

# Fabrication of Polytetrafluoroethylene Aerogels with Excellent Sound Absorption and Thermal Insulation

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## Electronic Supplementary Information

**Abstract** As the application scenarios of aerogels expand, higher requirements are put forward for the materials used to prepare aerogels. Due to the unique chemical structure, polytetrafluoroethylene (PTFE) has excellent properties such as high-temperature resistance, hydrophobicity, and chemical stability. However, the PTFE aerogels are difficult to be molded due to the weak interaction between resin particles. In this work, poly(ethylene oxide) (PEO) was selected as the carrier to assist the PTFE aerogels molding. The pure PTFE aerogels were prepared by homogeneously mixing PTFE aqueous dispersion and PEO, freeze-drying, and high-temperature sintering. When the mass fraction of PTFE and PEO were appropriate, the porosity of PTFE aerogels exceeded 90% and had a hierarchical honeycomb structure. Results showed that the PTFE aerogels not only had excellent hydrophobicity but also possessed superior acoustic insulation, mechanical strength, thermal insulation, and heat resistance properties. Specifically, the water contact angle is about 140°. The noise reduction coefficient is 0.34 and the average sound absorption coefficient is greater than 88% in the frequency range of 2000–6400 Hz. Meanwhile, the thermal conductivity in the air is about 0.045 W/(m·K), and the initial thermal decomposition temperature is 450 °C. More importantly, the PTFE aerogels had excellent temperature and corrosion resistance. Even after extremely thermal and chemical treatment, they remained unchanged porous structure as well as acoustic and thermal insulation properties, which exhibits great potential for application in many harsh environments.

**Keywords** Polytetrafluoroethylene; Fluoropolymer; Aerogel; Acoustic absorption; Thermal insulation

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## INTRODUCTION

Noise pollution manifests in transportation, industrial machinery, construction, and public clamor. Prolonged noise exposure not only interferes with daily life but also causes damage to the nervous and cardiovascular systems.<sup>[1]</sup> Therefore, taking effective measures to reduce noise pollution is essential to ensure people's health and environmental quality. A common method of noise reduction is to use sound-absorbing materials, in which sound waves can be lost through resonance and reflection.<sup>[2,3]</sup> Compared with traditional sound-absorbing materials, porous aerogel materials with high porosity and complex interface structures have better sound-absorption performances and are considered to be irreplaceable candidates for sound-absorbing materials.<sup>[4–6]</sup> Aerogel is a kind of solid material with a three-dimensional porous structure that is composed of interconnected colloidal particles or polymer chains.<sup>[7]</sup> The large amount of air

and the small pores inside the aerogels make them show unique properties such as high porosity, low density, high specific surface area, and low thermal conductivity, which make aerogels have great application prospects in many fields.<sup>[8–11]</sup> However, conventional aerogel materials are difficult to meet the requirements of multiple application scenarios and stable use in harsh environments, so there is an urgent need to develop high-performance and multifunctional aerogel materials.<sup>[12,13]</sup>

Polytetrafluoroethylene (PTFE) is an inert fluoropolymer with a main chain consisting of C—C bonds, and all side bonds replaced by fluorine atoms. Due to the strong C—F bonds, the tight packing of fluorine atoms around the main chain, and the low surface energy, PTFE has excellent heat resistance, chemical inertness, and hydrophobicity, making it show great application potential in harsh environments.<sup>[14,15]</sup> In addition, PTFE has a large density (2.16 g·cm<sup>−3</sup>) and a small distance between its molecules.<sup>[16]</sup> This feature easily hinders the transmission of sound waves and is not conducive to the sound propagation process, which makes PTFE a candidate for an outstanding sound insulation material.<sup>[17]</sup> In general, for inherently large-density materials, the construction of a

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porous structure can not only achieve lightweight which makes the materials apply in some special fields, but also improve the sound absorption performance of materials by diffracting and reflecting sound waves.<sup>[18]</sup> However, since PTFE has very high chemical stability, which means that it is not easily dissolved in a variety of solvents while having a high melting temperature and melt strength, it is difficult to obtain the three-dimensional porous structure using traditional processing methods such as conventional foaming.<sup>[19]</sup> Accordingly, the fabrication of PTFE aerogels with porous structure and low density remains a big challenge.

Normally, the preparation of aerogels requires two important steps. The first step is the preparation of hydrogel, which is to make the colloidal material form a network structure in a liquid solution.<sup>[20]</sup> There are several methods for the preparation of hydrogel, including the sol-gel, hydrothermal, molecular, and colloidal methods, which can be used to synthesize silica, carbon, biomass, and fiber aerogels respectively.<sup>[21–24]</sup> The second step is to remove the liquid in the gel by a special drying technique, where the liquid is replaced by gas while the pores and network are preserved intact. The commonly used drying method is freeze-drying, which can prevent the capillary force generated at the liquid-gas interface from destroying the spatial structure of the gel.<sup>[25,26]</sup> In the above two steps, the more critical point is the formation of the gel network structure, because PTFE molecules are difficult to entangle with each other. To overcome this obstacle, the usual strategy is to introduce carriers as the backbone of the network.<sup>[27,28]</sup> Baskakov *et al.*<sup>[29]</sup> constructed a three-dimensional network structure by distributing PTFE among the graphene oxide sheets, where GO acts as a carrier, making the PTFE form a continuous structure. The prepared aerogels were superhydrophobic and had high adsorption performance towards organic solvents. Nevertheless, due to the presence of GO, the toughness of PTFE-based aerogel deteriorated and elasticity decreased. Inversely, the polymer as the carrier-assisted molding can well help the matrix establish network support. For example, MXene sheets can be connected into continuous and ordered structures by distributing them in polymeric carriers.<sup>[30,31]</sup> Since PTFE is difficult to dissolve and melt, similar to inorganic particles, the above method may also be applicable to the preparation of PTFE aerogel. Recently, Guo *et al.*<sup>[32]</sup> chose PVA as the carrier in the preparation of PTFE aerogels. PVA assisted the aerogels in shape in the freeze-drying stage, yet the carbonization process reduced the porosity and performance of the PTFE/C aerogels, which is ascribed to the fact that the long carbonization time of PVA leads to shrinkage of the pore structure. In addition, pro-

longed sintering time may cause the porous structure to deform or even disappear. Compared with PVA, PEO with similar effects has a lower decomposition temperature and shorter decomposition time.<sup>[33]</sup> In the previous research, Shen *et al.*<sup>[34]</sup> prepared a PTFE fibrous membrane by dissolving PEO in PTFE aqueous dispersion. After high-temperature sintering, the membrane maintained the fibrous structure fabricated in electrostatic spinning, which indicates that PEO is a suitable carrier in the molding of PTFE products.

