Research Square

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Advanced fabrication and multi-properties of recycled textile waste fibers aerogels

Chunlei Dong
Chizhou University
Yangzhao Hu
Chizhou University
Yuxuan Zhu
Chizhou University
Jiale Wang
Chizhou University
Xuerui Jia
Chizhou University
Jianbing Chen (13856651860@139.com)
Chizhou University
Jingliang Li
Deakin University

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Abstract

In recent years, the treatment of textile waste has been attracted more and more attention around the world. The reuse of textile waste can contribute to the reduction of carbon emissions and the sustainable development of the economy. Herein, we proposed a facile and cost-effective approach to fabricating aerogel by using textile waste fibers as the matrix and polyvinyl alcohol (PVA) and glutaraldehyde (GA) as crosslinking agents. After coated with methyltrimethoxysilane (MTMS) via chemical vapor deposition, both the interior and exterior of the whole textile waste aerogels surface exhibit a super-hydrophobic property with a water contact angle of up to 136.9°. A comprehensive investigation of its structure, thermal performance and oil absorption capacity has been carried out for high-value applications such as building insulation and oil spill cleanup. The textile waste fibers aerogels have ultra-low density and high porosity, good thermal stability and outstanding heat insulation properties (K avg = 0.049–0.061 W/m·K). It has a competitive commercial application value that the maximum oil absorption value reaches 18.6 g/g.

Introduction

The textile industry is still one of the largest and most vibrant industries in the world [1]. The consumption of textile products has increased tremendously from 78 million tons to more than 103 million tons during the last decade. Due to population and economic development, this trend is expected to continue [2, 3]. The average consumption of textiles per person has increased from 7 kg in 1992 to 13 kg in 2013. According to one forecast, about 148 million tons of waste textiles will be produced in 2030, and more than 150 million tons of waste clothing will be incinerated or landfilled in 2050 [4]. The main components of textile wastes are polyester and cotton, which mainly include three categories, namely clothing, household materials, and industrial textiles and are mainly prepared by polyester and cotton [5–8]. Due to space constraints and leachate issues, the landfill method is banned in many regions and countries [9–11]. Such as European Union (EU) legislation has forbidden the landfill disposal of organic materials, including textile wastes, since 2016. Additionally, the member states of EU will be required to set up a separate collection for discarded textiles by 2025. Incineration can reduce the amount of textile wastes in a short period of time, while the combustion process of synthetic textiles will produce toxic chemicals (such as benzene derivatives and polycyclic aromatic hydrocarbons (PAHs)) and emit a large amount of greenhouse gas carbon dioxide[12, 13].

Therefore, an environmentally benign disposal process to upcycle and recycle the textile wastes is necessarily required to alleviate potential health, fossil energy and environmental issues. Textile waste materials have applications in the production of ethanol [14], glucose[10], nanocellulose and cellulose nanocrystals, microcrystalline cellulose [15], biogas [16], thermal and sound insulation materials [17], concrete and bricks [2], and polymer composites [18], and so forth. The traditional treatment method has complicated procedures or low economic value. In order to change the situation, there is an urgent need for more products with high economic value, such as aerogels, to enhance the financial incentive for textile waste recycling.

Aerogel, as a new material composed of solid framework structure and two different phases of gaseous medium, has the characteristics of typical nano-porous network structure, high specific surface area, high porosity, low density, excellent thermal insulation, outstanding acoustic insulation properties, low dielectric constant, high adsorption and so on[19]. Moreover, due to the size effect, surface effect and macroscopic quantum hazard effect caused by the nanoscale of the skeleton and pores, they have been widely used in many fields such as mechanics, thermal science and optics [20]

The application prospect for aerogel is broad. With the rapidly developing new energy automobile industry around the world, the global market for automotive sound insulation and heat insulation materials is expected to reach 3.2 billion USD by 2022 [21]. Thermal insulation energy-saving buildings have become a new trend. In addition, the market for absorbents used to absorb spilled oil is expected to reach 177.63 billion USD by 2025 [21]. Driven by the environmental issues and potential market application, we successfully developed aerogels from textile wastes with a facile and cost-effective method. The hydrophobicity, absorption capacity and thermal conductivity of textile waste aerogels have been comprehensively studied for the application of oil spill cleaning and heat insulation.

Experiments

Materials

The textile wastes fibers (TWF) have a length of approximately 2–20 mm from crushed waste clothing. Polyvinyl alcohol (PVA, 1799), glutaraldehyde (GA, 25% in water), NaOH, and methyltrimethoxysilane (MTMS) were purchased from Sinopharm Chemical Reagent Co. Ltd. Motor oils of 5w-30 and 5w-40 were purchased from Mobil.

