Supporting Information

Photo-thermal waxgels with fast regeneration alkane layer for anti-icing

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1. Experimental section

1.1 Preparation of materials

The precursor PDMS and curing agent (Sylagrd 184, Dow Corning, from taobao) were mixed in a mass ratio of 10:1. n-Hexane was purchased from Aladdin. n-Decane was purchased from Macklin, n-tetracosane, n-heptadecane, polypyrrole (PPY) (98%) and graphene oxide (GO) were purchased from MERYER. Dopamine (PDA) and multi-walled carbon nanotubes (CNT) were purchased from J&K. carbon black (CB), DOWSILTM PR-1200 RTV prime coat clear were purchased from Taobao. Sylgard 184 was obtained from Dow Corning. Unless otherwise indicated, all reagents and materials were obtained from commercial suppliers and were used without purification.

1.2 Preparation of waxgels

Taking the carbon black content of 0.10 wt % as an example. 5 g PDMS oligomer and 0.5 g curing agent were mixed at a weight ratio of 10: 1. And then 20 μL n-hexane, 5.5 mg carbon black were added to the system. The mixture was stirred with a

mechanical stirrer at 600 r/min for 1 h. The resulting mixture was poured into a mold, vacuum degassed for 30 min, and cured in an oven at 65 °C for 2 h. The cured PDMS was immersed into the 150 °C alkane bath for at least 6 hours to achieve swelling equilibrium. Then the swollen sample was taken out and cooled to room temperature. The excess alkanes on the surface was removed through filter paper. Waxgels with different photothermal reagents and different carbon black contents were also prepared according to the above operation.

1.3 Photothermal performance testing

The photothermal properties of different photothermal reagents and waxgel complex materials with different carbon black content were evaluated by the method of simulating sunlight irradiation. The temperature of the sample surfaces were measured by infrared imager.

1.4 SEM and optical microscopy characterization

The morphology and size distribution of carbon black particles used were observed by SEM. Observation of cross-sections (transmission mode) of samples with different carbon black contents before alkane dissolution, and cross-sections of samples with carbon black contents of 0.00 wt% and 0.10 wt% after alkane dissolution and regeneration of alkane layers by optical microscop.

1.5 Swelling ratio measurement of waxgels

The mass of PDMS samples with different carbon black content before and after swelling alkane was measured by electronic balance, and the swelling ratio ($R_{swelling}$) of waxgel was calculated according to the formula in the follow equation.

$$R_{swelling} = (m_{wg} - m_{PDMS})/m_{PDMS} \quad (1)$$

Where m_{PDMS} and m_{wg} are weight of materials before and after swelling equilibriums state, respectively.

1.6 The freezing process of water droplets on the waxgel-C24

At room temperature, the waxgel-C24 blocks without and with 0.10 wt% carbon black were placed on the cold table at -20 °C, and the 10 μL of water droplet was dropped on the surface of the substrate, turn the solar simulator on; At the same time, a digital camera was used to record the process and time during the freezing process.

1.7 Ice adhesion strength test

The ice adhesion strength is tested using a self-made device consisting of a cooling table and a motion table with a powerful sensor. 1 mL of ultrapure water was injected into a cuvette (10 mm × 10 mm × 50 mm) to form an ice column, which was placed on the surface of waxgels and kept at the test temperature for 2 h. During the test, the force probe was kept 1 mm above the sample surface, and the shear rate was 0.5 mm s^{-1}. The peak value of the shear force that separates the ice column from the surface of each waxgels is recorded for calculation. The ice adhesion strength was obtained by averaging the results of five tests. Calculation of ice adhesion strength according to formula (2).

$$\tau = F/A \quad (2)$$

A is the contact area between ice and waxgels, and F is the maximum shear force during the de-icing test of each waxgels.