In this work, PTFE aqueous dispersion was used as the matrix material, and PEO was selected as the carrier to assist the aerogel molding. The PTFE aerogels with high porosity and small pore size were prepared through homogeneous mixing, freeze-drying and sintering stages. The aerogels with different porous structures can be obtained by adjusting the mass fraction of PTFE and PEO. The final products not only obtain high sound absorption and thermal insulation properties but also have excellent hydrophobicity, temperature resistance, and corrosion resistance, which exhibits potential application in harsh environments.

## EXPERIMENTAL

### Materials

Commercial PTFE aqueous dispersion (JF4DCD) was offered by Zhejiang Juhua Group Co. LTD (China). For this dispersion, the PTFE solid content is about 60%; the surfactant content is 4%–7%; the viscosity is  $2 \times 10^{-2}$ – $4 \times 10^{-2}$  Pa·s. PEO was provided by Shanghai Mai Lin Biochemical Company (China) with a molecular weight of  $5 \times 10^6$  g/mol. Sodium hydroxide and sulfuric acid were obtained from Chengdu Kelong Chemical Reagent (China) without further purification. Deionized water was self-made.

### Preparation of PTFE Aerogels

Different amounts of PEO were added to water and stirred to dissolve completely. After that, PTFE emulsion of different masses was added to the above solution and magnetically stirred for 1 h to ensure that the PTFE particles and PEO molecules could be dispersed evenly. The detailed mass ratios of the PTFE/H<sub>2</sub>O/PEO solutions used in the experiments are listed in Table 1. According to different amounts of PTFE and PEO, samples are named Fx-Ey (x represents the numerical value of the mass fraction of PTFE to PTFE/H<sub>2</sub>O/PEO solutions and y represents the numerical value of the mass fraction of PEO to PTFE).

After mixing well, the above mixture was poured into the silicone molds and frozen in the refrigerator at –20 °C for 12 h. When the water in the sol solidified into ice, the mixture was freeze-dried in the freeze-dryer (LGJ-10FD, Yaxing Technolo-

**Table 1** Composition of PTFE/H<sub>2</sub>O/PEO solutions.

| Sample code | PTFE aqueous dispersion (g) | PEO content (g) | H <sub>2</sub> O content (g) | Solution content (g) | (PTFE/Solutions) ×100% | (PEO/(PTFE+PEO)) ×100% |
|-------------|-----------------------------|-----------------|------------------------------|----------------------|------------------------|------------------------|
| F5-E20      | 8.33                        | 1.25            | 90.42                        | 100                  | 5                      | 20                     |
| F8-E20      | 13.33                       | 2.00            | 84.67                        | 100                  | 8                      | 20                     |
| F10-E20     | 16.67                       | 2.50            | 80.83                        | 100                  | 10                     | 20                     |
| F15-E20     | 25.00                       | 3.75            | 71.25                        | 100                  | 15                     | 20                     |
| F10-E10     | 16.67                       | 1.11            | 82.22                        | 100                  | 10                     | 10                     |
| F10-E15     | 16.67                       | 1.76            | 81.57                        | 100                  | 10                     | 15                     |
| F10-E25     | 16.67                       | 3.33            | 80.00                        | 100                  | 10                     | 25                     |

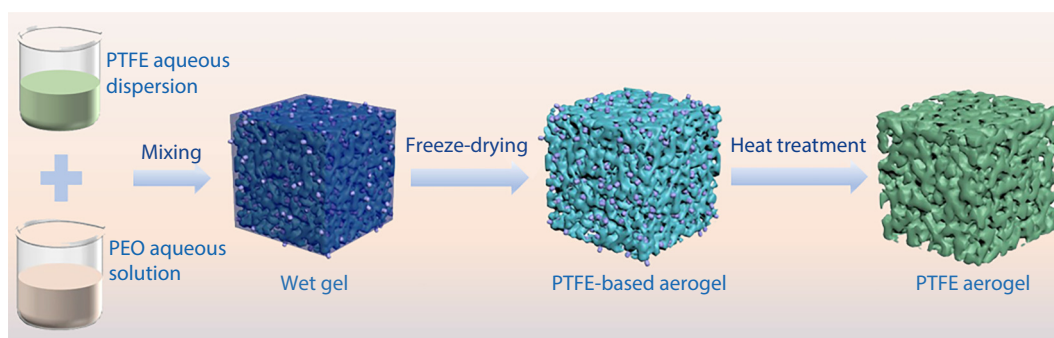


Fig. 1 Schematic diagram of preparation for PTFE aerogels.

gy Development Co., LTD., China) for 48 h to sublimate the ice crystal. Finally, the aerogels were placed in the oven (HF881, Huafei Electric Heating Equipment Co., Ltd., China) at 400 °C for 2 h to remove PEO and the pure PTFE aerogels were prepared. The schematic diagram of preparation for PTFE aerogels is shown in Fig. 1.

### Characterization

The microstructure and surface morphology of the PTFE aerogels were characterized using a scanning electron microscope (FE-SEM, Quanta250, FEI Company, America) with a 10 kV acceleration voltage. Before conducting the observation, a fine layer of gold was incorporated onto the surface of each sample in a vacuum.

Pore size distribution of the samples was measured by piezometric mercury meter (PML, Pore Master 33GT, Quantachrome Instruments, America) according to ISO 10534-2:1998; before testing, the samples were dried in an oven at 60 °C.

The porosities of PTFE aerogels were calculated using the following equation:<sup>[35]</sup>

$$P(\%) = \left(1 - \frac{\rho_0}{\rho}\right) \times 100 \quad (1)$$

where  $P$  is the porosity,  $\rho_0$  is the apparent density, and  $\rho$  is the skeletal density, which is estimated from the density of PTFE (2.16 g·cm<sup>-3</sup>). Pore areal density was determined and counted using the ImageJ software.

Water contact angles (WCA) of PTFE aerogels were measured using a contact angle instrument (CA20, Data Physics Company, German). Each measurement utilized a single 4 μL droplet of water. Five CA values were recorded at various positions for each sample and the averaged value was calculated.

The mechanical properties of the samples were tested by an electronic universal testing machine (CMT6503, Shenzhen Suns Instruments Corp., China) according to the EN ISO3386-1 standard. All measurements were carried out at room temperature and 65% relative humidity with a compression rate of 1 mm/min. Three times were tested for each sample, and the average stress values at 20% deformation were recorded.