Fabrication of textile waste fibers aerogels

Table 1
Chemical compositions of various textile waste fibers aerogels and the Thermal conductivity

Sample Name	Composition	Fiber Conc. (wt%)	Thermal conductivity (W/m·k)
TWF1a	TWF:PVA = 1	2.0	0.05731
TWF1b	TWF:PVA = 3	2.0	0.05050
TWF1c	TWF:PVA = 4	2.0	0.04891
TW01	TWF:PVA = 2	2.0	0.05162
TW02	TWF:PVA = 2	3.0	0.05818
TW03	TWF:PVA = 2	4.0	0.05916
TW04	TWF:PVA = 2	5.0	0.06164

The textile waste fibers aerogels were developed through using textile waste as the matrix and polyvinyl alcohol (PVA) and glutaraldehyde (GA) as crosslinking agents. The specific processes are as follows. In the initial stages of the process, the TWF were pretreated with alkali NaOH (40 g/L) at 80°C for 30 min with 1:100 material-to-liquor ratio is before being used as the matrix [11, 22]. Second, the different volume TWF were immersed in the PVA/GA/H_2O mixed solution and next sonicated for 400 W, 80°C for 20 min. The TWF concentrations were changed from 2 to 5 wt.%, The specific ratio of the TWF and the PVA is shown in Table 1. 50 µL the GA solution was added to each sample. Then the mixture was cured at 80°C for 3 h in oven. Lastly, the mixture was put in the refrigerator at -18°C to gel for 12 hours, and then freeze-dry at -60°C for 48 h.

Development of the super-hydrophobic TWF aerogels

The developed hydrophilic TWF aerogels were coated with MTMS on their highly porous network surface to form the super-hydrophobic aerogels materials [23–25]. The TWF aerogels and a small beaker containing MTMS were placed in a large closed container. Then, the container was heated in oven at 70°C for 3 h in oven. After the TWF aerogels surface was completely silanized, the excessive MTMS was removed by placing the aerogel sample in a vacuum oven.

Characterization

The structure and morphology of the TWF aerogels were examined using scanning electron microscope (Phenom Pro of China). The samples were coated with an ultrathin layer of gold for the 90 s at 20 mA using a sputter coater (SD-900, Vision Precision Instruments, China).

The hydrophobicity of the MTMS-coated aerogels was investigated by water contact angle which was carried out on an OCA25 goniometer (Dataphysics Products Inc., Germany). During the test, 10 µL water drops were dripped onto the surface of the aerogels and controlled by the syringe system of the tester. The contact angle was calculated according to the acquired photographic image with the angle between drop and surface measurement on the software system.

The thermal conductivity was analyzed using the TPS2500S Hot Disk (Hot Disk AB, Sweden) and transient plane source method. The samples were tested at a room temperature of 25°C.

The thermal gravimetric analysis (TGA) was carried out using a HCT-3 Thermogravimetric Analyzer (Henven, China) to evaluate the thermal stability of the specimens by heating from room temperature to 700°C at 10°C min^{-1} under air.

The aerogel was put into a beaker with motor oil to study the oil absorptivity. Two motor oil used for the absorption tests were 5W-30 and 5W-40. The motor oil specifications are displayed in Table 2. The sample was weighed and placed in motor oil for 1 h to ensure a swelling equilibrium. Then the wet sample was lifted from the oil container, drained for 30 s in air and weighed again. The second Motor oil absorption capacity was calculated using the following formula:

$$Q_t = \frac{M_w - M_d}{M_d}$$

1

Q_t is the crude oil absorption capacity of the aerogel, M_w (g) is the weight of the aerogel after absorption, and M_d (g) is the weight of the aerogel before absorption.

The squeezed ratio of crude oil (Q_s) was calculated using the formula :

$$Q_S = \frac{M_w - M_s}{M_w - M_d} \times 100\% \quad (2)$$

M_s (g) is the weight of the aerogel after squeezing.

Table 2
Specification of motor oil.

Motor oil	Viscosity (mPa·s)		
	25 °C	50 °C	75 °C
5W-30	96.6	50.4	21.0
5W-40	117.8	55.6	29.6

Results And Discussion

Morphologies and structures of aerogels

The TWFs aerogels obtained after freeze-drying were hydrophilic due to the large number of hydroxyl groups on the PVA and TWFs. Therefore, for cleaning oil spill applications, it is necessary to modify the surface of the aerogel to transform its properties from hydrophilic to hydrophobic. To achieve this, MTMS was coated on the surface of the aerogel through a simple chemical vapor deposition process to generate hydrophobic silane groups. For investigating the super-hydrophobicity of the coating aerogels effect, water contact angle measurement was performed on both the external and internal surfaces of aerogels. The aerogels without MTMS coated could immediately absorb water droplets during the test, resulting in no measurable contact angle. As shown in Fig. 3a, the large contact angles of 136.9° was measured on the external surface. To analyse the internal coated effect of aerogel, the sample was cut, and water contact angle of 123° was measured on the cross-section of the sample (Fig. 2b), proving that the entire aerogel is hydrophobic. Therefore, it indicates that the surface of the porous network was successfully chemically modified by MTMS to make the entire aerogel hydrophobic. The water contact angle value of the external surface is higher than that of the cross-section, which may attribute to by more opportunities for the external surface to contact MTMS and a higher degree of silanization.

