

Supplementary Information

Continuous MXene fibers with near-gigapascal tensile strength via radial confinement and axial stretching

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Supplementary References

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Supplementary Movies 1-7

Supplementary Methods

Characterization: X-ray diffraction (XRD) curves were recorded on a Shimadzu XRD-6000 using Cu-K α radiation at a scanning speed of 5° min⁻¹. X-ray photoelectron spectroscopy (XPS) spectra were characterized using an ESCALab220i-XL (ThermoScientific) with a monochromatic Al-K α X-ray source and collected using Advantage (Version 5.984). Fourier transform infrared (FTIR) spectra were obtained using a Thermo Nicolet NEXUS-470 FTIR instrument in attenuated total reflection mode. Differential scanning calorimetry (DSC) measurements were performed using an METZSCH DSC 204 F1 (Germany) under N₂ atmosphere with temperature rising from room temperature to 200 °C at a rate of 10 °C min⁻¹.

The rheological properties of MXene and sodium alginate (SA) sols were tested using a rheometer (Anton Paar MCR 302). Viscosity was measured at a shear rate ranging from 0.1 to 100 s⁻¹. The viscoelastic properties of MXene and SA sols were investigated by measuring the storage (G') and loss (G'') modulus as a function of frequency from 0.1 to 100 rad s⁻¹ at a constant strain amplitude of 0.1%.

Scanning electron microscopy (SEM) images for MXene, stretched MXene (SM), confined MXene (CM), and confined and stretched MXene (CSM) fibers were obtained using a field-emission SEM (JEOL-7500F) at an acceleration voltage of 10 kV. SEM elemental mapping analysis was conducted using an energy-dispersive X-ray spectroscopy (EDS) spectrometer (Oxford EDS equipped with INCA software). Transmission electron microscope (TEM) images were taken using a FEI Tecnai G20 instrument at 200 kV. MXene and CSM fibers were cut using a focused ion beam (FIB) to obtain cross-sections and axial-sections by a FEI Helios NanoLab 600i with an acceleration voltage of 30 kV and a current decreasing from 17 nA to 46 pA. Atomic force microscopy (AFM) images of MXene nanosheets were taken using a Bruker Multi Mode 8 scanning probe microscope in tapping mode and analyzed using NanoScope Analysis (Version 1.9).

Thermogravimetric analysis (TGA) measurements were performed on a TG/DTA6300 (NSK, Japan) under a nitrogen atmosphere with a temperature rising from room temperature to 550 °C at a rate of 10 °C min⁻¹. The water content of fibers was obtained by the weight loss in 100 °C. The weight fraction of SA in CM and CSM fibers was calculated from the weight loss curve over the temperature range from 100 to 550 °C. The SA weight fraction (w_1) in CM and CSM fibers is approximately determined as follows,

$$w_1 = \frac{M_{fiber} - \left(1 - w_2 \times \frac{111}{40}\right) M_{MXene}}{M_{SA} - M_{MXene}}, \quad (1)$$

where M_{fiber} , M_{SA} , and M_{MXene} are the fraction of weight loss for CM or CSM fibers, SA powder, and MXene powder, respectively, between 100 and 550 °C, while w_2 is the weight fraction of

calcium ions (Ca^{2+}) in the corresponding fibers tested by EDS. The detailed data for Ca^{2+} and SA weight percentage in fibers are tabulated in Supplementary Table 1.

As shown in Fig. 2b, the bridged SA encapsulation layer of CSM fibers show dense structure without any visible voids. It is reasonable to assume that the voids of CM and CSM fibers mainly exist in the inner MXene layer. Thus, the volume percent porosity (V_p) of the inner MXene layer in CM and CSM fibers is approximately given as follows,

$$V_p = \left(1 - \frac{\rho}{\rho_0}\right) \times \frac{V_{\text{fiber}}}{V_{\text{in}}}, \quad (2)$$

where ρ and ρ_0 are the bulk density of CM or CSM fibers and the theoretical density of the corresponding fibers without any voids, V_{in} and V_{fiber} are the volume of the inner MXene layer and whole fibers, respectively. The theoretical density of MXene nanosheets can be determined to be 3.65 g cm^{-3} by XPS characterization using a previously reported method¹. The theoretical densities of MXene, SM, CM, and CSM fibers without any voids are obtained based on the theoretical densities of MXene nanosheets, SA, calcium chloride (CaCl_2), and water. $V_{\text{fiber}}/V_{\text{in}}$ is approximately equal to the ratio of cross-sectional area for the whole fibers to that for the inner MXene layer. The volume percent porosity of MXene and SM fibers can be calculated by equation (2) using $V_{\text{fiber}}/V_{\text{in}} = 1$.

Wide-angle X-ray scattering (WAXS) and small-angle x-ray scattering (SAXS) tests were performed using a Xenocs Xeuss SAXS/WAXS System with an incident Cu-K α X-ray beam perpendicular to the axial direction of fibers. The length of the fiber sample is 3 cm. Scattering patterns were recorded on a PILATUS 300k detector. The distances between sample and detector for WAXS and SAXS measurements are 30 and 180 cm, respectively. MXene nanosheet alignment was quantified by Herman's orientation factor (f), which is defined as follows²:

$$f = \frac{1}{2} \left(3 \langle \cos^2 \phi \rangle - 1 \right), \quad (3)$$

where $\langle \cos^2 \phi \rangle$ represents the average value of the square of the cosine of the azimuthal angle for the 002 peak of fibers, which is calculated as follows,

$$\langle \cos^2 \phi \rangle = \frac{\int_0^{\pi/2} I(\phi) \cos^2 \phi \sin \phi d\phi}{\int_0^{\pi/2} I(\phi) \sin \phi d\phi}, \quad (4)$$

where $I(\phi)$ is the intensity at an azimuthal angle of ϕ .

Tensile stress-strain curves for MXene, SM, CM, CSM, SA, and stretched SA (SSA) fibers were tested under a humidity of 20% and a temperature of 25 °C using a Shimadzu AGS-X tester equipped with a 100 N load cell at a strain rate of 1 mm min^{-1} . The data were collected using MaterialTest (version 4.3) and analyzed using Origin software (version 8.5.1). The 12-mm-long fiber samples were adhesively attached to a rectangular paper frame with a rectangular hole that is

long enough to accommodate a gauge length of 5 mm. The cross-sectional area of each tested sample was determined by averaging the area of cryogenically fractured surface for the neighnering samples at 3~5 different positions, which was applied to calculate the mechanical properties of the corresponding sample. The average mechanical properties and corresponding standard deviations for each sample type were obtained based on 10 test results of different samples excluding those that fractured near the clamps. Tensile fatigue tests were performed at a stress amplitude of 50 MPa and a frequency of 1 Hz³ using an Instron ElectroPulsE1000 mechanical apparatus.

The resistances and electrical conductivities of fibers were tested on a Keithley 2400 multiple-function source meter using a two-probe method. The two ends of 20-mm-long fiber samples were connected with two probes by silver paste. The average electrical conductivity and the corresponding standard deviation for each sample type were obtained based on 3 test results of different samples.

Electromagnetic interference (EMI) shielding performance of CSM textiles in the frequency range between 8.2 and 12.4 GHz was tested on an AV3629 vector network analyzer using a coaxial air-line method. The samples used for EMI shielding tests were circular textiles having a diameter of 10 mm. Scattering parameters were obtained to determine the EMI shielding effectiveness (SE). To evaluate the Joule heating performance of fibers and textiles, the direct current voltage was applied to their two ends by a Keithley 2400 multiple-function source meter and the real-time temperature of their surface was recorded using a FOTRIC thermal imaging camera.

Coarse-grained molecular dynamics simulation: The structural evolution of MXene fibers during axial stretching and radial confining was investigated by coarse-grained molecular dynamics (CGMD) simulations using a large-scale atomic/molecular massively parallel simulator (LAMMPS) package⁴. The potential energy contributions from bond stretching and angle bending are described as follows⁵,

$$V_b = k_b (d - d_0)^2, \quad (5)$$

$$V_\theta = k_\theta (\theta - \theta_0)^2, \quad (6)$$

where d and d_0 (1 nm) are the bond length and its equilibrium value, while θ and θ_0 (120°) are the angle and its equilibrium value, respectively. k_b and k_θ are the spring constants for bonds and angles, respectively, which are given as follows,

$$k_b = \frac{\sqrt{3}K}{2(1-\nu)}, \quad (7)$$

$$k_\theta = \frac{\sqrt{3}d_0^2 K}{12(1+3\nu)}, \quad (8)$$

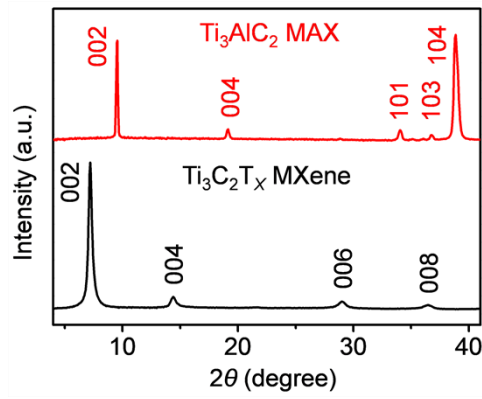
where K and ν represent the tensile stiffness and in-plane Poisson's ratio of MXene nanosheets, respectively, which have been reported to be 301 N m^{-1} and 0.21^6 . The interfacial adhesion was modeled using 12-6 Lennard-Jones (L-J) potential,

$$V_{\text{LJ}} = 4\varepsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 \right], \quad (9)$$

where ε is the depth of L-J potential well and σ (1 nm) is the L-J parameter associated with the equilibrium distance ($2^{1/6}\sigma$). The ReaxFF reactive force field was employed to obtain these parameters in the LAMMPS package^{7,8}.

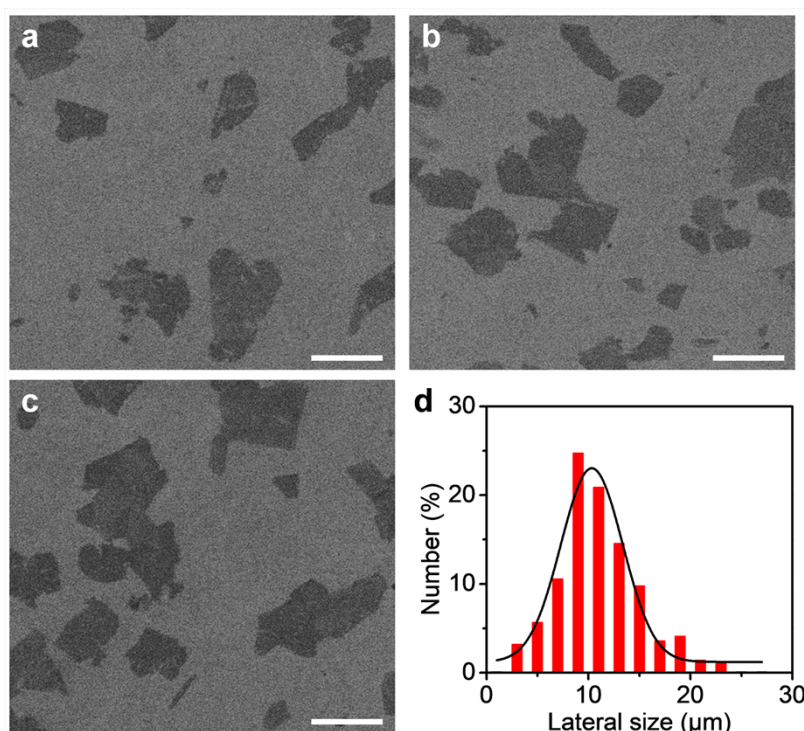
Four types of fiber structure were prepared by CGMD simulations based on experimental information: MXene (initial), SM (formed by axial stretching), CM (formed by radial confining), and CSM (formed by axial stretching and radial confining). Prior to the axial stretching and radial confining deformation protocol, the constructed structures were fully energy minimized. The mechanical responses of these structures were then investigated using a Nosé-Hoover thermostat. The Newton's equations of motion were integrated using the velocity-Verlet algorithm with a time step of 10 fs. The model snapshots of the structural evolution for MXene fibers during stretching under an axial loading and/or confining under a radial loading were created by a visual molecular dynamics package⁹.

Cytotoxicity evaluation: Fibroblasts were first seeded on coverslip and CSM textiles, which were denoted as control and CSM groups, respectively, in 24 well microplates having 1 mL of medium composed of 89 vol% minimal essential medium, 10 vol% fetal bovine serum, and 1 vol% penicillin/streptomycin. After culturing the fibroblasts for 1 day in a humidified incubator at 5% CO_2 and 37°C , the cell viability was assessed by calcein-AM/propidium iodide viability/cytotoxicity assay kit (Beyotime, C2015S). The calcein-AM and propidium iodide were conducted to stain live (green) and dead (red) cells, respectively. The fluorescence images of cells were taken using a confocal microscope (Leica). Additionally, after culturing the fibroblasts for 2 days, the cell viability was tested using cell counting kit-8 (Donjindo, Japan) assay.