Heat resistance of each sample was tested by a thermogravimetric analyzer (TGA, STA.449F3, NETZSCH Co., Germany) with a heating rate of 10 °C/min at air atmosphere; Infrared thermal images were taken by infrared thermal instrument (TiX620, Fluke Corp., America); The thermal conductivity coefficient ( $\lambda$ ) was measured by thermal constant analyzer

instrument (TPS2500S Hot Disk, AB Corp., Sweden). For each sample, the  $\lambda$  value was measured by placing the thermal probe between two samples with a diameter of 29 mm and a thickness of 10 mm. Each sample was tested three times and the average value was calculated.

The sound absorption coefficient was tested by the BK4206 impedance tube absorption testing system (BSWA Technology Co., Ltd., China). BSWA impedance tubes with diameters of 29 and 100 mm were used to measure the sound absorption coefficients in the frequency range of 250–6400 Hz. For each sample, three specimens were tested. Each specimen with a thickness of 10 mm was tested three times for calculating the average value.

To characterize the chemical stability, acidic (pH=1) and alkaline (pH=13) solutions were obtained using H<sub>2</sub>SO<sub>4</sub> and NaOH aqueous solutions, respectively. F10-E20 aerogel chosen as a typical sample was immersed in above solutions for 24 h before conducting performance testing. In order to characterize the temperature resistance, the F10-E20 aerogel was placed in a refrigerator at -50 °C and an oven at 300 °C for 6 h, respectively.

## RESULTS AND DISCUSSION

### Morphology and Structure

Fig. 2 shows the SEM images of PTFE aerogels. The prepared aerogels have a honeycomb porous structure with relatively uniform pore size distribution. On the one hand, with the increase of the content of PTFE, the tight stacking of the particles inside the aerogel is enhanced, so that the pore wall of the aerogel tends to thicken and the holes between the pore walls become smaller. When the solid content of PTFE is 5%, the stable porous structure of PTFE aerogels cannot be prepared (Fig. 2a), which is because a small number of PTFE particles are difficult to connect with each other to form a continuous pore wall structure and easy to collapse in the sintering process. When the solid content of PTFE particles is beyond 8%, the aerogel shows a uniform porous structure (Figs. 2b and 2c). Inversely, when the solid content of PTFE reaches 15%, the porous structure of the aerogel is destroyed due to the excessive increase of the pore wall (Fig. 2d). On the other hand, with the increase of PEO content, the pore structure of aerogels is more uniform and compact, which is due to the enhanced supporting effect of PEO on PTFE particles. However, when the PEO content reaches 25%, the excessively aggregated PEO leads to the appearance of larger defects in the aerogel (Fig. 2h). The preparation mechanism

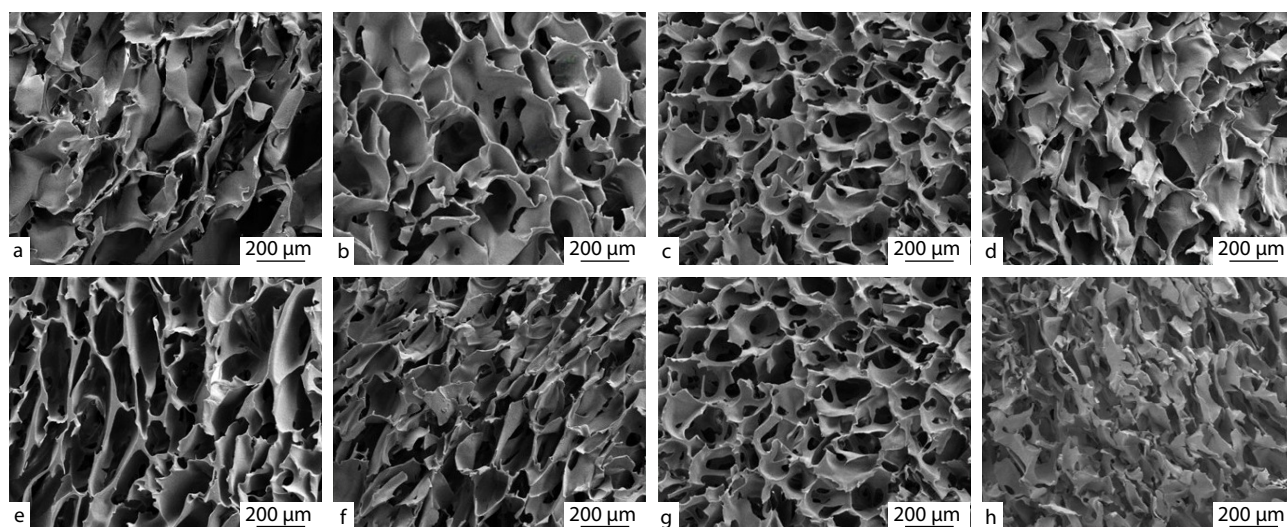


**Fig. 2** SEM images of PTFE aerogels: (a) F5-E20; (b) F8-E20; (c) F10-E20; (d) F15-E20; (e) F10-E10; (f) F10-E15; (g) F10-E20 and (h) F10-E25.