Thermal properties of aerogels

Thermal conductivity of aerogels

The thermal insulation properties of the TWFs aerogels were characterized by thermal conductivity measurement at room temperature of 25°C and demonstrated in Table 1 and Fig. 4. The TWFs aerogels present excellent thermal insulation owing to ultra-low thermal conductivities (K_{avg}= 0.049–0.062W/m·K) which are comparable with conventional thermal insulation materials such as foams and wools. This can be explained as air occupies most of the space in the porous structure of TWFs aerogels, which is a thermal insulator with very low thermal conductivity at ambient temperature and pressure. Figure 4 and Table 1 show that keeping the amount of TWF constant, the thermal conductivity decreases with the increases of the ratio of TWF and PVA. Keeping the ratio of TWF and PVA unchanged, the thermal conductivity increases with the increase of TWF's weight. In summary, the thermal conductivity increases with the increase of the total weight of the TWFs and PVA. The thermal conductivity of TWF1c with the least weight and TW04 with the most weight are 0.0491 W/m·K and 0.06164 W/m·K, respectively. This tendency can be explained by the increase in the volume of the aerogel solid phase in the unit space, which leads to a decrease in the volume of internal air, thus increasing the thermal conductivity [29]. In addition, the increase of fibers in the TWFs aerogel increases the heat transfer channels, which also causes the increasing of thermal conductivity. Generally, TWFs aerogels own ultra-low thermal conductivity and are prepared by textile wastes using environmentally friendly, low-cost, and less toxic emissions methods, which are promising candidates for practical thermal insulation applications.

Thermal stability of TWF aerogels

In order to evaluate the thermal stability properties of TWFs aerogels, TGA tests were measured and shown in Fig. 5 with different concentrations. It can be observed that the mass change exhibit three phases by the temperature as follows: (1) 50–125°C, (2) 220–500°C and (3) 500–700°C. Between 50°C and 125°C, the uncoated aerogel exhibit 3% weight loss, which likely be caused by the removal of the absorbed atmospheric moisture. The reason for this phenomenon may be that the materials contain many hydroxyl groups on PVA which absorb water in the air after fabrication. On the other hand, negligible weight loss was shown on the aerogels with coated MTMS. At the next phase between 220 and 450°C, a weight loss of about 70 wt.% can be observed for all samples, likely due to the oxidation decomposition of the TWF and PVA. At the final thermal degradation between 500°C and 700°C, the weight of all samples decrease slightly, which possibly be caused by the oxidation of the charred residue.

Oil absorption capabilities of the TWF aerogels

Table 3
The absorption capabilities of motor oil

Sample Name	Composition	Fiber Conc. (wt%)	Density (g/cm^3)	Oil absorption capacity (g/g)			
				5W-30		5W-40	
				25 oC	75 oC	25 oC	75 oC
TW01	TWF: PVA = 2	2.0	0.158	18.6 ± 1.2	15.3 ± 0.3	16.0 ± 1.5	15.5 ± 0.3
TW02	TWF: PVA = 2	3.0	0.194	14.1 ± 0.5	13.7 ± 0.3	13.5 ± 0.5	13.3 ± 0.3
TW03	TWF: PVA = 2	4.0	0.242	11.6 ± 0.5	10.2 ± 0.3	10.6 ± 0.4	10.1 ± 0.2
TW04	TWF: PVA = 2	5.0	0.406	9.4 ± 0.2	8.3 ± 0.1	8.7 ± 0.3	8.4 ± 0.1