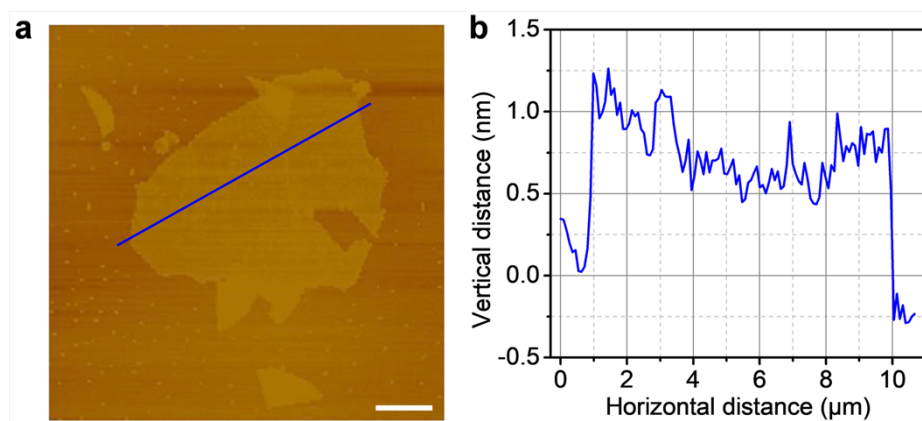
Supplementary Figure 1. XRD curves of Ti_3AlC_2 MAX and $\text{Ti}_3\text{C}_2\text{T}_x$ MXene.

The 104 peak of Ti_3AlC_2 MAX at $\sim 39^\circ$ disappears in the curve of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, demonstrating the successful synthesis of MXene nanosheets. Additionally, the interplanar spacing (002) of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (1.23 nm) is larger than for Ti_3AlC_2 MAX (0.93 nm) because of the introduction of intercalated water and surface functional groups¹⁰.



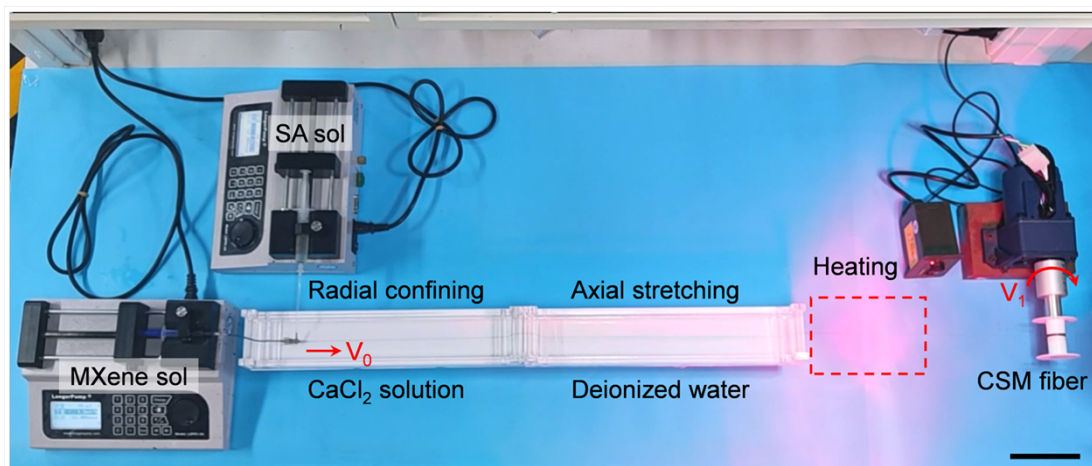
Supplementary Figure 2. Calculation of lateral size of exfoliated MXene nanosheets.

a–c, SEM images of MXene nanosheets. Scale bars, 10 μm . **d**, Lateral size distribution of MXene nanosheets, indicating that the average lateral size of MXene nanosheets is approximately 11.0 μm .



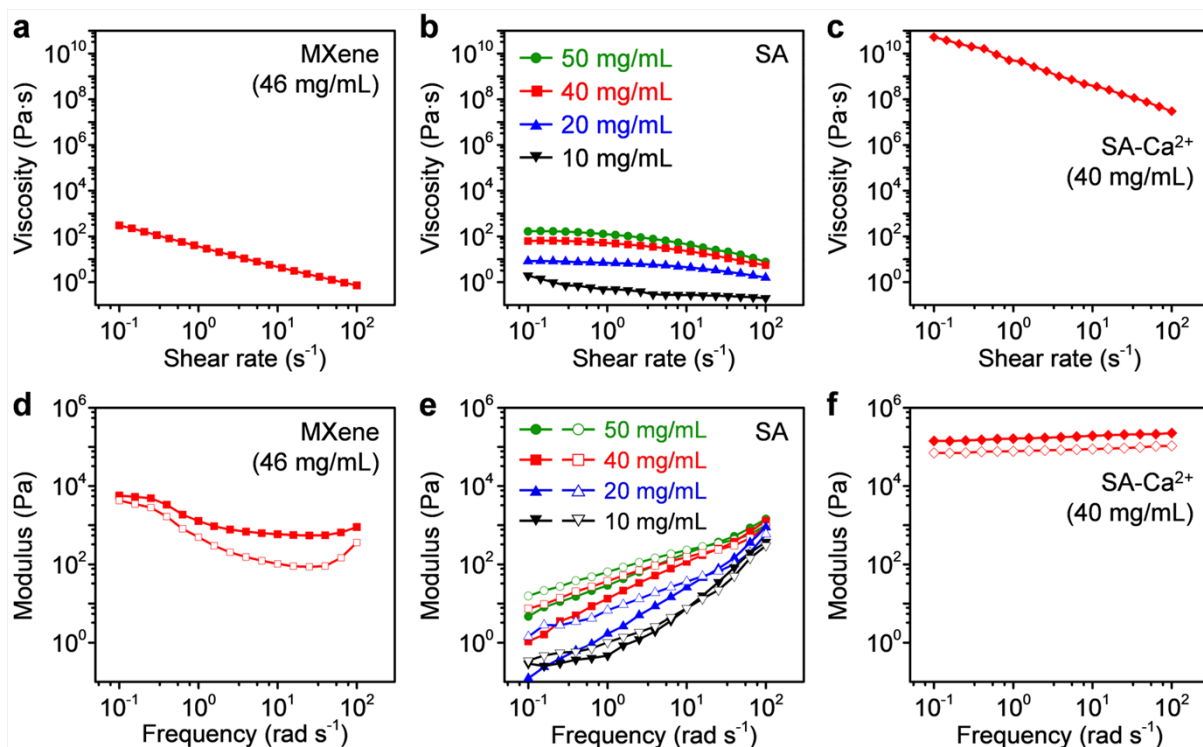
Supplementary Figure 3. Thickness of MXene nanosheets.

a, AFM image of MXene nanosheets (repeated independently with similar structures for three times). Scale bar, 2 μm. **b**, Height profile of MXene nanosheets in (a) measured along the blue line. The thickness of MXene nanosheets is about 1.25 nm, which is larger than the theoretical thickness of monolayer MXene because of the presence of water on the MXene surface¹¹.



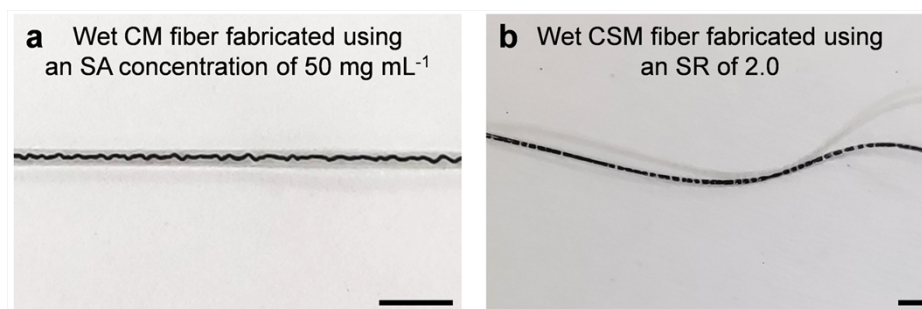
Supplementary Figure 4. Continuous fabrication of CSM fibers.

MXene and SA sols were extruded into CaCl_2 solution at a velocity of V_0 , followed by continuous stretching, washing in DIW, and drying by infrared heating. Finally, a roll of CSM fibers was collected at a velocity of V_1 . Scale bar, 20 cm.



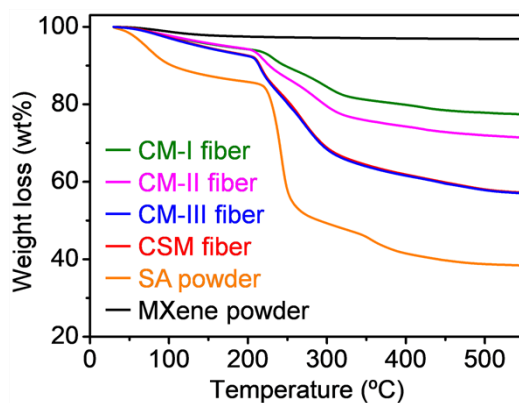
Supplementary Figure 5. Rheological and viscoelastic properties of MXene, SA, and SA-Ca²⁺ sols.

a–c, Viscosity as a function of shear rate for MXene (**a**), SA (**b**) and SA-Ca²⁺ (**c**) sols. **d–f**, Storage (G' , solid symbols) and loss (G'' , hollow symbols) modulus as a function of frequency for MXene (**d**), SA (**e**), and SA-Ca²⁺ (**f**) sols. The viscosity of MXene, SA and SA-Ca²⁺ sols is gradually decreased with increasing shear rate, indicating the rheological shear-thinning behavior and good processability. Compared with SA sol, SA-Ca²⁺ sol has higher viscosity and modulus because of the coordination between Ca²⁺ and –COO[–] groups of SA molecules.



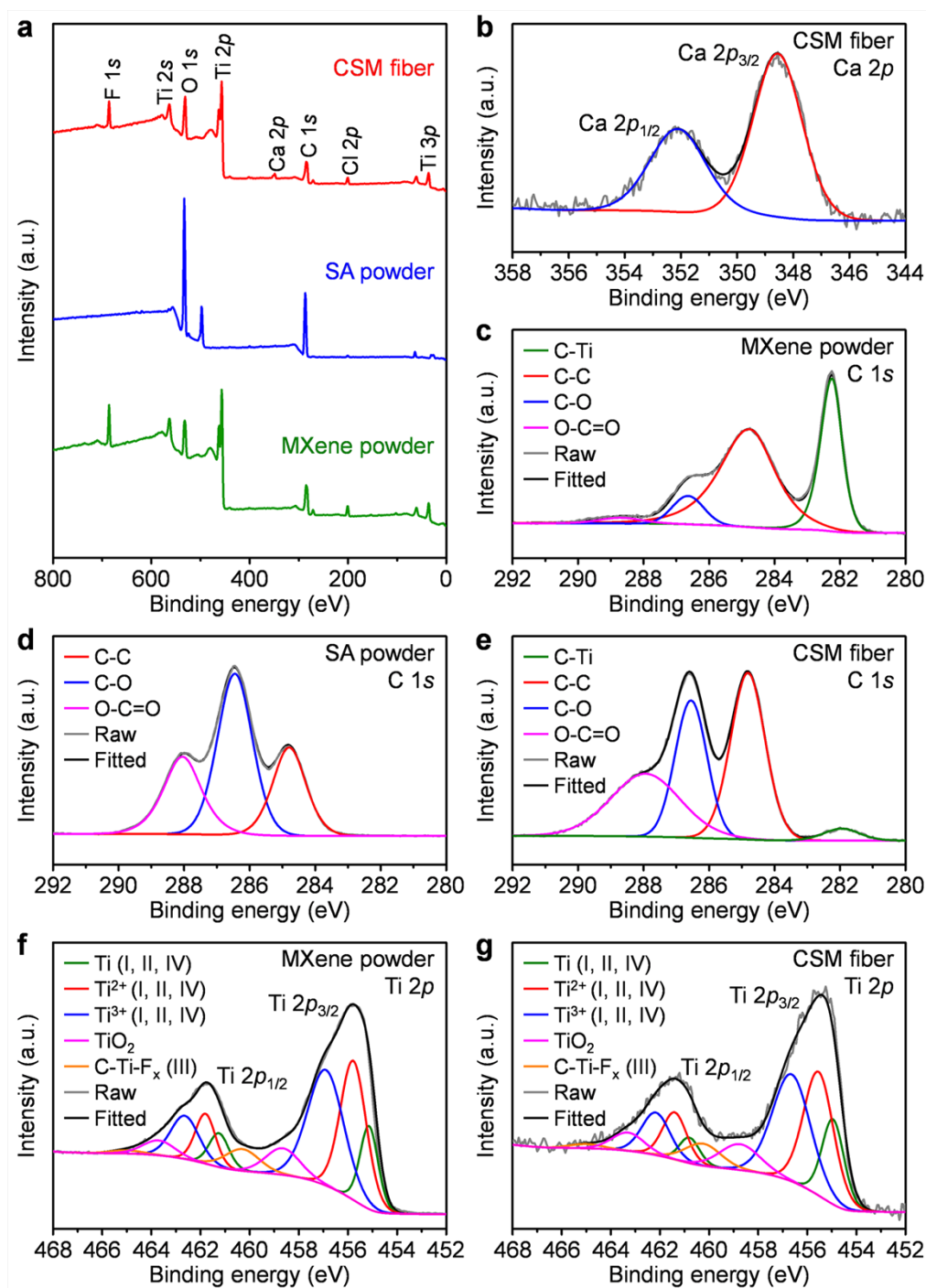
Supplementary Figure 6. Photographs of wet fibers.

a, Wet CM fiber fabricated using an SA concentration of 50 mg mL⁻¹. **b**, Wet CSM fiber fabricated using a stretching ratio (defined as SR) of 2.0. Scale bars, 2 mm. Wet CM fibers become wrinkled using excess SA concentration (50 mg mL⁻¹), while wet CSM fibers become discontinuous using excess SR (2.0).