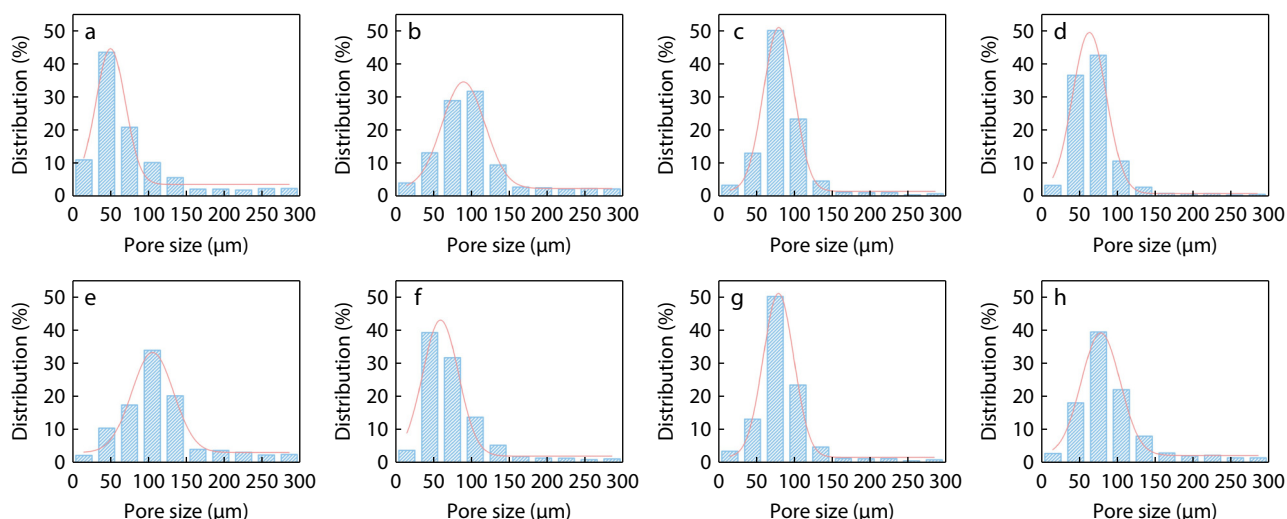


**Fig. 3** Pore size distribution of PTFE aerogels: (a) F5-E20; (b) F8-E20; (c) F10-E20; (d) F15-E20; (e) F10-E10; (f) F10-E15; (g) F10-E20 and (h) F10-E25.

of PTFE aerogel is shown in Fig. 1. In the stirring stage, PEO acts as a carrier to connect the PTFE particles dispersed in the aqueous dispersion, which prevents the aerogel from cracking during freeze-drying. In the sintering process, the temperature exceeds the melting point of PTFE particles. The interdiffusion movement of PTFE molecular chains makes the adjacent PTFE particles join together forming continuous pore walls (Fig. S2 in the electronic supplementary information, ESI), meanwhile PEO is decomposed quickly (Figs. S1 and S3 in ESI). As a result, the aerogel consisting of PTFE walls and numerous porous structures is fabricated with a low density.

Furthermore, the pore size distribution of PTFE aerogels is shown in Fig. 3. The pore size distribution of the aerogels is relatively uniform, in which the pore size is concentrated in 30–100  $\mu\text{m}$ , and a small number of pore sizes are in the range of 0–30  $\mu\text{m}$  or 100–300  $\mu\text{m}$ . With the increase of the solid content of PTFE as well as PEO, the distribution of the pore size is gradually narrowed and the porous structure of the aerogel is more homogeneous. Interestingly, when the mass fractions of PTFE and PEO are 15% and 25%, the pore size dis-

tribution becomes wider as that appears in SEM images. It is considered that the water distributed in the wet gel is removed in the freeze-drying process which forms larger pores in the aerogel, whereas the small amount of PEO distributed in the PTFE wall is degraded during the sintering process which forms smaller pores in the aerogel. Thus, the hierarchical honeycomb-structured aerogels with a wide pore size distribution were generated.

Fig. 4 shows the porosity and pore areal density of PTFE aerogels. The aerogels have high porosity, which is maintained above 90%. By calculating, it is found that the pore areal density increases with the mass fraction of PTFE from 5% to 10% and PEO from 10% to 20%. This can be attributed to the strengthening of PTFE particle stacking, which led to the growing number of pore walls and the uniform distribution of pore size. In addition, the excessive accumulation of PTFE particles in F15-E20 and F10-E25 aerogels would reduce the porosity and the pore areal density.

### Hydrophobicity and Self-cleaning Performances

As shown in Fig. 5(a), the WCA values of the aerogels fluctuate

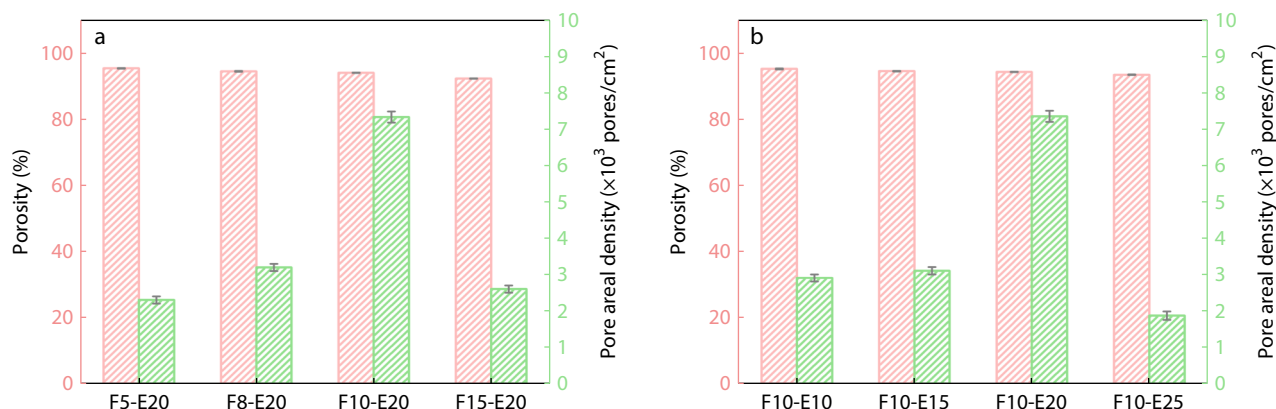


**Fig. 4** Porosity and pore areal density of PTFE aerogels with (a) different PTFE contents and (b) different PEO contents.