The oil absorption capabilities of the TWF aerogels were investigated through the motor oil of 5W-30 and 5W-40. Table 3 and Fig. 6 show the first round of oil adsorption capacity. When the amount is kept to be TWF: PVA = 2 and increasing the fiber concentration from 2 to 5 wt.% at 25 ℃ or 75 ℃, the measured 5W-30 and 5W-40 absorption capacities of the aerogels decreased respectively. The maximum absorption capacity of 18.6 g/g is achieved with the 2 wt.% fiber aerogel for 5W-30 due to it has more space within the per unit volume. The absorption capacity of aerogels materials for the 5W-30 motor oil is higher than the 5W-40 caused by its lower viscosity. As exhibited in Table 3 and Fig. 6, the maximum oil absorption capacity of TWF aerogels diminishes, when the temperature increases from at 25 ℃ or 75 ℃. This trend occurs in the absorption behaviour of two oils on all aerogels. The absorption process of oils on adsorbent material is affected by compatibility between the oils and absorbents, capillary effect, van der Waals forces, pore morphology, diffusion effect and oil viscosity [23, 30]. Temperature is considered to be the significant factor involving the viscosity and the diffusion rate of the oils penetrating into the interior of the aerogel. It can be observed in Table 2 that the viscosity of the oil decreases with increasing temperature, which facilitates oil penetration into the porous aerogel networks. On the other hand, the low viscosity reduces the amounts of the oil anchored in the porous structure of aerogel for the oils, having a negative effect on the total oil absorption of the aerogel. At 75°C, the adsorption capacity of aerogels to the two kinds of motor oil is similar, due to the viscosity of the two oils being lower. At 25°C the amount of 5W-30 adsorbed is higher than 5W-40, probably due to 5W-30 having a lower viscosity than 5W-40, which is beneficial to diffusion into the porous structure. The amount of adsorption at 75°C is lower than that at 25°C caused by the viscosity of the oil being too low at 75°C, which is not conducive to the anchoring of the oil inside the aerogel. The experimental results demonstrate that the super-hydrophobic TWF aerogels with excellent oil absorption capacity could be the candidate materials for oil spill cleaning.

The absorbed motor oil can be re-collected through extruding oil containing aerogel. Figure 7a shows the effect of cycles of sorption on the oil absorption capacity of the TW01 aerogel on 5W-30 at 25°C. The sample achieved a high absorption capacity of 18.6 ± 1.2 g/g in cycle 1. However, the absorption capacity dramatically dropped to 3.2 ± 0.3, 2.8 ± 0.2, 2.7 ± 0.2 and 2.8 ± 0.2g/g in cycles 2, 3, 4, and 5, respectively. Figure 7b exhibits the squeezed ratio of the absorbed oil. 77.9 ± 3.0, 97.3 ± 1.3, 98.5 ± 1.0, 99.3 ± 0.4, and 99.4 ± 0.3% of the absorbed motor oil was re-collect after cycles 1, 2, 3, 4, and 5, respectively, by simple squeezing. This phenomenon can be explained based on the change of the aerogel volume and weight. The sample used in cycle 2 was squeezed while collecting the oil absorbed in cycle 1, causing partial collapse of the porous structure of the aerogel, which could not be completely recovered in later cycle. In addition, the adsorbed oil could not be completely removed, and the initial weight of the sample in cycle 2 increased, which sharply reduced the oil absorption values. In later cycles, the oil absorption values and the squeezed ratio are similar to the value after the first cycle, may due to the sample structure having not changed anymore and the weight of the remaining oil in the squeezed aerogel is close in each cycle.

Conclusions

In conclusion, an advanced and cost-effective method of the textile waste fibers aerogels from textile waste has been successfully developed. After being coated with MTMS, the developed aerogels exhibit excellent super-hydrophobicity with a water contact angle of up to 136.9°. The textile waste fibers aerogels can be used as heat insulation materials of buildings with excellent heat insulation properties and thermal stability. It is found that the initial fiber concentration, the temperature and the oil viscosity significantly affect the oil absorption. This development will provide yet another way to deal with waste textile and a new method to enhance the commercial value of the textile wastes.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

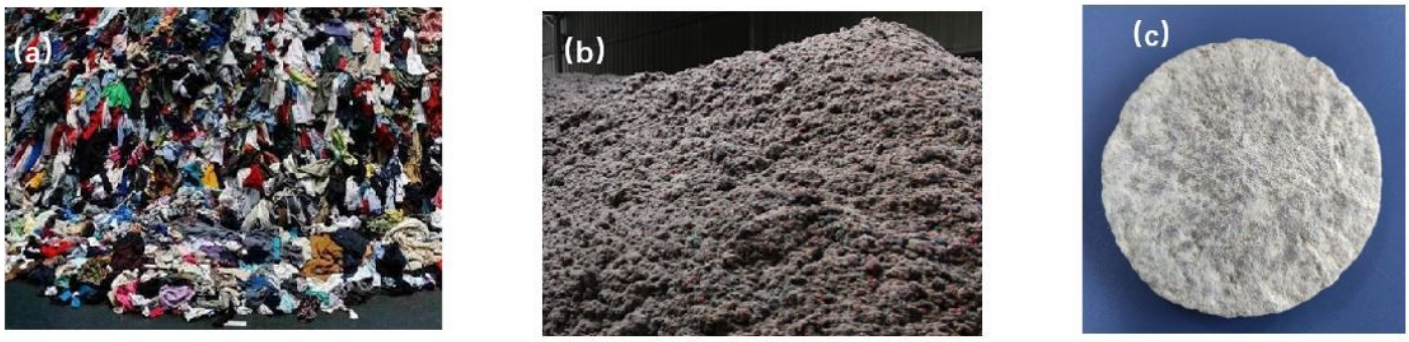

Figure 1

(a) The textile wastes, (b) the raw TWFs obtained from shredding the textile wastes, (c)the textile wastes fibers aerogel