Supplementary Figure 7. TGA curves of MXene powder, CM-I to CM-III fibers, CSM fibers, and SA powder.

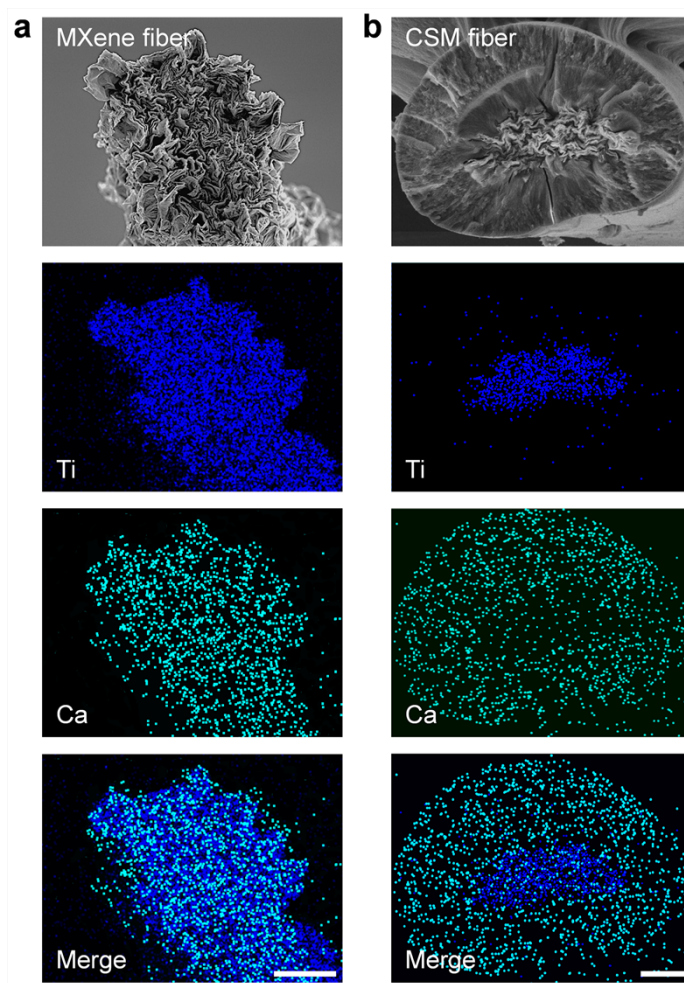
TGA curves were tested under a nitrogen atmosphere with a temperature rising from room temperature to 550 °C at a rate of 10 °C min⁻¹.



Supplementary Figure 8. XPS spectra characterization of MXene powder, SA powder, and CSM fibers.

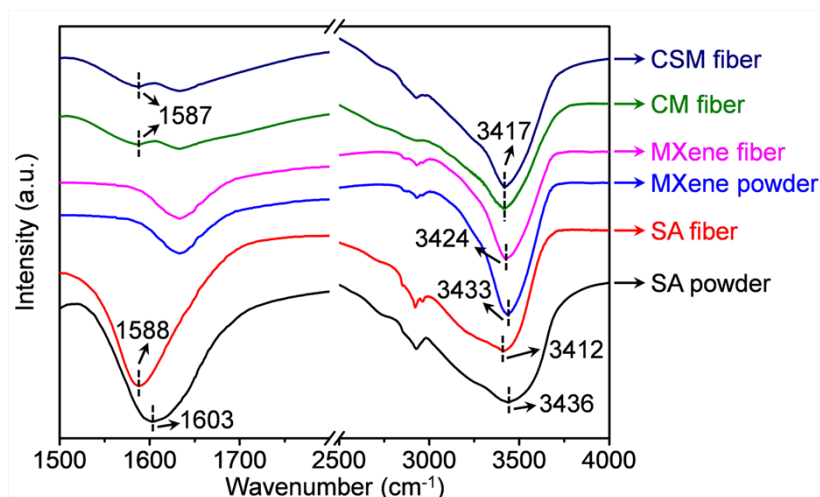
a, XPS spectra of MXene powder, SA powder, and CSM fibers. **b**, Ca 2p spectra of CSM fibers. **c–e**, C 1s spectra of MXene powder (**c**), SA powder (**d**), and CSM fibers (**e**). **f, g**, Ti 2p spectra of MXene powder (**f**) and CSM fibers (**g**). Compared with MXene powder, CSM fibers have new peaks for Ca 2p_{1/2} (352.1 eV) and Ca 2p_{3/2} (348.6 eV), indicating the modification of Ca²⁺. The C 1s main peak of SA powder can be fitted by three peaks at 284.8 (C–C), 286.6 (C–O), and 288.2 (O–C=O) eV, while that of CSM fibers can be fitted by four peaks at 282.0 (C–Ti), 284.8 (C–C), 286.6 (C–O), and 287.9 (O–C=O) eV. The O–C=O peak of CSM fibers is slightly downshifted from 288.2 eV for SA powder to 287.9 eV, verifying the coordination between Ca²⁺ and –COO[–].

groups of SA molecules¹². The Ti $2p_{3/2}$ main peak of MXene powder can be fitted by five peaks at 455.0 (Ti (I, II, IV)), 455.8 (Ti^{2+} (I, II, IV)), 456.9 (Ti^{3+} (I, II, IV)), 458.7 (TiO_2), and 460.3 (C–Ti–F_x (III)) eV, while that of CSM fiber can be fitted by five peaks at 455.0 (Ti (I, II, IV)), 455.5 (Ti^{2+} (I, II, IV)), 456.6 (Ti^{3+} (I, II, IV)), 458.7 (TiO_2), and 460.3 (C–Ti–F_x (III)) eV. Ti^{2+} (I, II, IV) $2p_{3/2}$ and Ti^{3+} (I, II, IV) $2p_{3/2}$ peaks are downshifted from 455.8 eV and 456.9 eV for MXene powder to 455.5 eV and 456.6 eV for CSM fibers, respectively, demonstrating that Ca^{2+} was bonded onto MXene nanosheets¹².



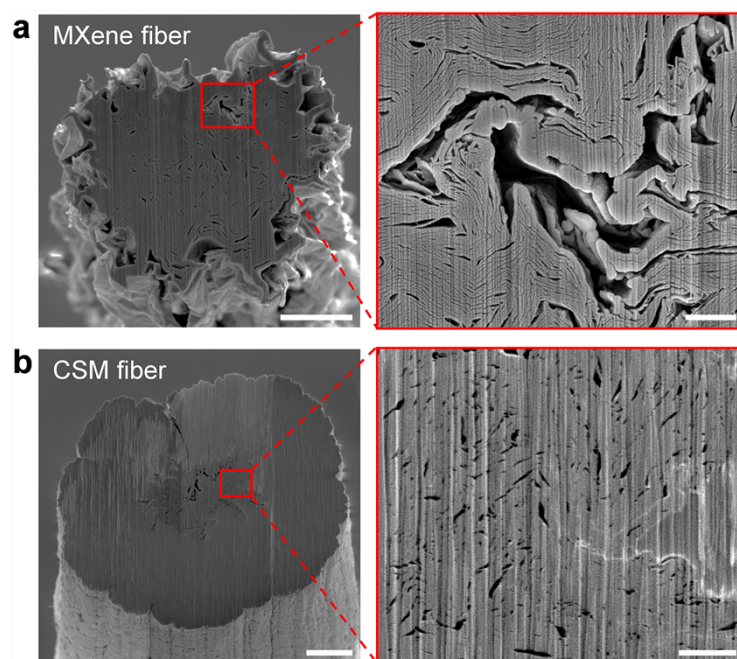
Supplementary Figure 9. Cross-sectional morphology of fibers.

SEM images and EDS mapping of element Ti and Ca for the cross-sections of (a) MXene and (b) CSM fibers (repeated independently with similar structures for three times), exhibiting the uniform distribution of Ca²⁺. Scale bars, 10 μm.



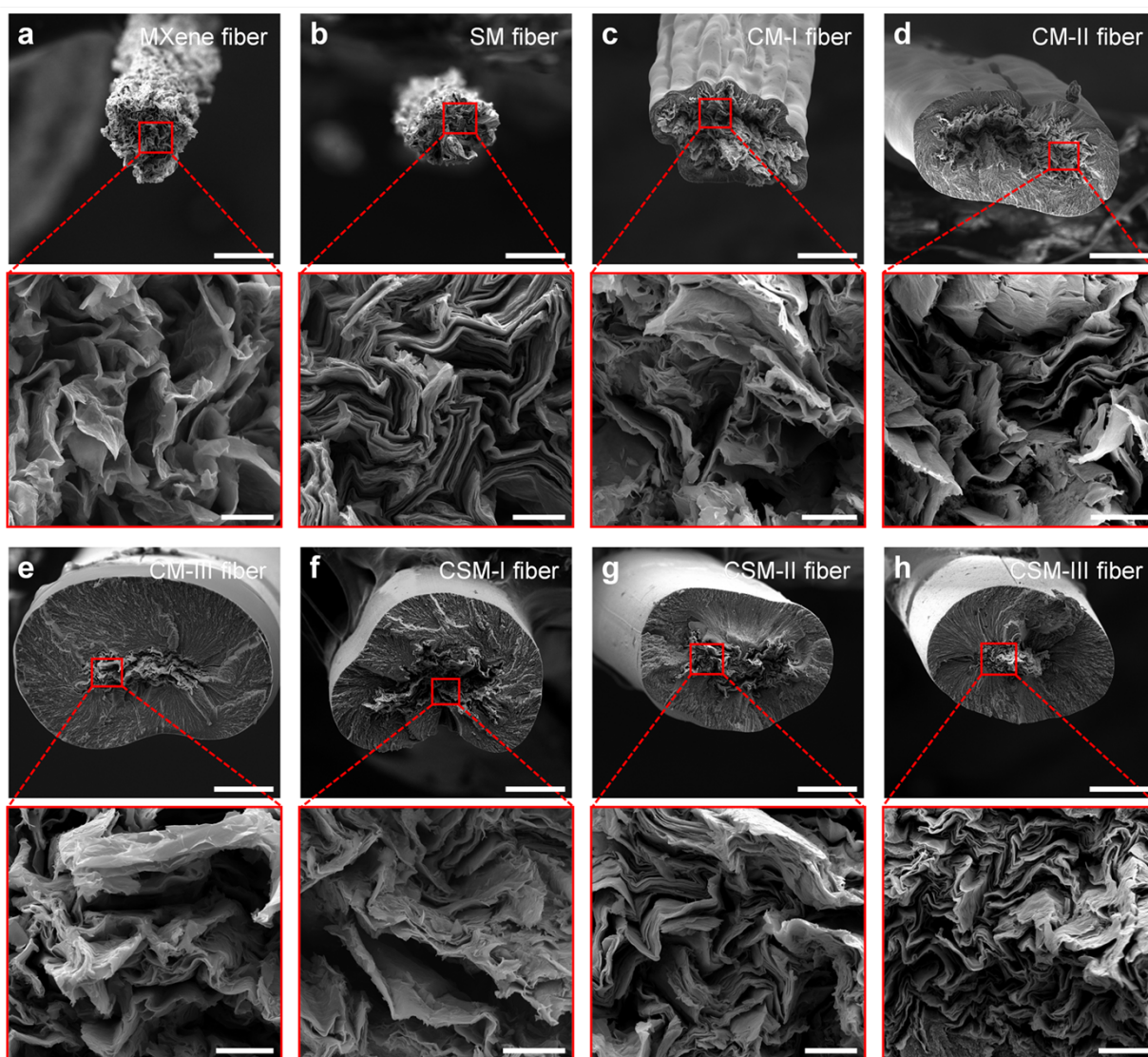
Supplementary Figure 10. FTIR spectra of MXene and SA powder, and MXene, SA, CM, and CSM fibers.