1.8 Measurement of mechanical properties of waxgel-C24

An electrical universal material testing machine (Instron) with a 2000 N load cell was used to perform the mechanical tests. The sample were cut into a cube (the length, width, and height are 10 mm × 10 mm × 10mm) for compressive tests. The crosshead velocity was kept at 1 mm/min for compressive tests

1.9 Determination of useful lifetime of waxgel-C24

The initial mass of waxgel-C24 was weighed with an electronic balance, the wax layer on the surface of waxgel-C24 was glued off with transparent tape, the surface of waxgel-C24 without the wax layer was observed by a microscope and weighed, the surface of waxgel-C24 without the wax layer was irradiated with a xenon lamp (1 sun) for 5 min, the xenon lamp was switched off and left to stand for 4 h, and recorded by a microscope, and the process was repeated 50 times. The sample size are 50 mm (length) × 50 mm (width) × 5 mm (height)

2.0 Determination of sample transmittance

The transmittance of the samples was determined using a UV-Vis spectrophotometer with a sample thickness of 350 μm and a wavelength range of 200-2500 nm.

2. Supporting Tables

Table S1. The physical and chemical properties of paraffin waxes.

	n-decane	n-heptadecane	n-tetracosane
Melting point (°C)	-30	22-24	49-52
Boiling point (°C)	174	292	319
Vapor pressure (mmHg, 25°C)	1.58	0.00185	5.69×10^{-6}

Table S2. Prices of different photothermal reagents.

Photothermal reagents	Market value (CNY/g)
Carbon black (CB)	0.4
Multi-Walled Carbon Nanotubes (CNT)	112.9
Polypyrrole (PPY)	224.18
Dopamine (PDA)	2380.9
Graphene Oxide (GO)	3404.9

3. Supporting Figures

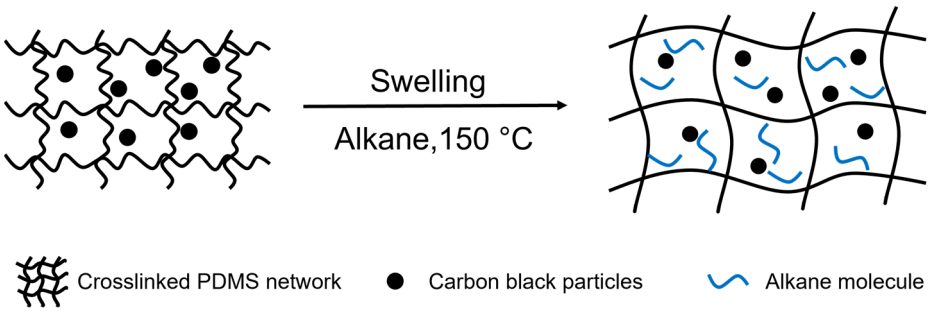

Fig. S1. Scheme of the preparation procedure of photo-thermal waxgels.