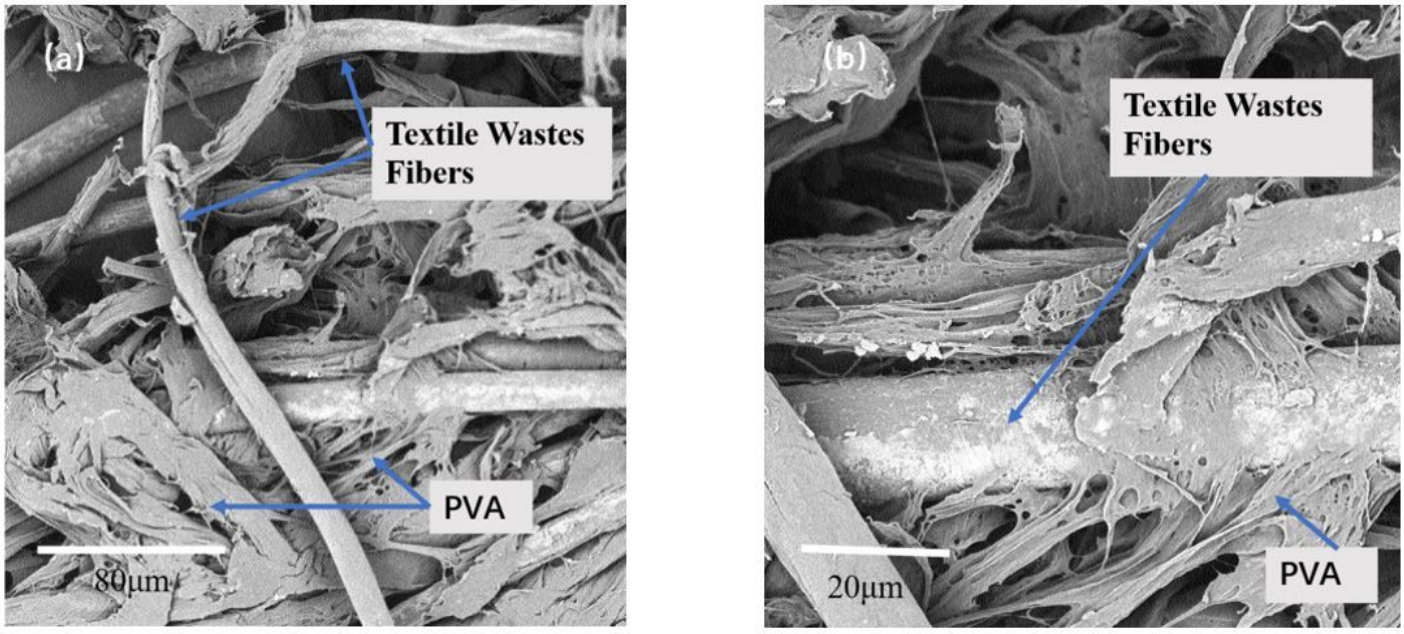

Figure 2

SEM images of the textile wastes fibers aerogel TW01 with different magnification