The -OH peak of MXene fibers is redshifted from $3,433\text{ cm}^{-1}$ for MXene powder to $3,424\text{ cm}^{-1}$, demonstrating the formation of $\text{H-O} \rightarrow \text{Ca}^{2+}$ coordination^{12,13}. Compared with MXene fibers, the -OH peak of CM and CSM fibers is further redshifted to $3,417\text{ cm}^{-1}$, indicating the hydrogen bonding between MXene nanosheets and SA molecules^{12,13}. Additionally, the -COO^- peak is redshifted from $1,603\text{ cm}^{-1}$ for SA powder to $1,587\text{ cm}^{-1}$ for CM and CSM fibers, confirming the coordination between Ca^{2+} and -COO^- groups of SA molecules¹².



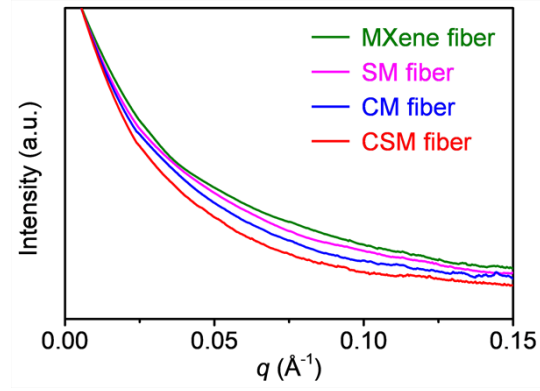
Supplementary Figure 11. SEM images of the cross-sections for fibers cut using a FIB.

a, MXene. **b**, CSM. All experiments are repeated independently with similar results for three times. Scale bars, 10 μm in low-resolution images and 1 μm in high-resolution images.



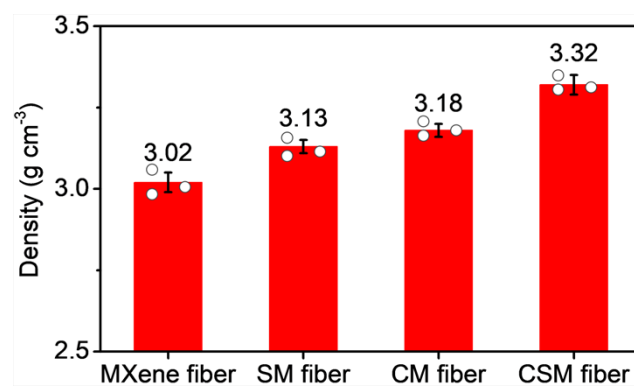
Supplementary Figure 12. Front-view SEM images of the fracture surface for fibers.

a, MXene. **b**, SM. **c–e**, CM-I to CM-III. **f–h**, CSM-I to CSM-III. All experiments are repeated independently with similar results for three times. Scale bars, 20 μm in low-resolution images and 2 μm in high-resolution images.

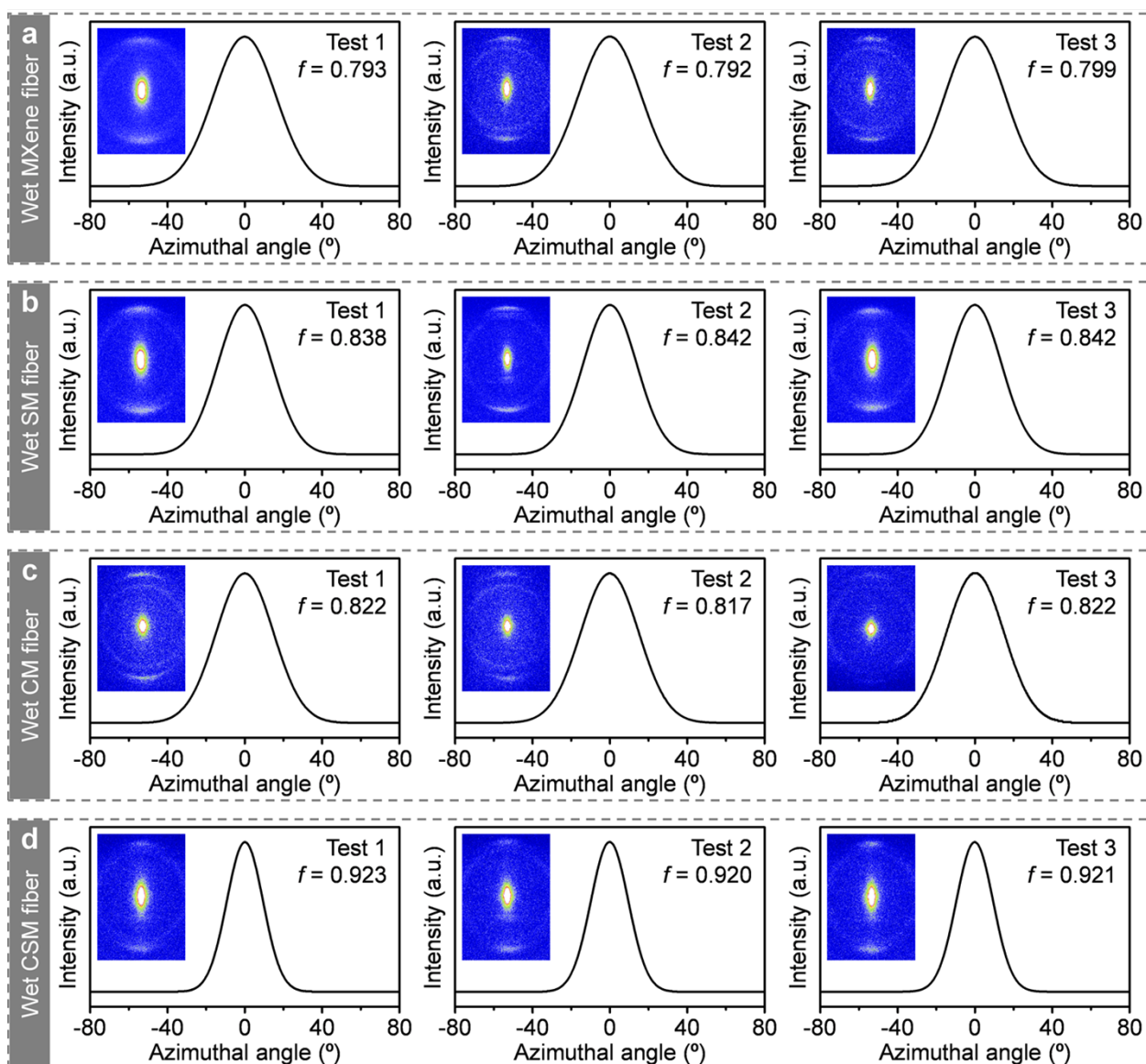


Supplementary Figure 13. SAXS intensity as a function of scattering vector (q) for an incident Cu-K α X-ray beam perpendicular to the axial direction of MXene, SM, CM, and CSM fibers.

The result indicates that the magnitude of the porosity for fibers decreases as follows: MXene > SM > CM > CSM.

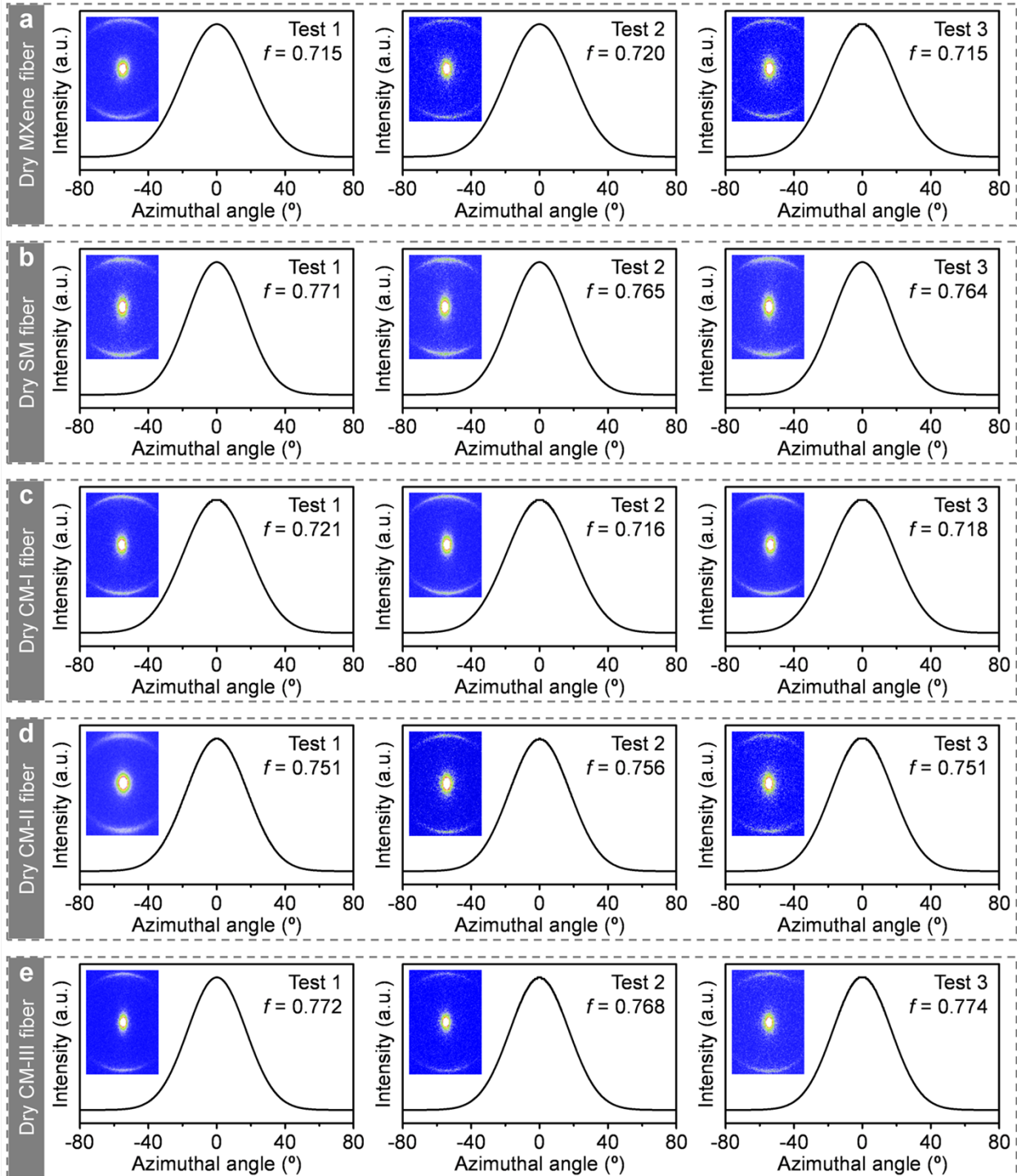


Supplementary Figure 14. Density of the MXene layer in MXene, SM, CM, and CSM fibers. Data are presented as mean $\pm$ standard deviation from three independent experiments.



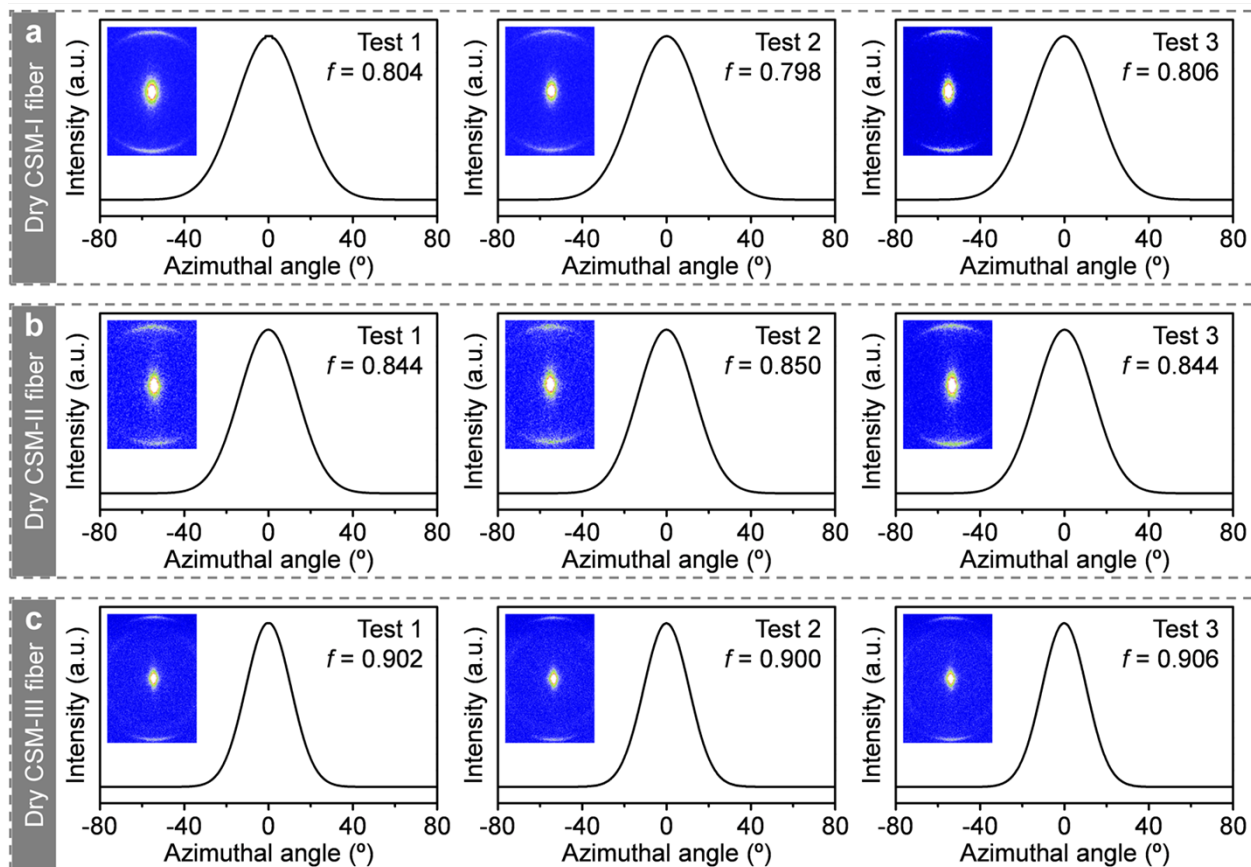
Supplementary Figure 15. WAXS patterns for an incident Cu-K α X-ray beam perpendicular to the axial direction of fiber and corresponding azimuthal scan profiles for the 002 peak for wet fibers.

a, MXene. **b**, SM. **c**, CM. **d**, CSM. The alignment of wet MXene, SM, CM, and CSM fibers is 0.795 ± 0.004 , 0.841 ± 0.002 , 0.820 ± 0.003 , and 0.921 ± 0.002 , respectively.