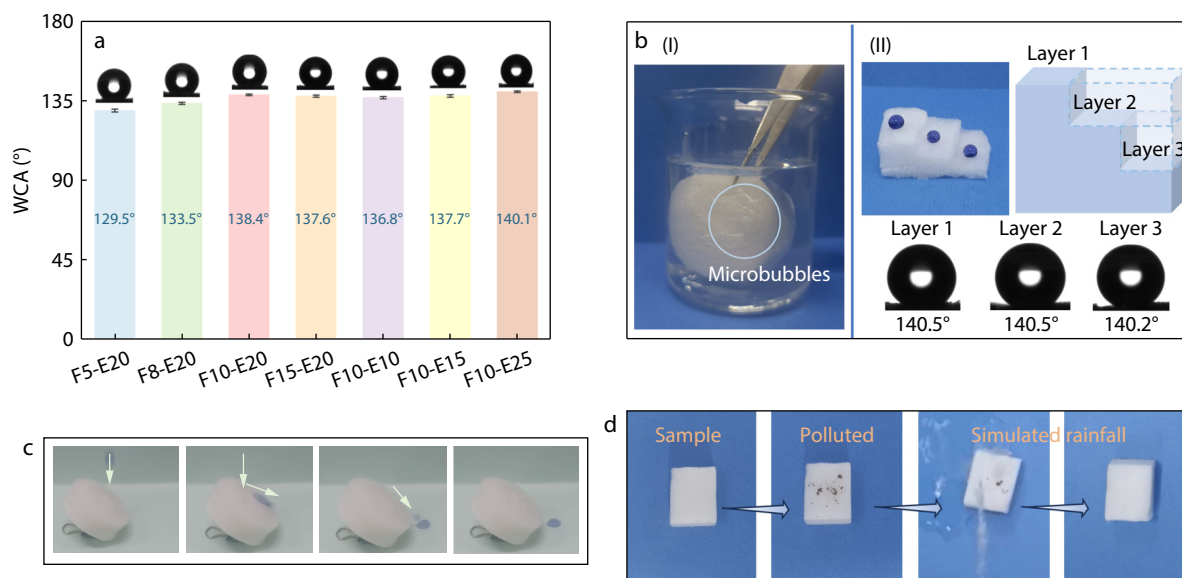


**Fig. 5** (a) Static WCA of PTFE aerogels; (b) Hydrophobic characteristics: (I) Photograph of the F10-E25 aerogels immersed in the water and (II) the WCA of the different surfaces on F10-E25 aerogels after mechanical cutting; (c) Photograph of liquid repellency to impinging water droplet and (d) self-cleaning performances.

from 129.5° to 140.1° with the change of PTFE and PEO contents, indicating that all of them have hydrophobic characteristics. When the aerogel was immersed in water through tweezers, there was an air cushion between the water and the aerogel, which resulted in a large number of microbubbles coming out of the surface of the aerogel (Fig. 5b-I). This phenomenon indicates that the interaction between water and PTFE aerogel was very weak.<sup>[36]</sup> The hydrophobicity of PTFE aerogels can be attributed to the following aspects: (1) the presence of C and F atoms in the molecular chains of PTFE endows the material with very low interfacial energy, which is not easy to interact with other substances; (2) the hierarchical microstructure of PTFE aerogel leads to a relatively rough surface, making the aerogel surface resistant to water. To demonstrate its hydrophobic reliability and stability, the F10-E25 aerogel was cut horizontally twice at 5 mm intervals along the vertical direction using a freezing blade, and the contact angles of the three surfaces along the horizontal direction were tested, as shown in Fig. 5(b-II). The WCA values of these surfaces remained above 140° and the free-falling water droplets rebounded quickly on the 45°

slope surface (Fig. 5c), indicating that the aerogels have strong hydrophobicity as a whole. In the artificial rainfall experiment, water droplets roll on the hydrophobic surface of the F10-E20 aerogels while adsorbed pigments and dust can be removed (Fig. 5d), implying that PTFE aerogels exhibit obvious self-cleaning properties.

### Mechanical Performances

Fig. 6 shows the mechanical properties of PTFE aerogels. As displayed in Fig. 6(a), it can be seen that the stress corresponding to 20% strain ( $\epsilon$ ) of the PTFE aerogel rises from 2 kPa to 108 kPa with the increase of PTFE content. This is mainly because the increase of PTFE particles improves the resistance to compression deformation. As given in Fig. 6(b), the stress-strain curves recorded in the cyclic compression process exhibit a two-stage deformation. The first stage is the linear elastic zone ( $\epsilon < 3\%$ ), where the stress increases linearly; the second stage is the structural densification zone ( $3\% < \epsilon < 20\%$ ), where the stress increases rapidly. After 10 cycles, the stress of F10-E20 aerogel at 20% strain is unchanged and the deformation is 9.1%. It is obvious

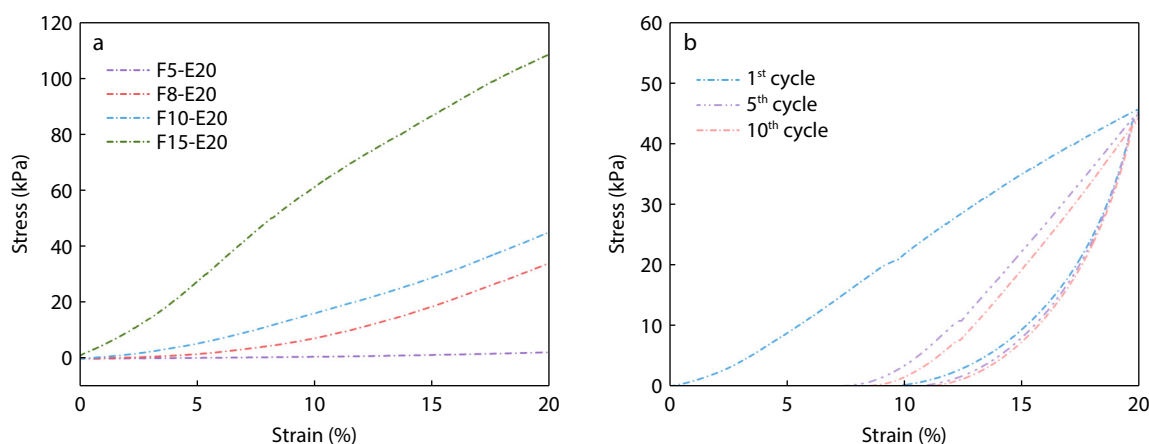


**Fig. 6** (a) Stress-strain curves of PTFE aerogels with different PTFE content; (b) Stress-strain curves of F10-E20 aerogel recorded in the cyclic compression process (the maximum strain is 20%).

that the stress-strain curve of aerogel changes little after the initial compression. This indicates that the PTFE aerogel has a certain flexibility, resilience, and resistance to compression cycles.