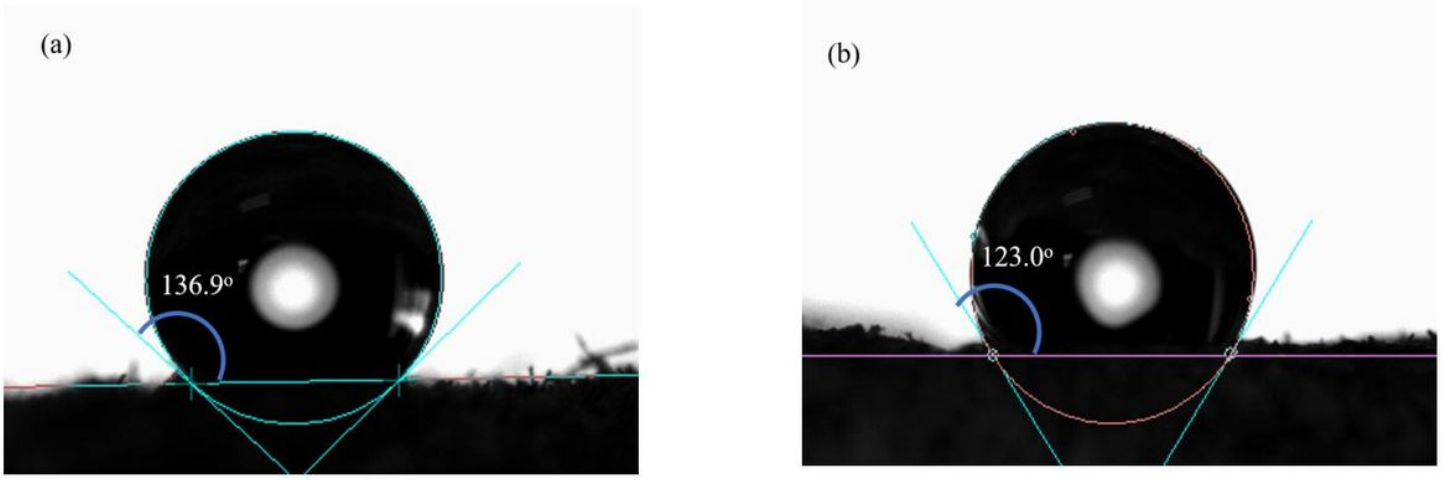

Figure 3

Water contact angles on (a) the external surface and (b) the cross-section of the MTMS-coated TWFs aerogel.