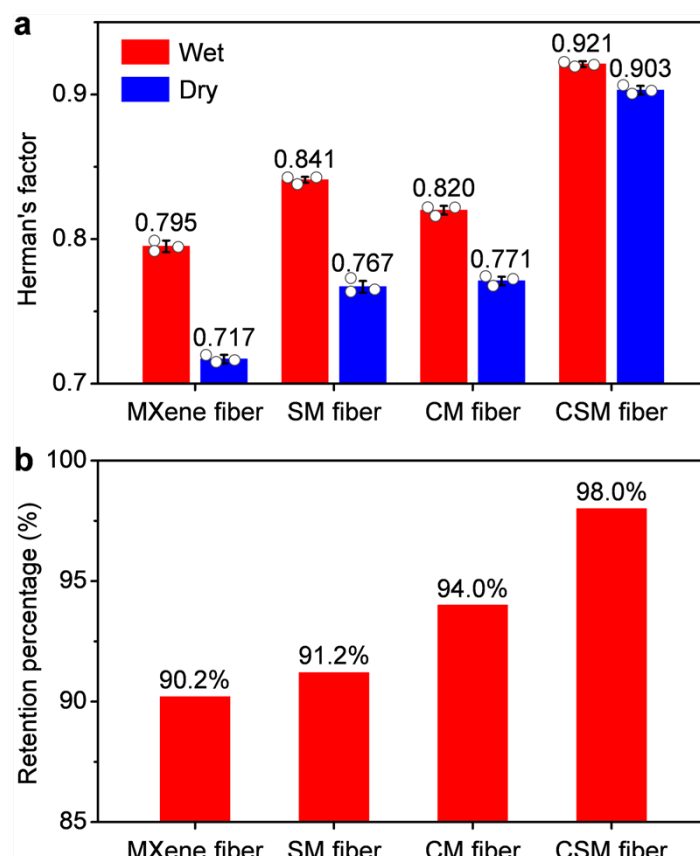
Supplementary Figure 16. WAXS patterns for an incident Cu-K α X-ray beam perpendicular to the axial direction of fiber and corresponding azimuthal scan profiles for the 002 peak for dry fibers.

a, MXene. **b**, SM. **c–e**, CM-I to CM-III. The alignment of dry MXene, SM, CM-I, CM-II, and CM-III fibers is 0.717 ± 0.003 , 0.767 ± 0.004 , 0.718 ± 0.003 , 0.753 ± 0.003 , and 0.771 ± 0.003 , respectively. The alignment of dry CM fibers is gradually increased from CM-I to CM-III, indicating that the radial confinement is increased with increasing thickness of bridged SA encapsulation layer.



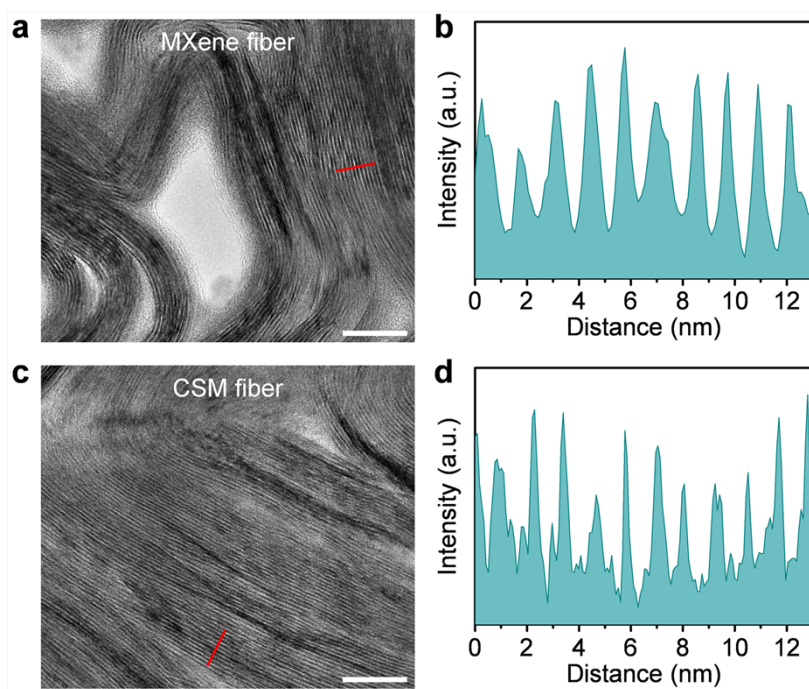
Supplementary Figure 17. WAXS patterns for an incident Cu-K α X-ray beam perpendicular to the axial direction of fiber and corresponding azimuthal scan profiles for the 002 peak for dry fibers.

a, CSM-I. **b**, CSM-II. **c**, CSM-III. The alignment of dry CSM-I, CSM-II, and CSM-III fibers is 0.803 ± 0.004 , 0.846 ± 0.003 , and 0.903 ± 0.003 , respectively, indicating that axial stretching using a larger SR can induce better synergistic effect with radial confining on improving the alignment of CSM fibers.



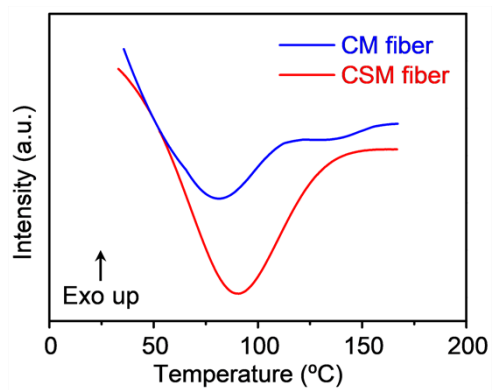
Supplementary Figure 18. Alignment characterization of fibers.

a, Herman's orientation factor of wet and dry MXene, SM, CM, and CSM fibers. Data are presented as mean $\pm$ standard deviation from three independent experiments. **b**, Retention percentage of the alignment for MXene, SM, CM, and CSM fibers after drying.



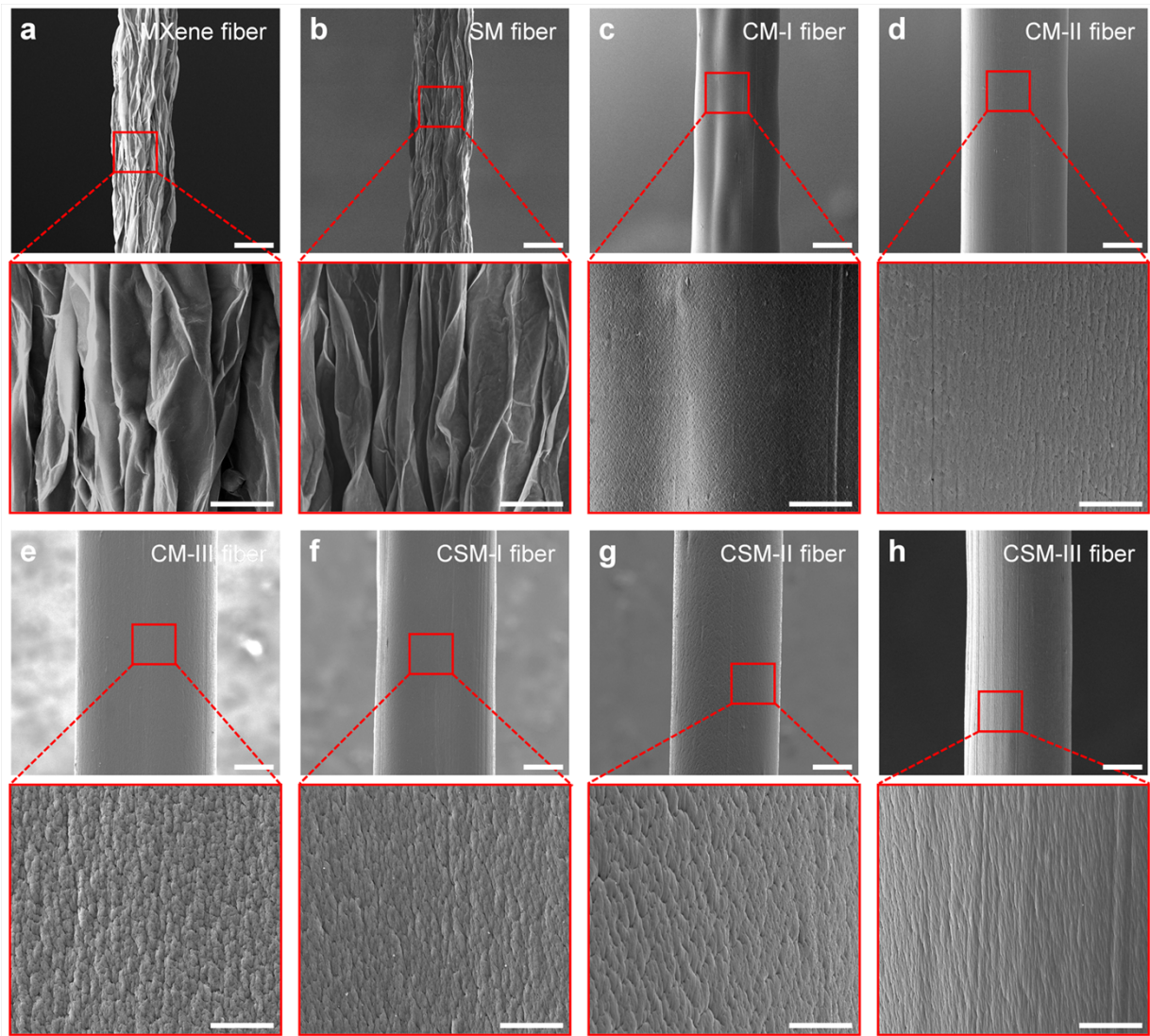
Supplementary Figure 19. Interplanar spacing characterization of fibers.

a, c, TEM images of the cross-sections cut by a FIB for MXene (**a**) and CSM (**c**) fibers (repeated independently with similar structures for three times). Scale bars, 20 nm. **b, d,** Profiles measured along red lines in the corresponding TEM images for MXene (**b**) and CSM (**d**) fibers. The average interplanar spacing of CSM fibers (1.20 ± 0.01 nm) is smaller than for MXene fibers (1.32 ± 0.01 nm) because of the synergistic densification of radial confining and axial stretching.



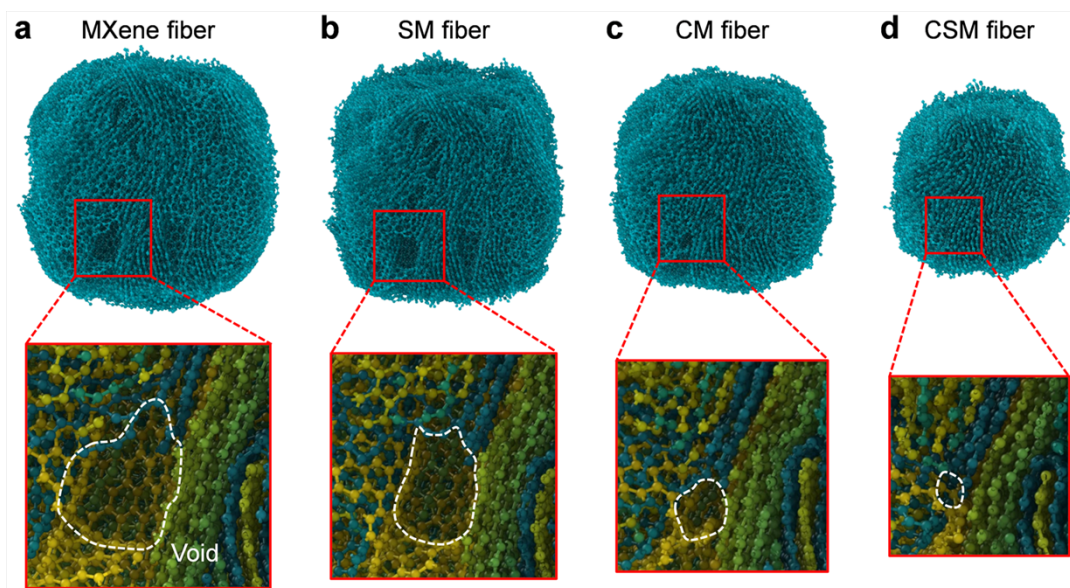
Supplementary Figure 20. DSC curves of CM and CSM fibers.