### Thermal Insulation Performances

Fig. 7(a) shows the thermal stability of PTFE aerogel. The thermal decomposition temperature of the F10-E20 is 450 °C, which is consistent with pure PTFE and satisfies the many application environments at high temperatures. As shown in Fig. 7(b), the thermal conductivity ( $\lambda$ ) values of PTFE aerogels increase slightly with the amount of PTFE from 5% to 15% and PEO from 10% to 25%, while all the  $\lambda$  values are still at a low level (0.041–0.049 W/(m·K)). The low  $\lambda$  values can be attributed to the low intrinsic thermal conductivity of PTFE and the presence of a large amount of air in the aerogel. Furthermore, the thermal insulation properties of the aerogels were confirmed by using infrared thermal imaging, as can be seen from Fig. 7(c), the upper surface temperature of F10-E20 aerogel with a thickness of 8 mm increased from 30.1 °C to 52.7 °C and from 30.7 °C to 92.2 °C, after being placed at 100 and 200 °C high-temperature stages for 5 min, respectively. This shows that PTFE aerogels have a good insulation effect against high temperatures. Intuitively, the thermal insulation performance of the PTFE aerogel can be further characterized by using paraffin. The same mass paraffins were placed on PTFE aerogel, PTFE block without porous structure, and Al<sub>2</sub>O<sub>3</sub> ceramic with the same height, respectively. The temperature of the thermal plateau was maintained at 100 °C. To observe clearly, white paraffin is dyed orange by Sudan III. It is shown that the paraffin placed on the ceramic melted very quickly. After 40 min, the paraffin on the PTFE block without porous structure began to melt. In comparison, the paraffin placed on the PTFE aerogel did not melt even after 100 min (Fig. 7d), which vividly proved that the aerogel has a low  $\lambda$  value. The thermal insulation mechanism of aerogels is shown in Fig. 7(e). It is considered that the  $\lambda$  value of aerogel in air is mainly composed of  $\lambda_{\text{air}}$  and  $\lambda_{\text{solid}}$ . For PTFE aerogel, the high porosity makes it full of air inside and the porous structure also limits the movement of the air molecule, which leads to low  $\lambda_{\text{air}}$  in the aerogel. Moreover, the presence of PTFE as an excellent phonon barrier can substantially reduce the  $\lambda_{\text{solid}}$ . As a result, PTFE aerogels exhibit a low  $\lambda$  value while also being used in harsh environments, which still exhibits a low thermal conduc-

tivity after temperature, acid, and alkali treatments (Fig. S4 in ESI).

### Sound Absorption Performances

Figs. 8(a) and 8(b) show the sound absorption coefficients of PTFE aerogels with different formulations. As the solid content of PTFE changes from 5% to 10%, the sound absorption coefficient of the aerogel gradually increases at low frequency and decreases at high frequency. This is attributed to the presence of small pores in PTFE aerogels that can absorb low-frequency sound waves, while the aerogels lack large pores to absorb high-frequency sound waves.<sup>[37]</sup> The average sound absorption coefficient in 2000–6400 Hz remains above 86% as PTFE content changes from 5% to 10% and the value of F10-E20 aerogels reaches 88% (Fig. 8c). The noise reduction coefficient (NRC) is another important index to characterize sound absorption performance. Its calculating method is as follows:

$$\text{NRC} = \frac{1}{4} \sum_{i=1}^4 \text{SAC}_i \quad (2)$$

where  $\text{SAC}_i$  represents the sound absorption coefficient at four frequencies: 250, 500, 1000, and 2000 Hz.<sup>[38]</sup> As shown in Fig. 8(c), the NRC of PTFE aerogels gradually increases from 0.27 for F5-E20 aerogels to 0.38 for F15-E20 aerogels. The NRC of F10-E20 aerogels with a density of 0.13 g/cm<sup>3</sup> can reach 0.34. This is attributed to the high porosity which allows most of the acoustic wave energy to be dissipated well through multiple reflections. Besides, the aerogels with a wide pore size distribution enhance the sound absorption performance over a wide frequency range, resulting in a high NRC. When the mass fraction of PTFE is 15%, the porosity of aerogel is reduced, and the average sound absorption coefficient in 2000–6400 Hz decreases. Due to its high sound absorption coefficient at low frequency, it still has a higher NRC value. With the change of PEO content from 10% to 20%, the average sound absorption coefficient of the aerogels gradually increases from 0.80 to 0.88 and the NRC of the aerogels increases from 0.32 to 0.34 (Fig. 8d). This can be attributed to the strengthening of the adhesive effect of PEO, which leads to the bigger pore areal density of the aerogels (Fig. 4). Therefore, the interfaces in the material can scatter, diffract, and refract the acoustic wave energy to a greater extent. When the PEO mass fraction is 25%, the porous structure of the aerogel is destroyed and has a low average sound absorption coefficient.