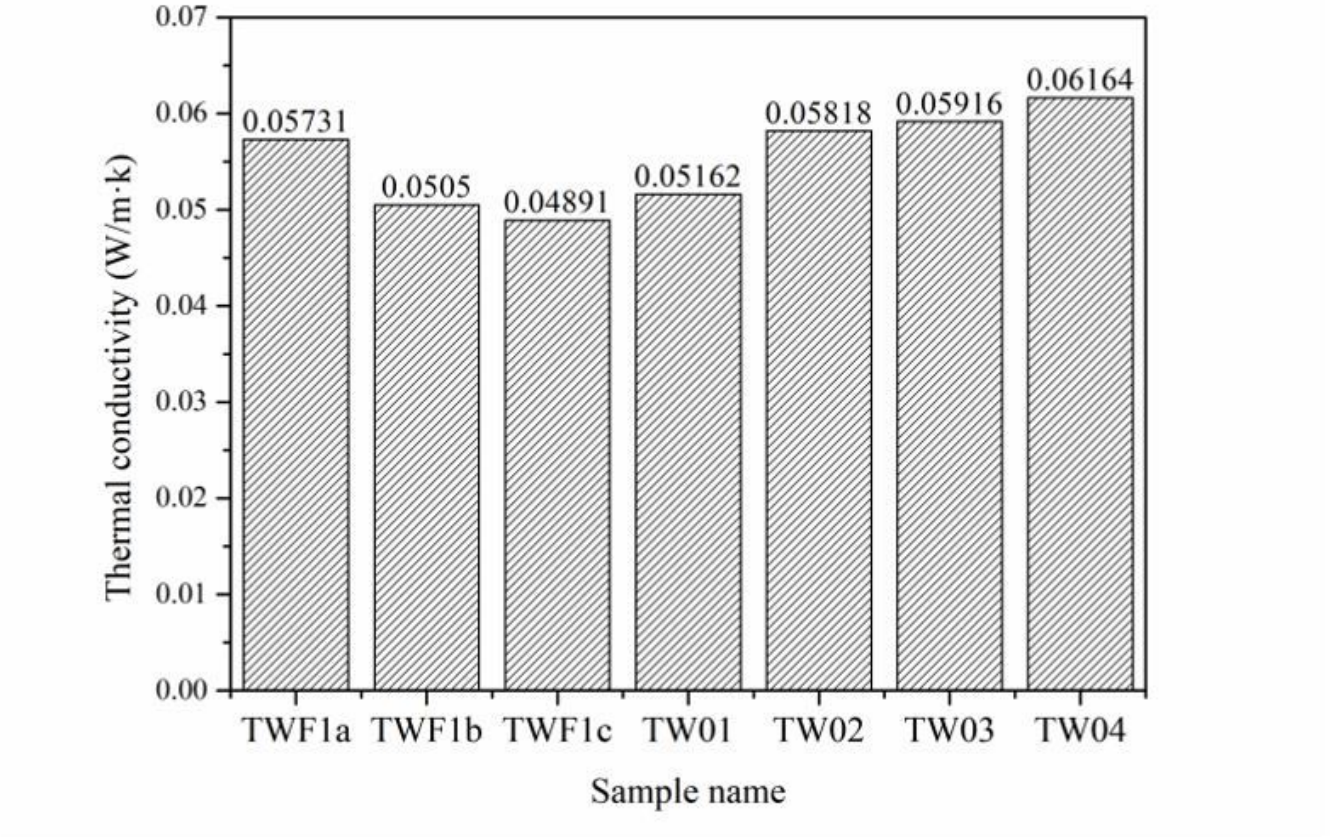

Figure 4

The thermal conductivity of TWFs aerogels

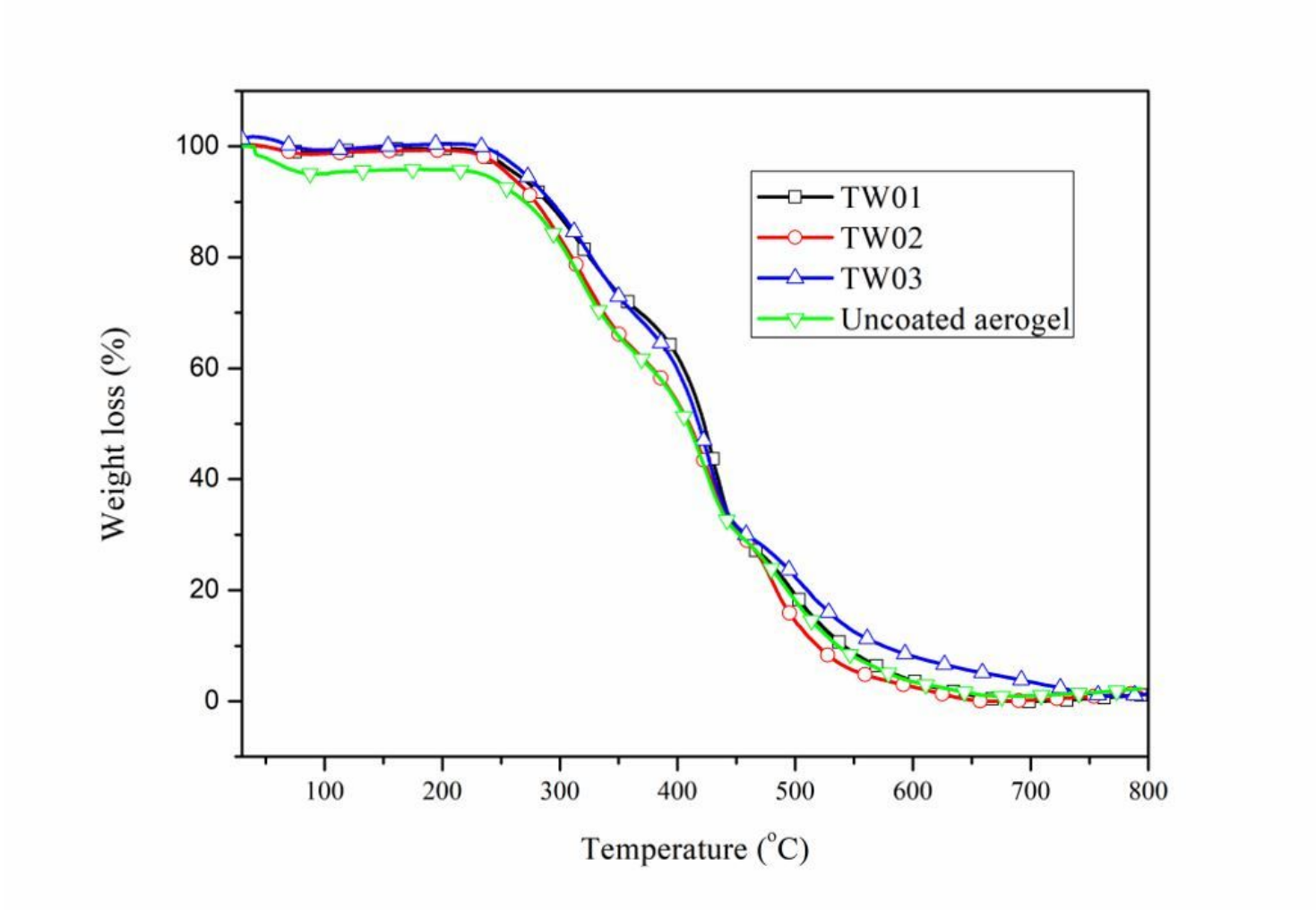

Figure 5

TGA curves of the TWF aerogels with different fiber concentrations

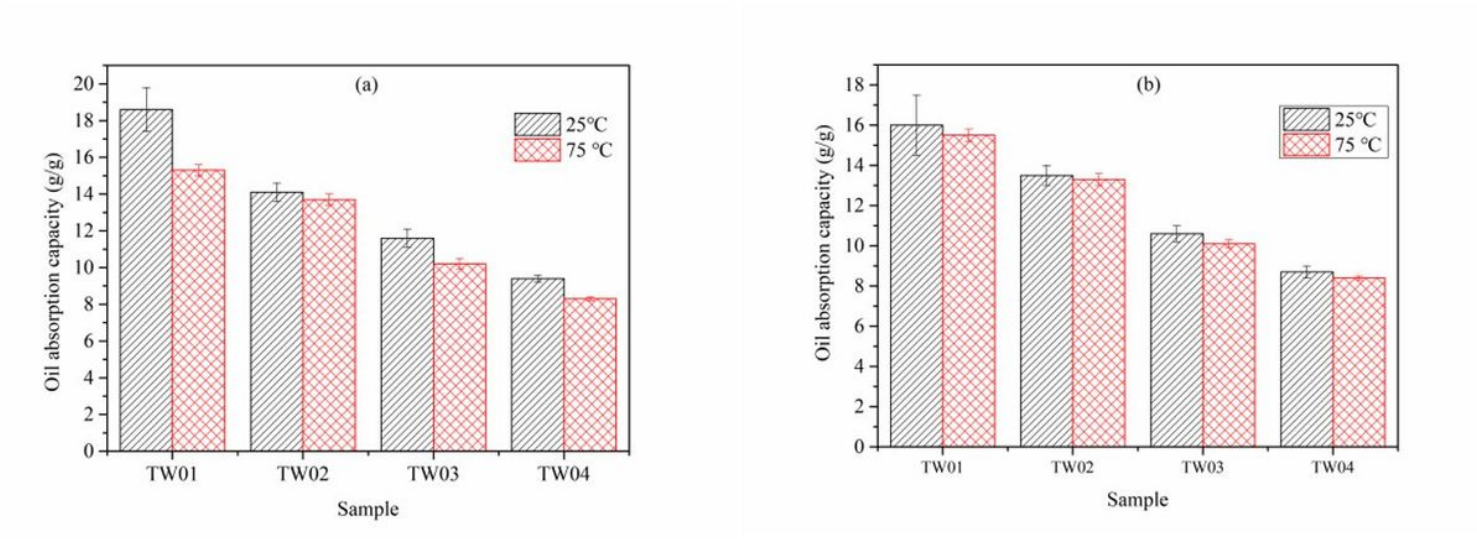

Figure 6