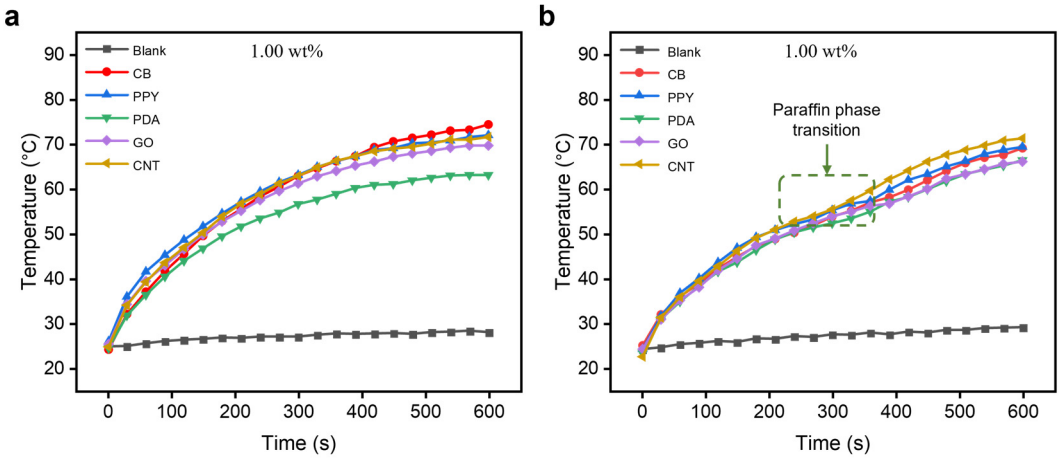

Fig. S2. Photothermal effect of PDMS with different types of photo-thermal reagents before (a) and (b) after swelling with C24 under 1 Sun irradiation (All experiments were conducted at room temperature with a humidity of 37%, and sample thickness is 2 mm).

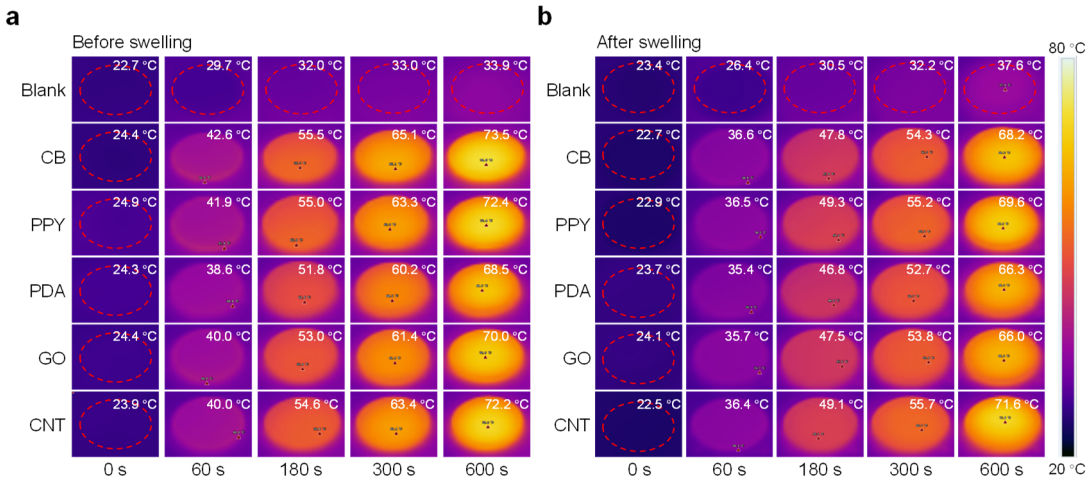

Fig. S3. Infrared thermal camera images of PDMS with 1.00 wt% photothermal reagents before (a) and (b) after swelling of n-tetracosane under 1 sun illumination conditions (All experiments were conducted at room temperature with a humidity of 37%, and sample thickness is 2 mm).