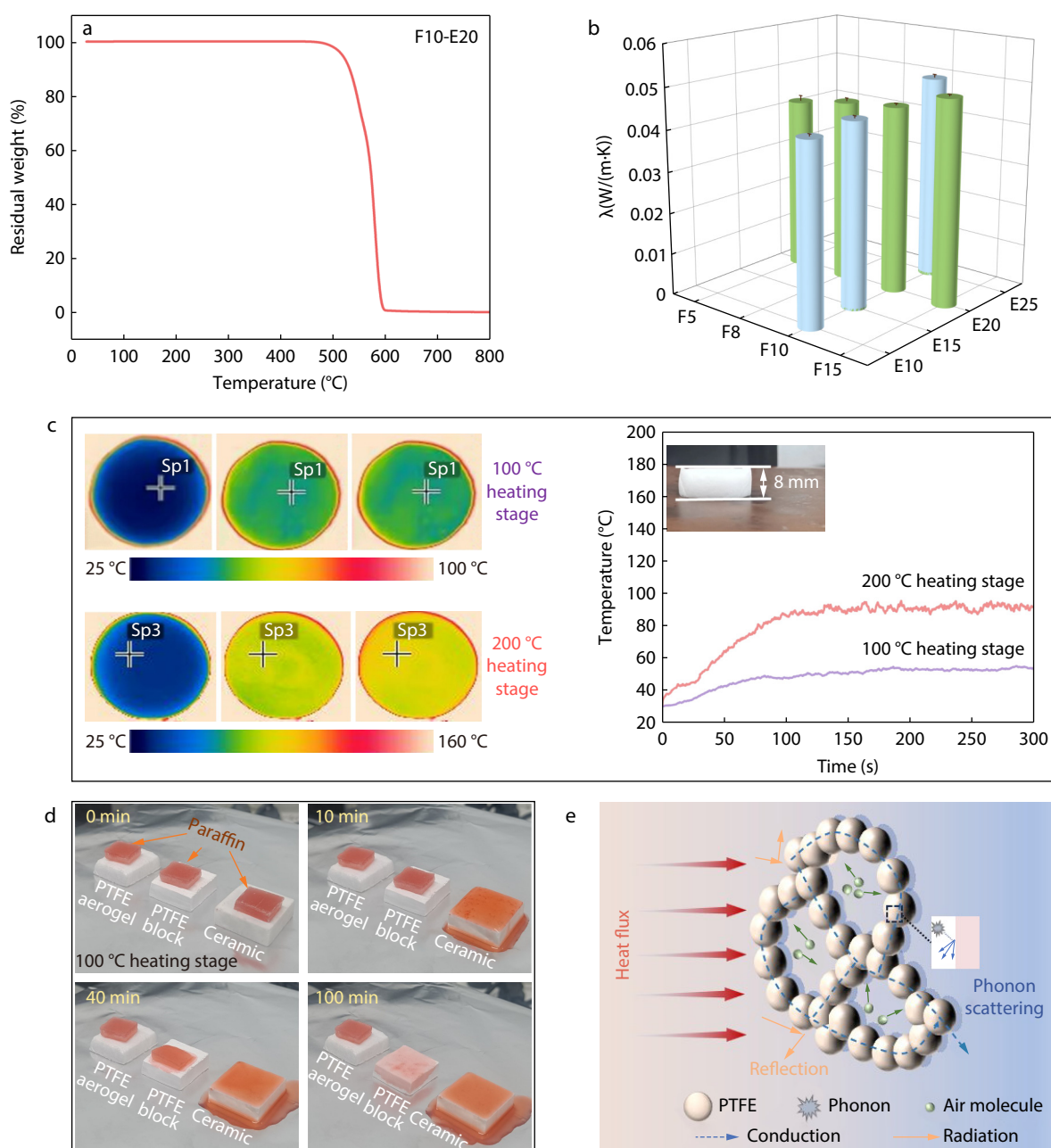


**Fig. 7** (a) The TGA curve of F10-E20 aerogels; (b)  $\lambda$  values of PTFE aerogels; (c) Infrared thermal imaging images of F10-E20 aerogel on different constant temperature heating stages (100 and 200 °C) and the corresponding curves of the upper surface temperature vs time; (d) Melting process of Sudan III-dyed paraffin placed on different insulating materials (PTFE aerogel, PTFE block, and  $\text{Al}_2\text{O}_3$  ceramic) at a constant temperature of 100 °C; and (e) schematic of thermal insulation mechanism of PTFE aerogels.

cient and NRC. Moreover, the application of aerogels in complex environments can be affected by stress and strain. The sound absorption performance of PTFE aerogels after 10 compression cycles was tested (Fig. 8e). Compared with the uncompressed aerogels, the sound absorption coefficient is reduced but still maintained at a high level. In the range of 250–2000 Hz, the sound absorption coefficient did not change. In the range of 2000–6400 Hz, the average sound absorption coefficient was 0.79, which still retained 89.8%, indicating that PTFE aerogels show great sound absorption performance in complex environments. Fig. 8(f) shows the sound absorption mechanism. When

the sound wave is shot into the aerogels, part of the sound wave will be reflected out by the aerogel surface. The rest of the sound wave entering the material will be multiple reflected and scattered in the pores, which creates friction with the air and converts the acoustic energy into internal energy to be dissipated, leaving a small part of the sound wave to penetrate the material. Specifically, high-frequency sound waves with shorter wavelengths will be reflected into larger pore structures while low-frequency sound waves with longer wavelengths will be reflected into smaller pore structures to dissipate the sound energy.

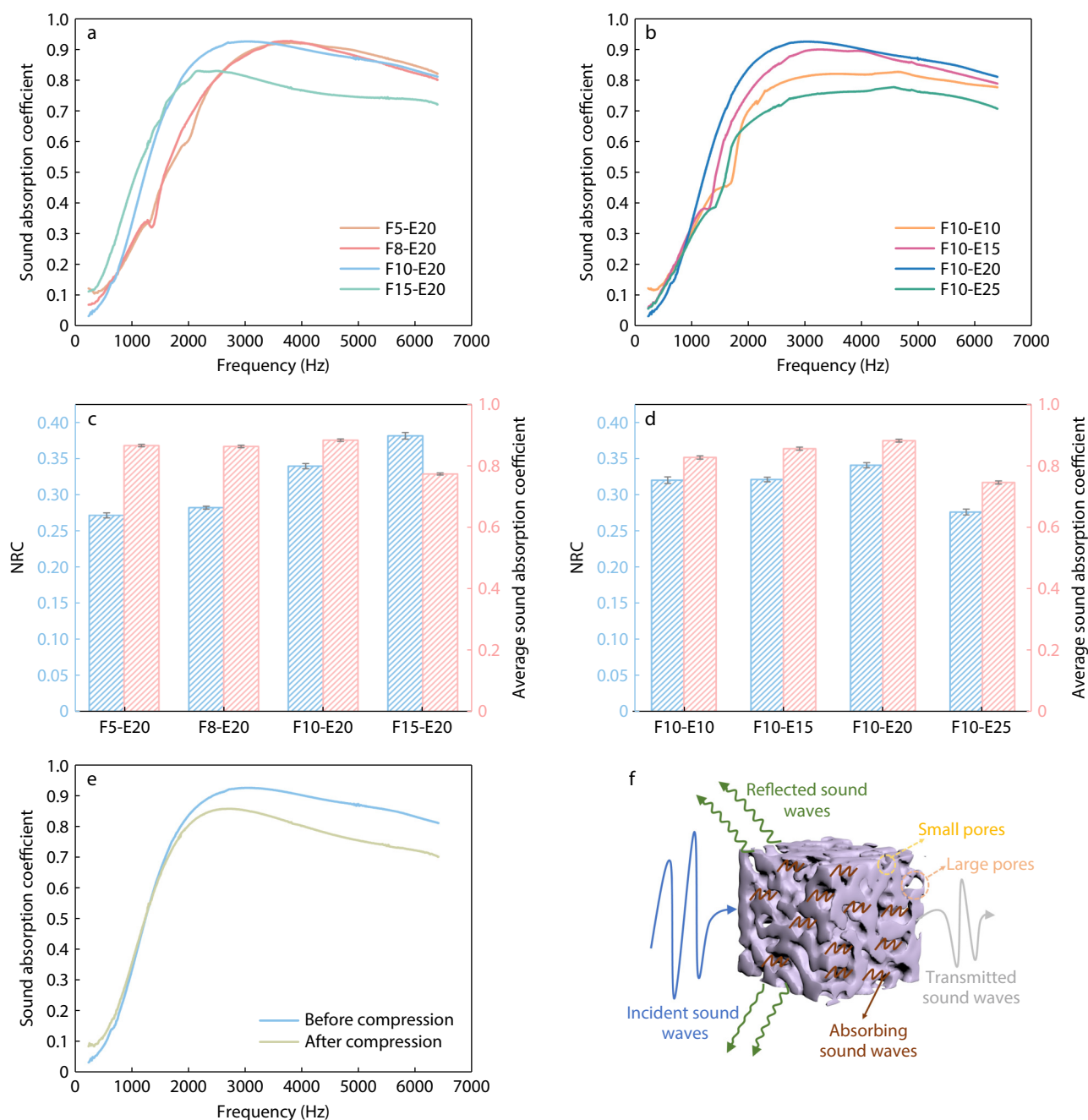


**Fig. 8** Sound absorption coefficients of PTFE aerogels with different (a) PTFE contents and (b) PEO contents; NRC and the average sound absorption coefficient in 2000–6400 Hz of PTFE aerogels with different (c) PTFE contents and (d) PEO contents; (e) Sound absorption coefficients of F10-E20 aerogels after 10 compression cycles and (f) schematic of sound absorption mechanism of aerogels.