The absorption capabilities of motor oil (a) 5-W30, (b)5W-40

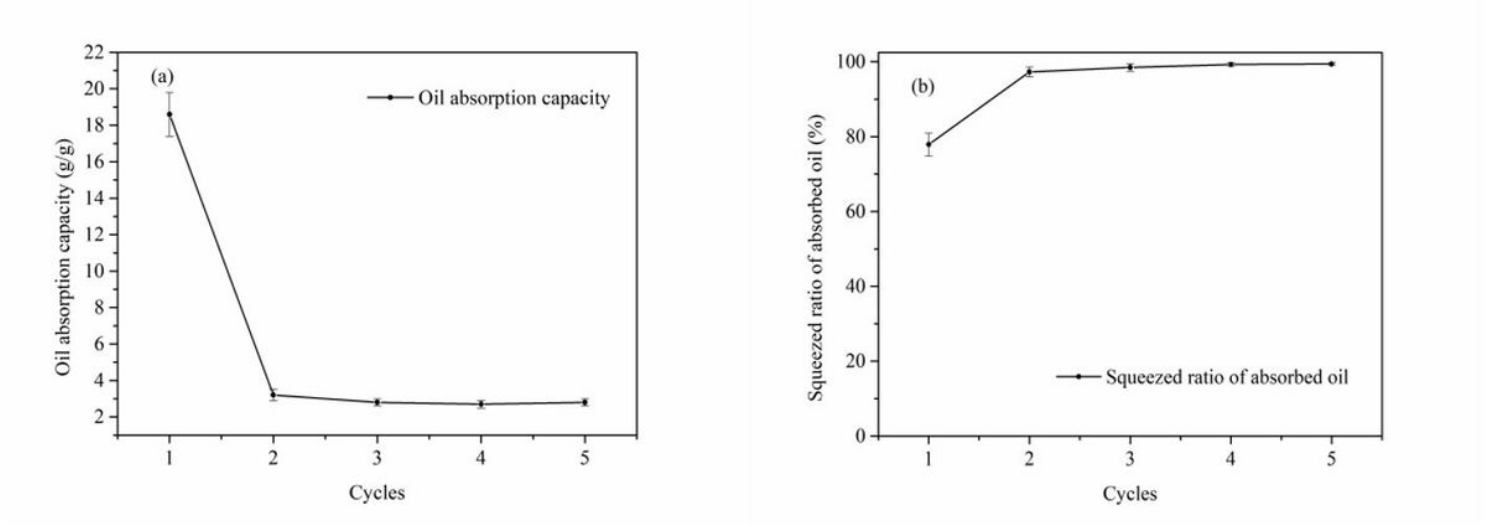

Figure 7

Effect of cycles of sorption on (a) oil absorption capacity and (b) squeezed ratio of absorbed oil.

Supplementary Files

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