:// doi.org/10.1007/s12221-016-6745-8

[37] A. Shaid, L. Wang, R. Padhye, The Flammability Of Aerogel And PCM Coated Cotton Fabric For Firefighter's Garment, Proc. 9th Textil. Bioeng. Inform. Symp.- 6th Asian Protect. Cloth. Conf., Melbourne, Australia, 12-16 July 2016, pp. 61–68

[38] M.A. Jahid, J. Hu, S. Thakur, Mechanically robust, responsive composite membrane for a thermoregulating textile, ACS Omega 5 (8) (2020) 3899–3907, https://doi.org/10.1021/acsomega.9b03268

[39] F.J. Jimenez-Espadafor, J.A.B. Villanueva, M.T. García, E.C. Trujillo, A.M. Blanco, Optimal design of acoustic material from tire fluff, Mater. Des. 32 (6) (2011) 3608–3616, https://doi.org/10.1016/j.matdes.2011.02.024

[40] K.W. Oh, D.K. Kim, S.H. Kim, Ultra-porous flexible PET/Aerogel blanket for sound absorption and thermal insulation, Fibres Polym. 10 (5) (2009) 731–737, https:// doi.org/10.1007/s12221-010-0731-3

[41] Z. Talebi, P. Soltani, N. Habibi, F. Latifi, Silica aerogel/polyester blankets for efficient sound absorption in buildings, Construct. Build. Mater. 220 (2019) 76–89, https://doi.org/10.1016/j.conbuildmat.2019.06.031

[42] M. Venkataraman, R. Mishra, V. Arumugam, H. Jamshaid, J. Militky, Acoustic Properties Of Aerogel Embedded Nonwoven Fabrics, Proc. 6th Int. Conf. Nanomater. NANOCON, Brno, Czech Republic, 2014, pp. 5–7

[43] S. Motahari, H. Javadi, A. Motahari, Silica-aerogel cotton composites as sound absorber, J. Mater. Civ. Eng. 27 (9) (2015) 237, https://doi.org/10.1061/(ASCE) MT.1943-5533.0001208, 4,014

[44] T. Yang, X. Xiong, M. Venkataraman, R. Mishra, J. Nov´ak, J. Militký, Investigation on sound absorption properties of aerogel/polymer nonwovens, J. Text. Inst. 110 (2) (2019) 196–201, https://doi.org/10.1080/ 00405000.2018.1472540

[45] T. Yang, X. Xiong, R. Mishra, J. Nov´ak, J. Militký, Acoustic evaluation of Struto nonwovens and their relationship with thermal properties, Text, Res. J. 88 (4) (2016) 426–437, https://doi.org/10.1177/0040517516681958

[46] S.J. McNeil and H. Gupta, Emerging applications of aerogels in textiles, Polymer Testing 106 (2022) 107426, https://doi.org/10.1016/j.polymertesting.2021.107426

[47] A.V. Lunchev, V.T. Lipik, Membranes for apparel with the additional barrier function for the reduction of irradiation heat loss, in: Proc. 19th World Text, Conf.-Autex, Ghent, Belgium, 2019

[48] J. Naeem, A. Mazari, Z. Kus, P. Kejzlar, Comparative study of radiant heat flux density transmission through firefighter protective clothing, Vl´akna Textil./Fibres Text 25 (2) (2018) 79–86

[49] M. Venkataraman, R. Mishra, J. Wiener, M. ˇStˇep´ankov´a, V. Arumugam, J. Militky, Effect Of Laser Irradiation On Kevlar Fabric Treated With Nanoporous Aerogel, Proc. 7th Int. Conf. Nanomater. NANOCON, Brno, Czech Republic, 2015, pp. 631–638

[50] S. Bi, J. Tang, D.J. Wang, Z. Su, G.L. Hou, H. Li, J. Li, Lightweight non-woven fabric graphene aerogel composite matrices for assembling carbonyl iron as flexible microwave absorbing textiles, J. Mater. Sci. Mater. Electron. 30 (18) (2019) 17137–17144, https://doi.org/10.1007/s10854-019-02060-y

[51] P. Wang, S. Liu, M. Zhang, G. Wu, K. Wang, H. Li, F. Li, H. Wang, Preparation and properties of graphene aerogel/cotton composite flexible fabric with electromagnetic interference (EMI) shielding function, J. Ind. Textil. In Press. https://doi.org/10.1177/1528083721989272

[52] M.R. Bhuiyan, L. Wang, A. Shaid, I. Jahan, R.A. Shanks, Silica aerogel-integrated nonwoven protective fabrics for chemical and thermal protection and thermophysiological wear comfort, J. Mater. Sci. 55 (6) (2020) 2405–2418, https://doi.org/10.1007/s10853-019-04203-2

[53] M.R. Bhuiyan, L. Wang, R.A. Shanks, Z.A. Ara, T. Saha, Electrospun polyacrylonitrile–silica aerogel coating on viscose nonwoven fabric for versatile protection and thermal comfort, Cellulose 27 (17) (2020) 10501–10517, https://doi.org/10.1007/s10570-020-03489-9

[54] M.R. Bhuiyan, L. Wang, A. Shaid, R.A. Shanks, J. Ding, Polyurethane-aerogel incorporated coating on cotton fabric for chemical protection, Prog. Org. Coating 131 (2019) 100–110, https://doi.org/10.1016/j.porgcoat.2019.01.041

[55] Y. Wang, Y. Cui, Z. Shao, W. Gao, W. Fan, T. Liu, H. Bai, Multifunctional polyimide aerogel textile inspired by polar bear hair for thermoregulation in extreme environments, Chem. Eng. J. 390 (2020), 124623, https://doi.org/10.1016/j.cej.2020.124623

[56] Y. Jiang, L. Zhang, H. Xu, Y. Zhong, Z. Mao, Preparation and characterization of thermal protective aluminium hydroxide aerogel/PSA fabric composites, J. Sol. Gel Sci. Technol. 82 (2) (2017) 370–379, https://doi.org/10.1007/s10971017-4323-1

[57] L. Xu, H. Wang, Z. Yan, X. Zhou, The Performance study of SiO2 aerogel hybrid aramid nonwoven fabric, Adv. Textil. Technol. 26 (1) (2018) 22–25, https://doi.org/10.19398/j.att.2018.01.006

[58] A. Shaid, L. Wang, S. Islam, J.Y. Cai, R. Padhye, Preparation of aerogel-eicosane microparticles for thermoregulatory coating on textile, Appl. Therm. Eng. 107 (2016) 602–611, https://doi.org/10.1016/j.applthermaleng.2016.06.187

[59] A. Shaid, L. Wang, R. Padhye, The thermal protection and comfort properties of aerogel and PCM-coated fabric for firefighter garment, J. Ind. Textil. 45 (4) (2016) 611–625, https://doi.org/10.1177/1528083715610296

[60] A. Shaid, L. Wang, S.M. Fergusson, R. Padhye, Effect of aerogel incorporation in PCM-containing thermal liner of firefighting garment, Cloth. Text. Res. J. 36 (3) (2018) 151–164, https://doi.org/10.1177/0887302X18755464

[61] K. El-Tahlawy, Chitosan phosphate: a new way for production of eco-friendly flame-retardant cotton textiles, J. Text. Inst. 99 (3) (2008) 185–191, https://doi.org/10.1080/00405000701584311