Due to the harsh application environment, another parameter that affects the sound absorption performance is the stability and durability of PTFE aerogels. Fig. 9 shows the sound absorption coefficients of F10-E20 aerogels after treatment at low temperature at  $-50\text{ }^{\circ}\text{C}$  for 6 h and high temperature at  $300\text{ }^{\circ}\text{C}$  for 6 h, and acid treatment at  $\text{pH}=1$  and alkali treatment at  $\text{pH}=13$  for 24 h, respectively. It can be seen that the sound absorption properties (Figs. 9a and 9b) of the treated aerogels remain essentially unchanged compared with that of the untreated samples. This indicated that the PTFE aerogels possess excellent high and low temperature resistance and

corrosion resistance, which is mainly attributed to the special molecular structure and stable chemical properties of PTFE (Fig. 9c).

To sum up, due to the high porosity and hierarchical pore structure, the PTFE aerogels have excellent sound absorption and thermal insulation properties. Because of the existence of the PTFE skeleton, aerogels have good hydrophobicity, temperature resistance, and corrosion resistance. Fig. 9(d) collects the performances of the F10-E20 aerogel and other materials. The relevant data are listed in Table S1 (in

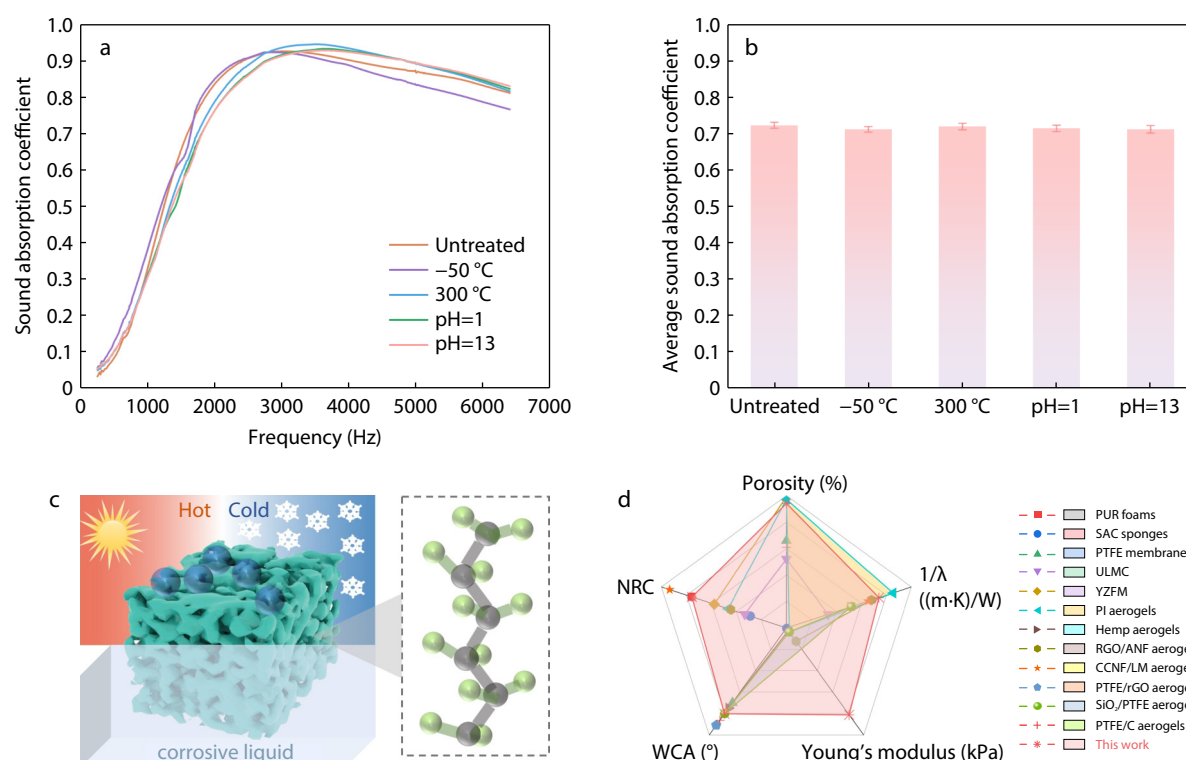


**Fig. 9** (a) Sound absorption coefficients and (b) their average values of untreated F10-E20 aerogels and the one treated at different conditions in the frequency range of 250–6400 Hz; (c) Schematic of PTFE aerogels in harsh environments; (d) Comparison of comprehensive performances between F10-E20 aerogels and some of other previously reported materials.

ESI).<sup>[29,32,39–48]</sup> Compared with other PTFE porous materials, the F10-E20 aerogel has a higher porosity and better mechanical performance. Moreover, the hydrophobicity, sound absorption, and thermal insulation of the F10-E20 aerogel are superior among most reported porous materials, exhibiting potential application in harsh environments.

## CONCLUSIONS

PTFE aerogels with high porosity were successfully prepared by the freeze-drying method using PEO as the carrier. This kind of aerogels have a honeycomb three-dimensional interconnected pore structure and a certain degree of hierarchical pore size distribution, which is conducive to the improvement of the broadband sound absorption performance. Therefore, the PTFE aerogels can be well used as sound-absorbing materials in the frequency range of 2000–6400 Hz. Additionally, the PTFE aerogels also show superior thermal insulation ( $\lambda$  is as low as 0.045 W/(m·K)) and heat resistance performances (thermal decomposition temperature of 450 °C). More importantly, due to the hydrophobicity, temperature resistance, and corrosion resistance of PTFE, the PTFE aerogels are expected to be applied in some harsh environments such as high-temperature, underwater, and corrosion environments for noise reduction and thermal insulation.

## Conflict of Interests

The authors declare no interest conflict.

## Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <http://doi.org/10.1007/s10118-025-3317-7>.

## Data Availability Statement

The related data for this paper are available from the corresponding authors upon reasonable request.

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