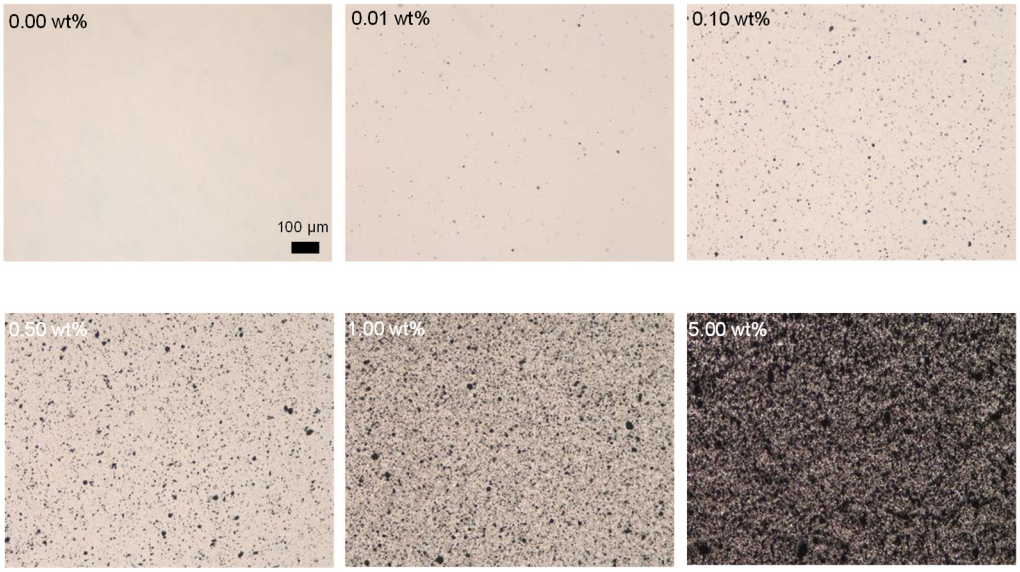

Fig. S4. Optical microscope images of the cross section of PDMS with different content of carbon black particles at room temperature with a humidity of 37%. The samples thickness are 62.5 μm.

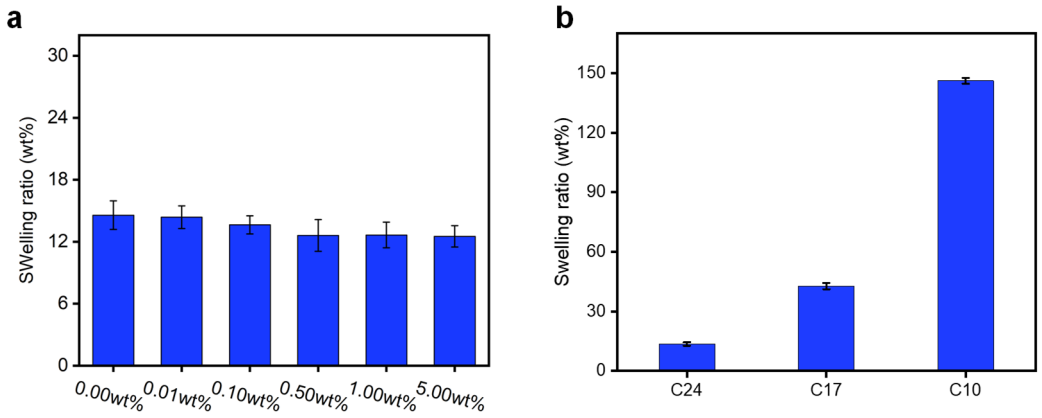

Fig. S5. (a) Swelling ratio of waxgel-C24 with increasing content of CB after swelling for 6h. (b) Swelling ratios of waxgels with different carbon number. (All experiments were conducted at room temperature with a humidity of 37%, and sample thickness is 2 mm.)

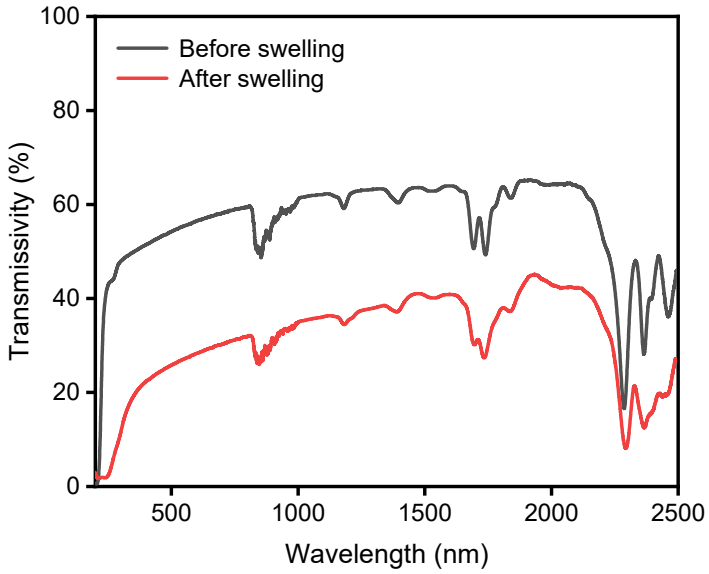

Fig. S6. The transmittance test of waxgel-C24 before and after swelling n-tetracosane. (All the samples were conducted at room temperature with a humidity of 32%, and sample thickness is 350 μm.)