Compared with CM fibers, CSM fibers have a larger melting enthalpy, indicating that axial stretching improves the crystallinity of SA molecules.



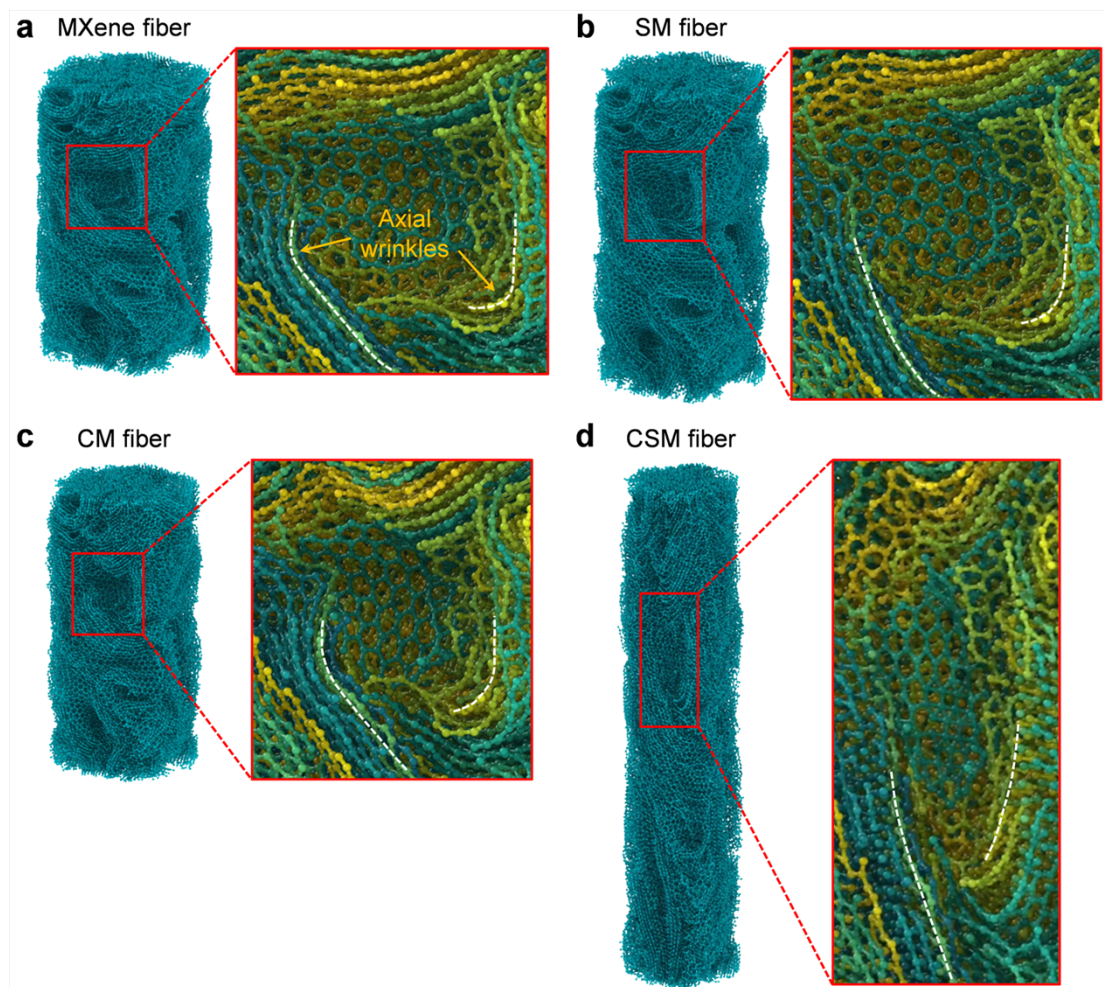
Supplementary Figure 21. SEM images of the surface for fibers.

a, MXene. **b**, SM. **c–e**, CM-I to CM-III. **f–h**, CSM-I to CSM-III. All experiments are repeated independently with similar results for three times. Scale bars, 20 μm in low-resolution images and 5 μm in high-resolution images.



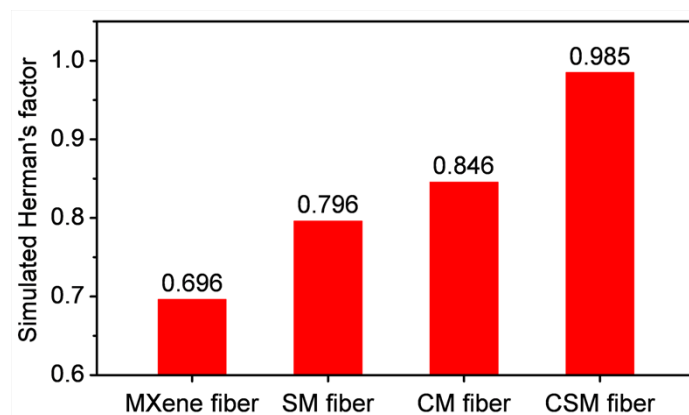
Supplementary Figure 22. Model snapshots from CGMD simulations of the cross-sectional view for fibers.

a, MXene. **b**, SM. **c**, CM. **d**, CSM. The magnitude of the porosity for fibers decreases as follows: $\text{MXene} > \text{SM} > \text{CM} > \text{CSM}$, which is consistent with the experimental results.



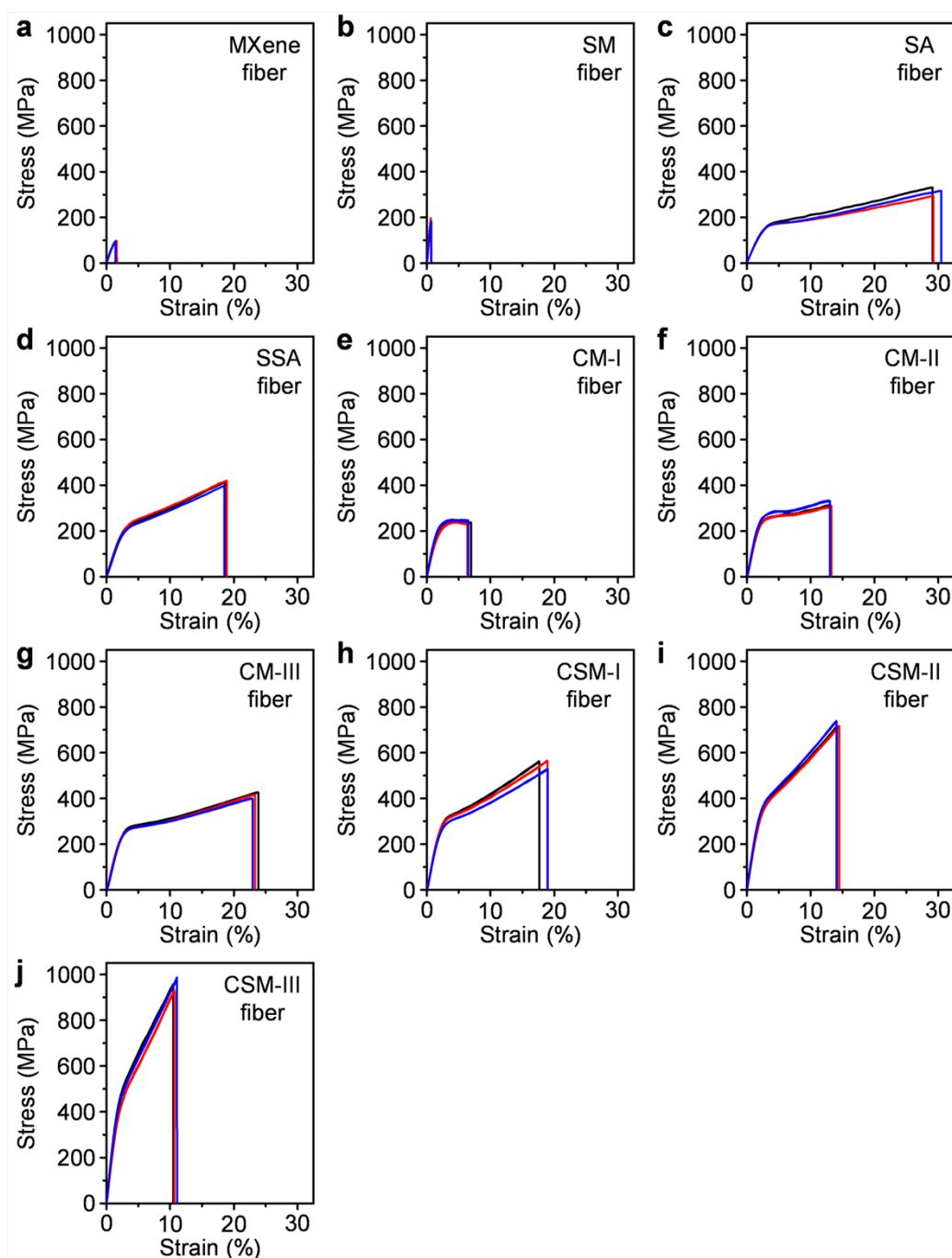
Supplementary Figure 23. Model snapshots from CGMD simulations of the longitudinal view for fibers.

a, MXene. **b**, SM. **c**, CM. **d**, CSM.



Supplementary Figure 24. Simulated Herman's orientation factor of MXene, SM, CM, and CSM fibers.

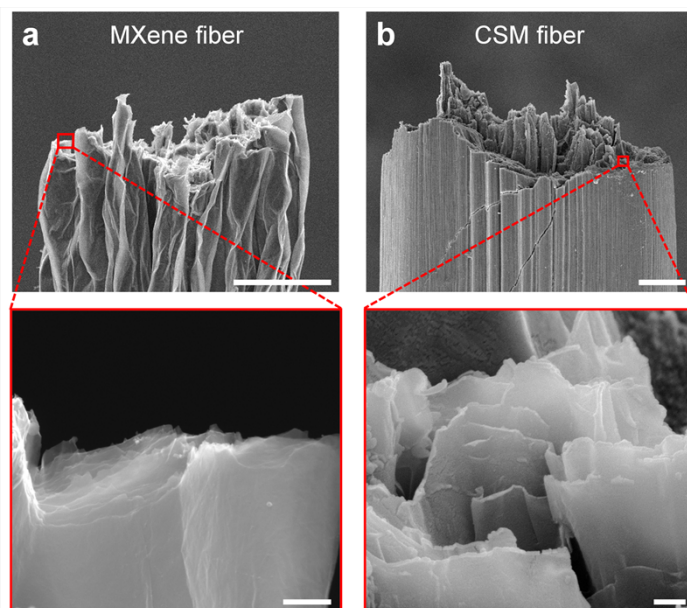
The magnitude of the alignment for fibers increases as follows: MXene < SM < CM < CSM, which is consistent with the experimental results.



Supplementary Figure 25. Representative tensile stress-strain curves of fibers.
a, MXene. **b**, SM. **c**, SA. **d**, SSA. **e–g**, CM-I to CM-III. **h–j**, CSM-I to CSM-III.

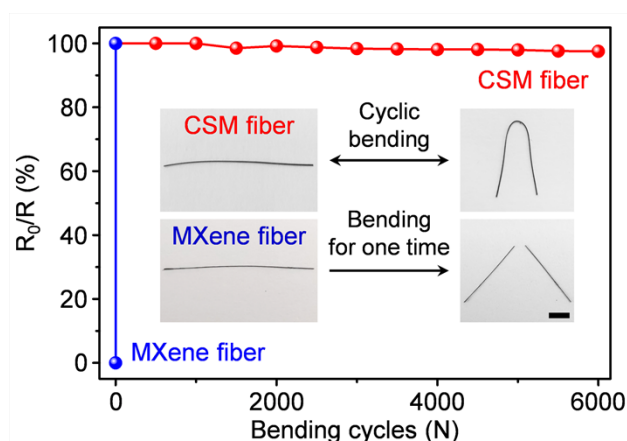


Supplementary Figure 26. Photograph exhibiting a folded CSM fiber lifting the weight of 400 g. Scale bar, 1 cm.