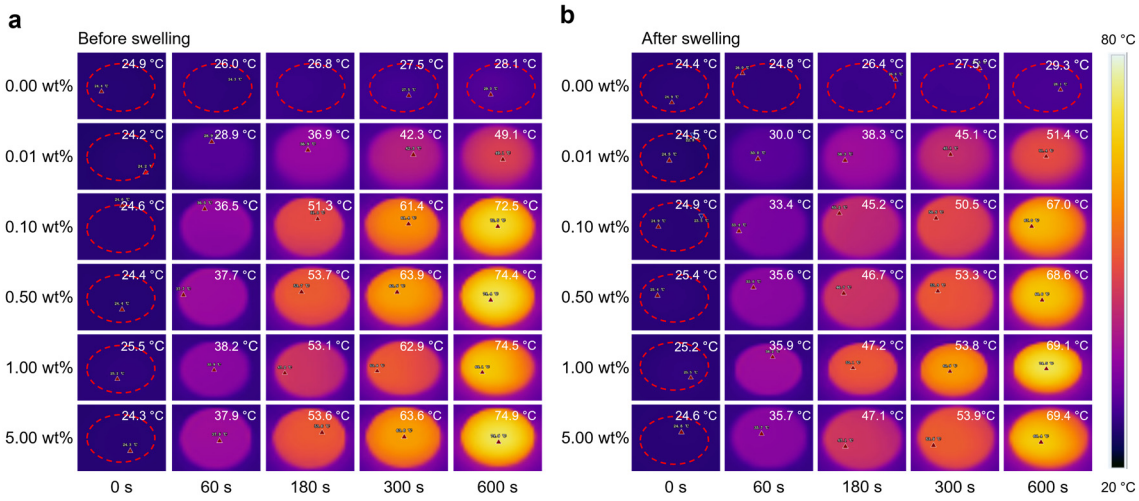

Fig. S7 Infrared thermal camera images of PDMS before (a) and (b) after swelling n-tetracosane at different carbon black content under 1 sun illumination conditions (All the samples were conducted at room temperature with a humidity of 37%, and sample thickness is 2 mm).

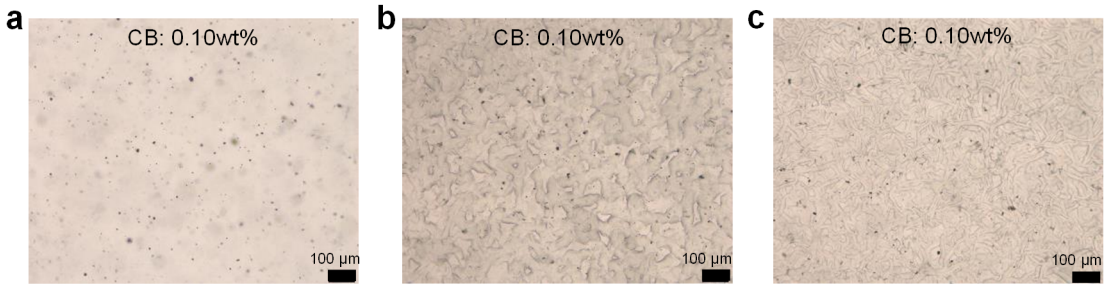

Fig. S8. The optical microscope images of waxgels of (a) waxgel-C10, (b) waxgel-C17, and (c) waxgel-C24 (All experiments were conducted at room temperature with a humidity of 37%, and sample thickness is 350 μm).