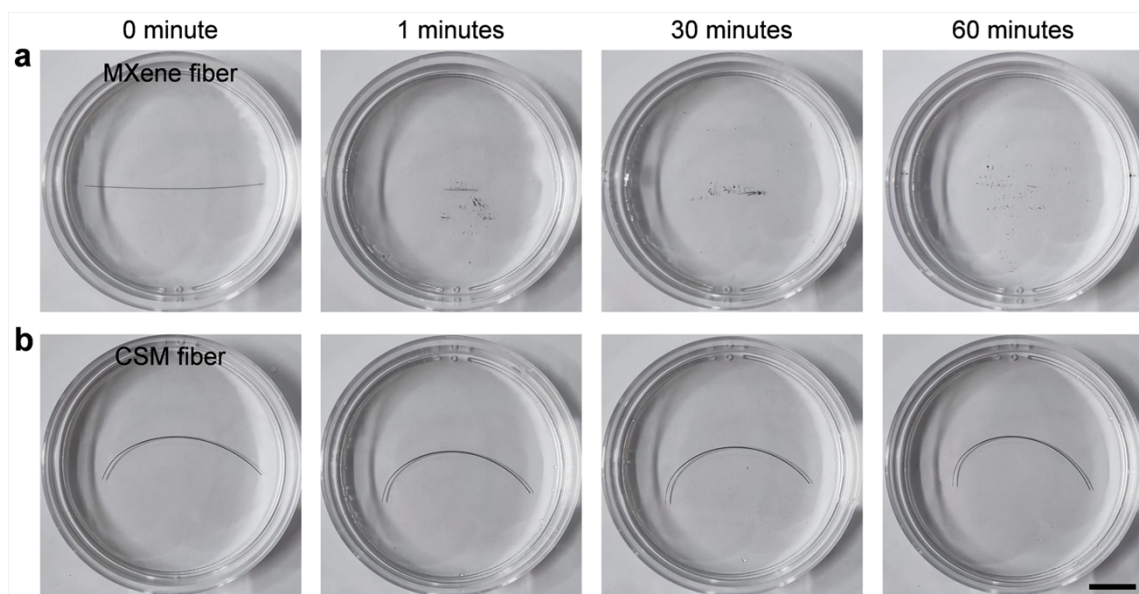
Supplementary Figure 27. Inclined-view SEM images of the fracture surface for fibers.

a, MXene. **b**, CSM. All experiments are repeated independently with similar results for three times. Scale bars, 10 μm in low-resolution images and 200 nm in high-resolution images. MXene fibers show flat fracture edges, while CSM fibers show curled fracture edges, demonstrating the improved interlayer interactions in CSM fibers.



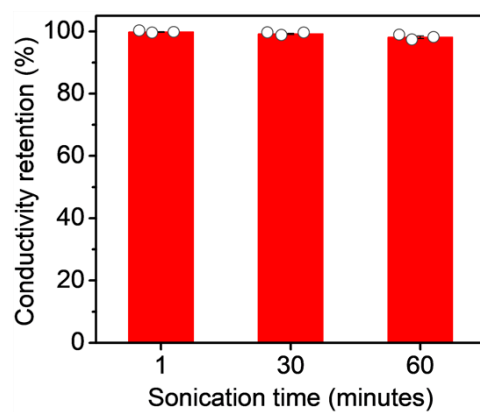
Supplementary Figure 28. Electrical conductance retention percentages as a function of cycle number for MXene and CSM fibers that are cyclically bent from 0° to 180°.

The insets show that CSM fibers have good structural integrity during cyclically bending, while MXene fibers are broken after bending for one time. Scale bar, 2 mm.

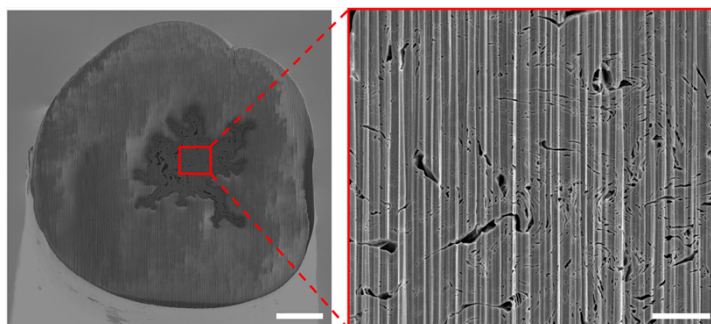


Supplementary Figure 29. Photographs of fibers during sonication using a 100 W and 40 kHz sonicator in water.

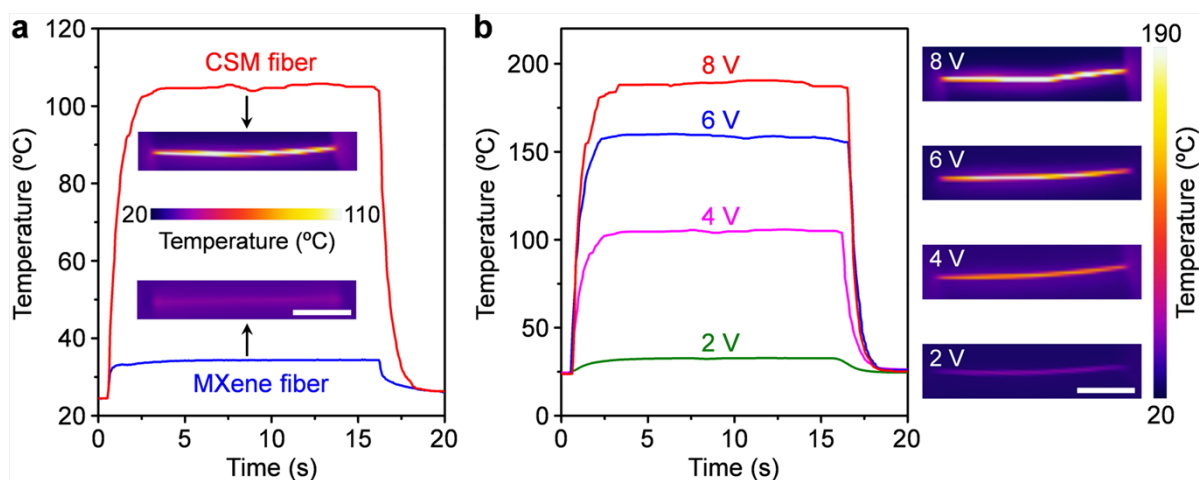
a, MXene. **b**, CSM. Scale bar, 1 cm. MXene fibers are disintegrated after sonicating for 1 minute, while CSM fibers remain intact after sonicating for 60 minutes, indicating the improved resistance to sonication destruction of CSM fibers.



Supplementary Figure 30. Electrical conductivity retention percentage of CSM fibers after sonicating for 1, 30, and 60 minutes. Data are presented as mean $\pm$ standard deviation from three independent experiments.

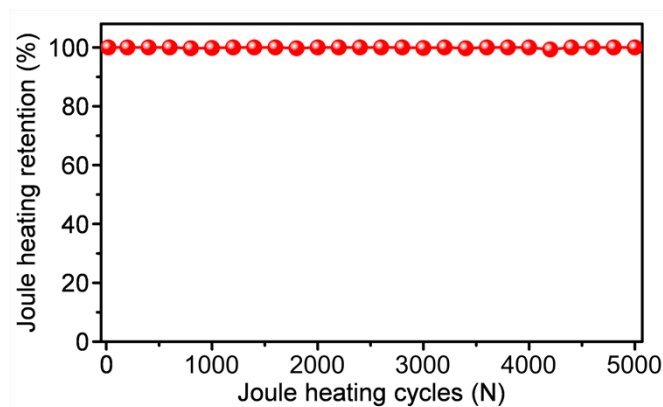


Supplementary Figure 31. SEM images of the cross-section cut by focused ion beam for CSM fibers after sonicating for 60 minutes (repeated independently with similar structures for three times). Scale bars, 10 μm in low-resolution image and 1 μm in high-resolution image.



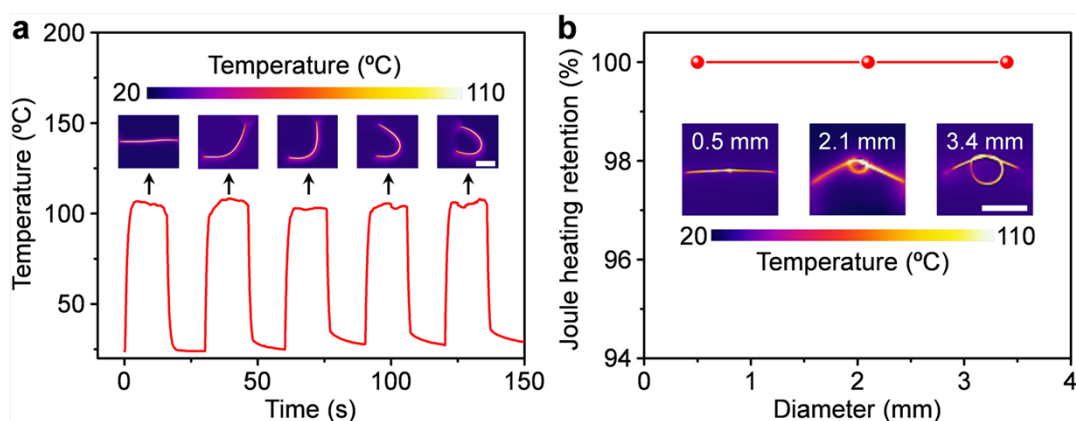
Supplementary Figure 32. Joule heating performance of MXene and CSM fibers.

a, Surface temperature as a function of time for MXene and CSM fibers electrically heated using a voltage of 4 V. The insets show the infrared images of electrically heated MXene and CSM fibers. **b**, Surface temperature as a function of time and infrared images for a CSM fiber electrically heated using a voltage of 2 V, 4 V, 6 V, and 8 V. Scale bars, 1 cm.



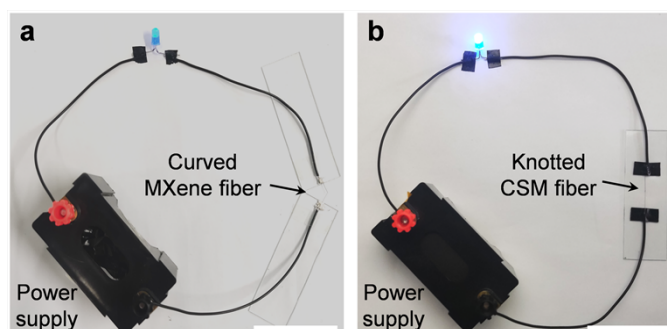
Supplementary Figure 33. Joule heating retention percentages as a function of cycle number for CSM fibers that are cyclically heated at a voltage of 4 V.

CSM fibers exhibit an exceptional long-term Joule heating stability during cyclic on-off Joule heating for 5,000 times.



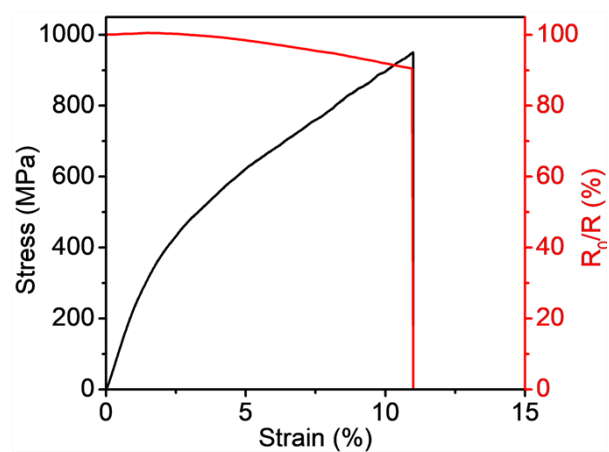
Supplementary Figure 34. Joule heating performance of deformed CSM fibers.

a, Surface temperature as a function of time for a CSM fiber electrically heated using a voltage of 4 V, which are bent at an angle ranging from 0° to 180°. The insets show the corresponding infrared images of the heated and bent CSM fiber. Scale bar, 1 cm. **b**, Joule heating retention percentages of CSM fibers electrically heated using a voltage of 4 V, which are knotted with a diameter of 0.5 mm, 2.1 mm, and 3.4 mm. The insets show the corresponding infrared images of the heated and knotted CSM fiber. Scale bar, 5 mm.