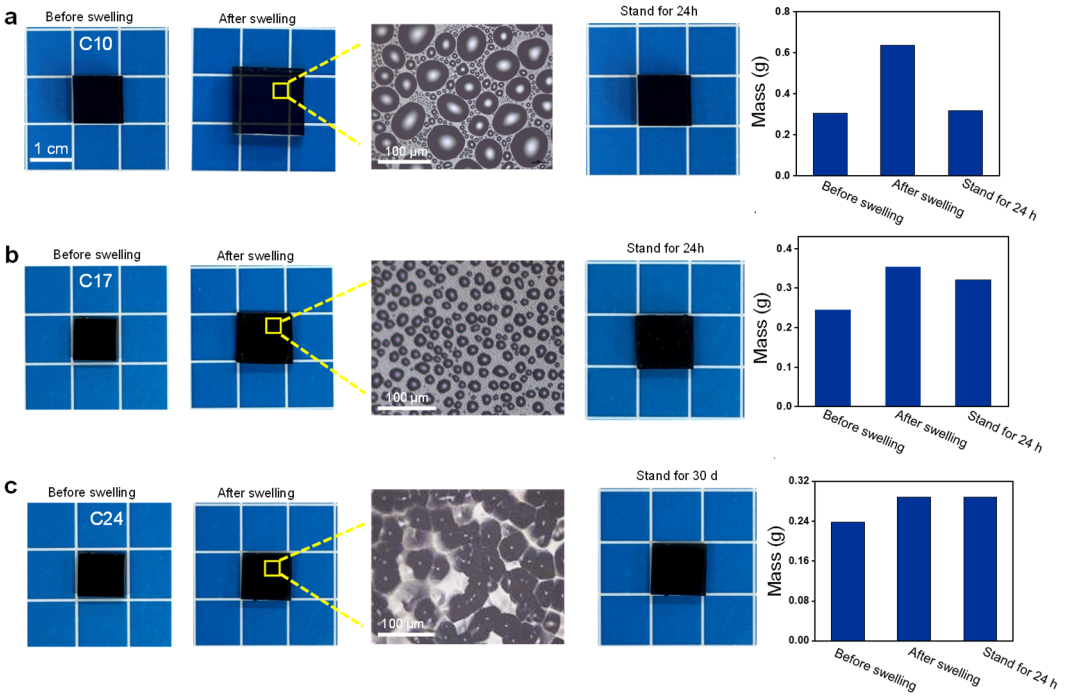

Fig. S9. The stability experiment of (a) waxgel-C10, (b) wagel-C24, and (c) waxgel-C17 through standing for room temperature at a humidity of 32%. The sample thickness is 2 mm.

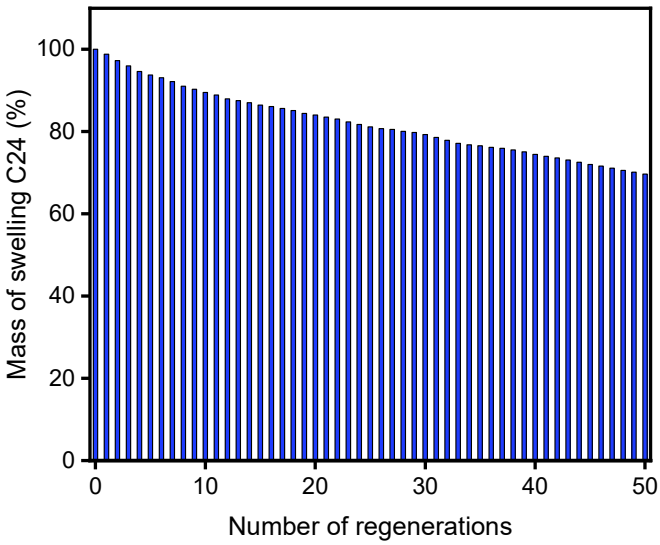

Fig. S10. The useful life time test of wagel-C24 containing 1.5 g wax under 50 cycle of completely stripping and regeneration. The samples (50 mm (length) × 50 mm (width) × 5 mm (height)) were conducted at room temperature with a humidity of 32%.

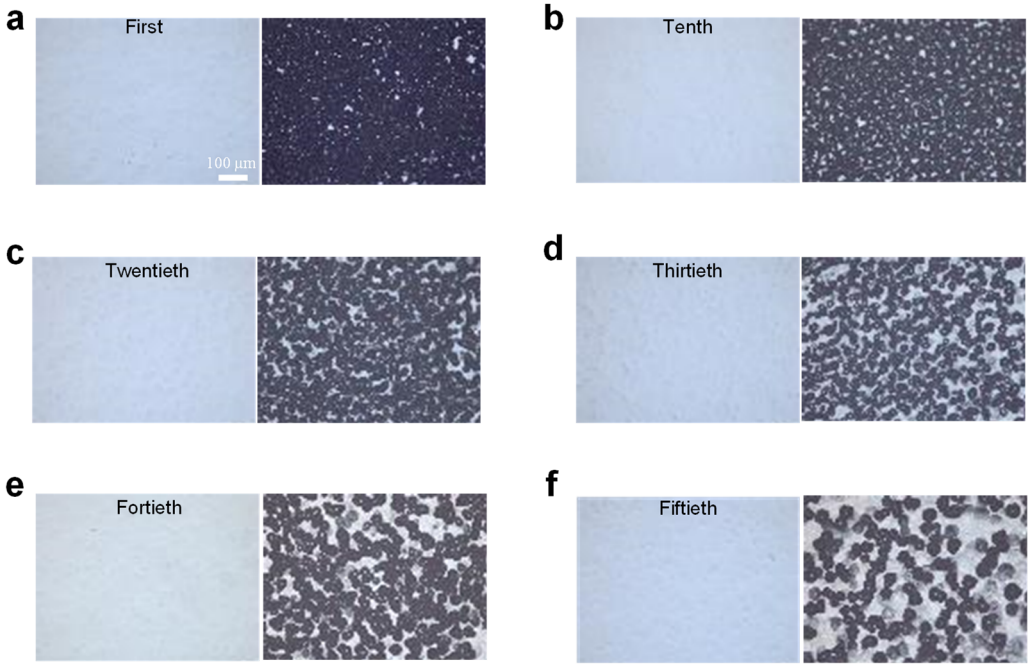

Fig. S11. The optical microscope images of waxgel-C24 after stripping and regeneration after (a) the first time, and (b) the tenth time, (c) the twentieth time, (d) the thirtieth time, (e) the fortieth time, and (f) the fiftieth time. The samples (50 mm (length) × 50 mm (width) × 5 mm (height)) were conducted at room temperature with a humidity of 32%.

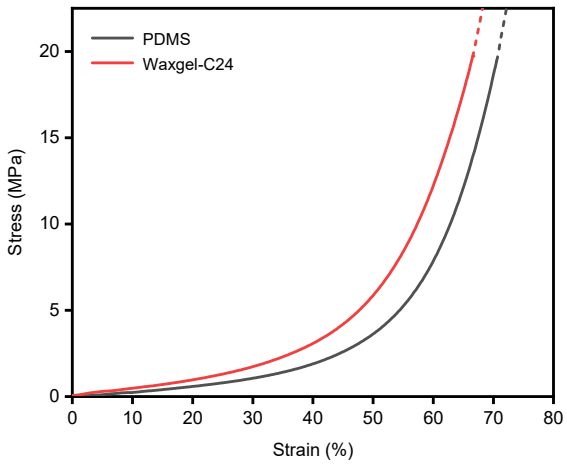

Fig. S12. The compressive stress-strain curves of pure PDMS, and waxgel-C24 at room temperature with a humidity of 37%. The sample is a cube with an edge length of 10 mm.

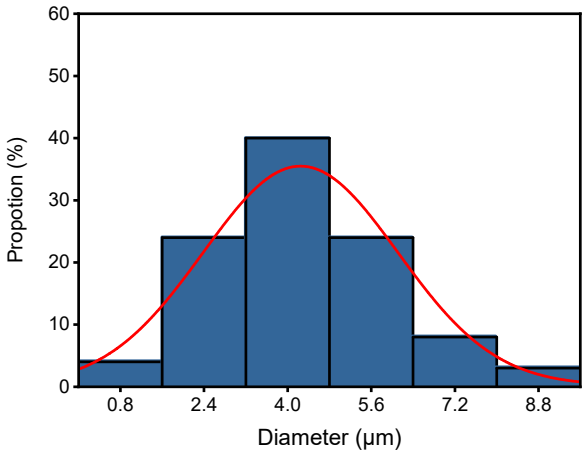

Fig. S13. The size distribution of CB particles in PDMS.

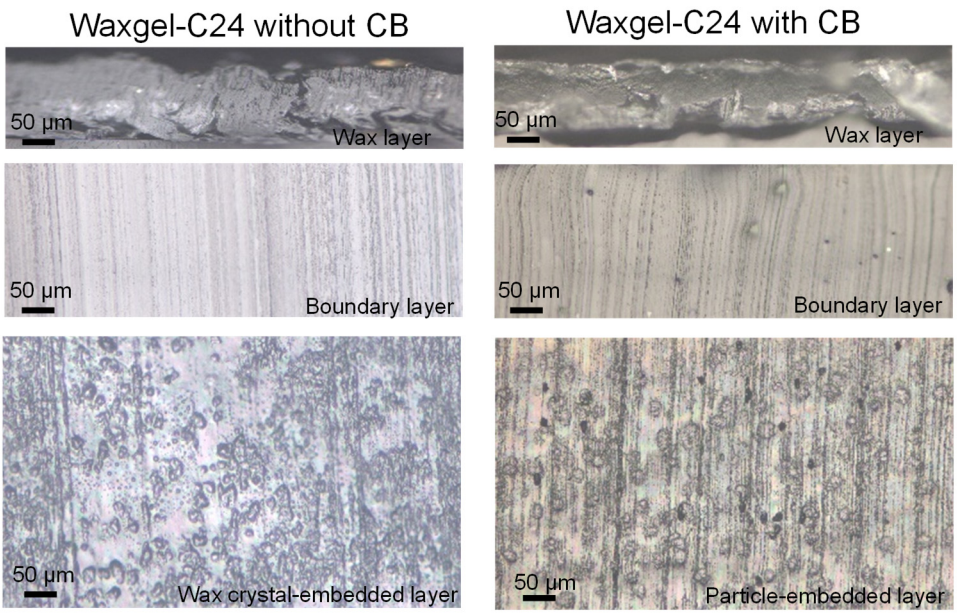

Fig. S14. Optical microscopy image of the cross section of waxgel-C24 without and with CB, respectively. This experiments were conducted at 25 °C with a humidity of 30%, and the sample thickness is 2 mm.

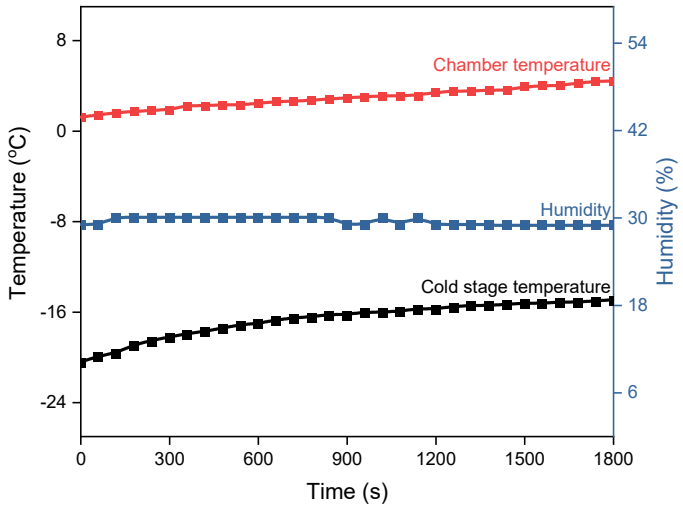

Fig. S15. The humidity in the chamber, temperature of cooling stage and chamber in the experiment of anti-icing application test.