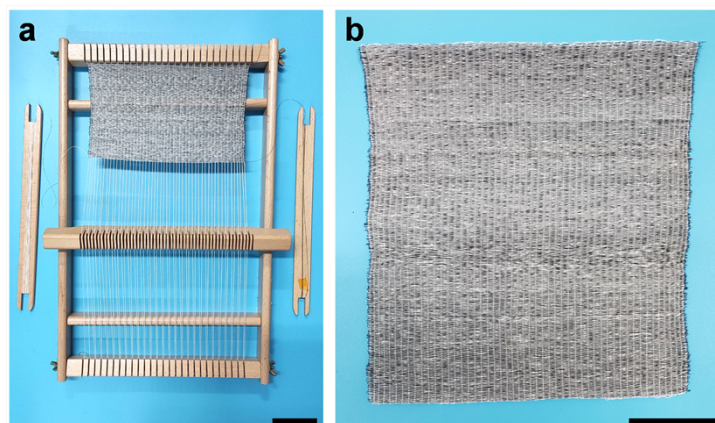


Supplementary Figure 35. Photographs exhibiting fibers used as electrical wires to light up a light-emitting diode (LED).

a, Curved MXene fiber. **b**, Knotted CSM fiber. Scale bars, 5 cm. MXene fibers bent at an angle of 90° are failed to light up a LED, while knotted CSM fibers can normally light up the LED.

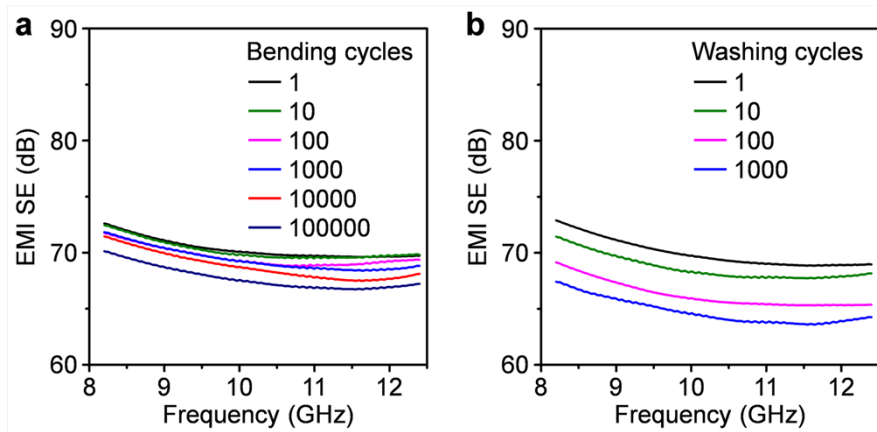


Supplementary Figure 36. Tensile stress-strain curve of CSM fibers and their electrical conductance retention percentage during tensile testing.



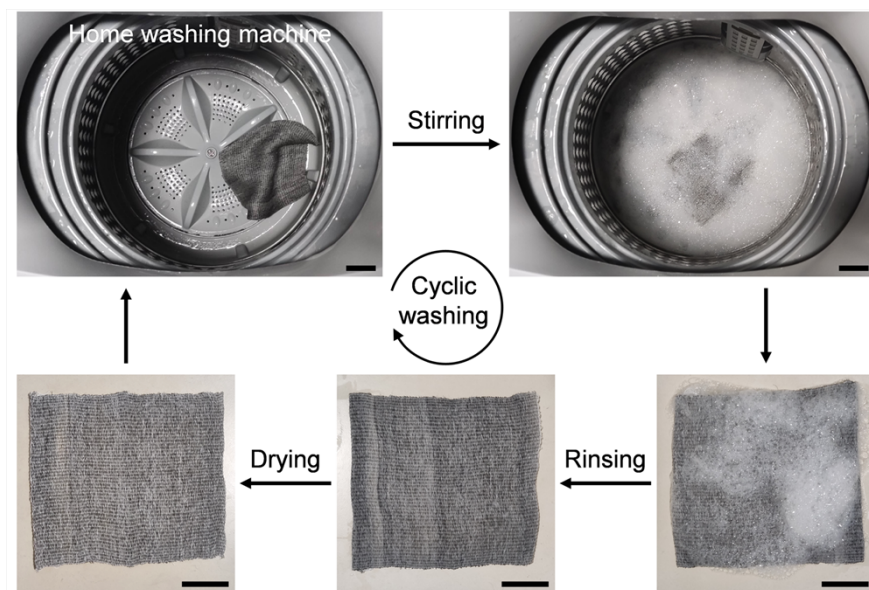
Supplementary Figure 37. Photographs of large-area CSM textiles.

a, Weaving apparatus. **b**, A textile woven from CSM and cotton fibers, having a lateral size of $18 \times 20 \text{ cm}^2$. Scale bars, 5 cm.



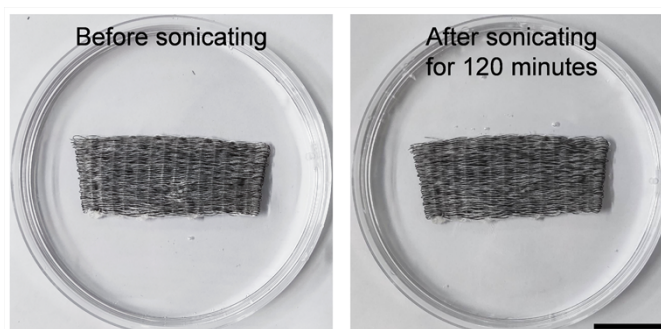
Supplementary Figure 38. EMI shielding performance of CSM textiles after cyclic bending and washing.

EMI SE as a function of frequency for CSM textiles (a) cyclically bent for 1, 10, 100, 1,000, 10,000, and 100,000 times and (b) cyclically washed for 1, 10, 100, and 1,000 times.



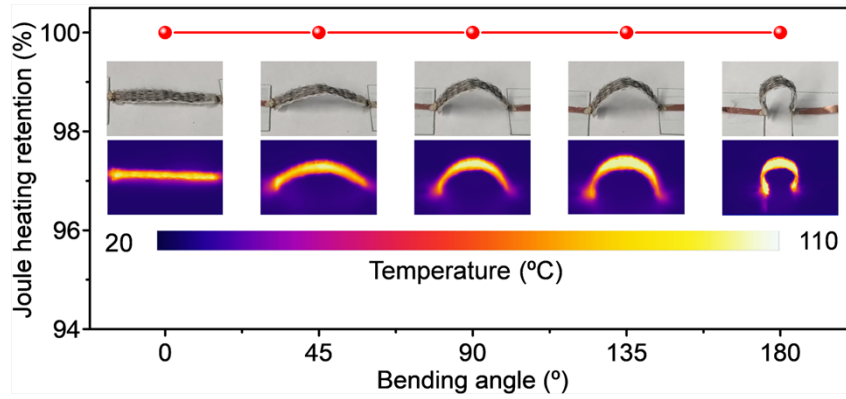
Supplementary Figure 39. Photographs exhibiting the washing process of CSM textiles using home washing machine.

Scale bars, 5 cm. CSM textiles show good structural integrity without obvious disintegration after cyclic washing.



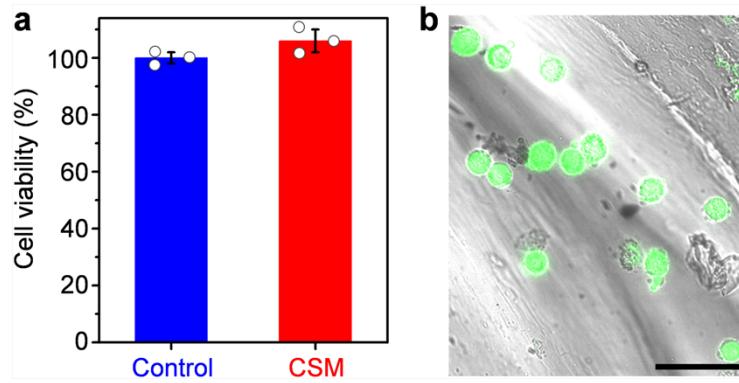
Supplementary Figure 40. Photographs of CSM textiles before and after sonicating in water for 120 minutes using a 100 W and 40 kHz sonicator.

Scale bar, 2 cm. CSM textiles show good structural integrity without obvious disintegration after sonicating for 120 minutes.



Supplementary Figure 41. Joule heating retention percentages for CSM textiles electrically heated using a voltage of 8 V, which are bent at an angle of 0°, 45°, 90°, 135°, and 180°.

The insets show the optical and infrared images of heated CSM textiles. Scale bar, 2 cm. CSM textiles bent at an angle of 45°, 90°, 135°, and 180° maintain 100% of Joule heating performance for flat textiles.



Supplementary Figure 42. Biocompatibility evaluation of CSM textiles.

a, Cell viability of control and CSM groups. Data are presented as mean $\pm$ standard deviation from three independent experiments. **b**, Fluorescence images of fibroblasts cultured on CSM textiles (repeated independently with similar results for three times), demonstrating their good biocompatibility. Scale bar, 50 μm .

Supplementary Table 1. Ca²⁺ and SA content in MXene, SM, CM, and CSM fibers, determined by EDS and TGA characterizations.

Sample	Ca²⁺ content (wt%)	SA content (wt%)
MXene	1.23	-
SM	1.29	-
CM-I	3.24	30.3
CM-II	4.56	42.5
CM-III	4.29	67.1
CSM	4.31	67.1

Supplementary Table 2. Porosity of MXene, SM, CM, and CSM fibers.

Sample	Porosity (%)
MXene	15.3 ± 0.4
SM	12.1 ± 0.3
CM-I	14.7 ± 0.4
CM-II	13.9 ± 0.2
CM-III	11.9 ± 0.3
CSM-I	10.4 ± 0.4
CSM-II	9.44 ± 0.09
CSM-III	7.47 ± 0.30

Supplementary Table 3. Herman's orientation factor of wet and dry MXene, SM, CM, and CSM fibers.

Sample	Herman's orientation factor
Wet MXene	0.795 ± 0.004
Dry MXene	0.717 ± 0.003
Wet SM	0.841 ± 0.002
Dry SM	0.767 ± 0.004
Dry CM-I	0.718 ± 0.003
Dry CM-II	0.753 ± 0.003
Wet CM-III	0.820 ± 0.003
Dry CM-III	0.771 ± 0.003
Dry CSM-I	0.803 ± 0.004
Dry CSM-II	0.846 ± 0.003
Wet CSM-III	0.921 ± 0.002
Dry CSM-III	0.903 ± 0.003

Supplementary Table 4. Mechanical properties of MXene, SM, SA, SSA, CM, and CSM fibers.

Sample	Young's modulus (GPa)	Tensile strength (MPa)	Toughness (MJ m⁻³)	Strain to failure (%)
MXene	8.71 ± 0.45	96.2 ± 1.6	0.871 ± 0.091	1.53 ± 0.10
SM	32.3 ± 2.5	188 ± 8	0.708 ± 0.025	0.678 ± 0.037
SA	6.73 ± 0.10	314 ± 19	65.3 ± 3.5	29.5 ± 0.8
SSA	8.38 ± 0.49	410 ± 11	52.3 ± 2.2	18.6 ± 0.2
CM-I	14.4 ± 1.9	244 ± 5	13.2 ± 0.9	4.36 ± 0.22
CM-II	14.2 ± 1.1	319 ± 12	33.9 ± 1.1	13.0 ± 0.2
CM-III	11.7 ± 0.7	414 ± 14	72.3 ± 3.3	23.2 ± 0.5
CSM-I	15.1 ± 0.8	551 ± 21	70.4 ± 2.7	18.5 ± 0.8
CSM-II	19.1 ± 1.0	724 ± 13	68.4 ± 0.9	14.2 ± 0.3
CSM-III	26.7 ± 1.5	958 ± 29	66.3 ± 3.7	10.7 ± 0.3

Supplementary Table 5. Tensile strength, toughness, and electrical conductivity of CSM fibers and previously reported wet-spun MXene fibers.

Number	Materials	Tensile strength (MPa)	Toughness (MJ m ⁻³)	Electrical conductivity (S cm ⁻¹)	Reference
1	MXene	40.5	0.34	7,750	14
2	MXene	63.9	0.091	7,713	15
3	MXene	343.68	0.48	12,504	16
4	MXene-Ac	42	0.6	2,458	17
5	MXene-PEDOT:PSS	58.1	0.267	1,489.8	18
6	MXene-CNCs	74	0.148	345	19
7	MXene-CMC	81	1.13	1,073	20
8	MXene-ANF	18	0.3	0.1128	21
9	MXene-TOCNF	136.5	3.4	4.8	22
10	MXene-Cs	261	5.45	2,215	23
11	MXene-CNT	161	12.5	1,715	24
12	MXene-BP	401	2.49	6,019	25
13	MXene-rGO	145.2	2.98	28	26
14	MXene-rGO	110.7	3.8	743.1	27
15	MXene-K ⁺	199	1.69	9,643	28
16	MXene-Zn ²⁺	151	1.11	3,638	29
17	MXene-Zn ²⁺	252	1.767	11,200	30
18	MXene-Mg ²⁺	118	1	7,200	31
19	MXene-ANF-Fe ²⁺	104	4.11	1,025	32
20	MXene-PR-CDI-Mg ²⁺	502.3	59.7	1,106.5	33
21	MXene-SA-PVA	364.5	10.34	1,006	34
22	MXene-ANF-Borate	242.6	1	1,412	35
23	MXene-GA-PVA	565.2	19.2	8,110.4	36

Number	Materials	Tensile strength (MPa)	Toughness (MJ m⁻³)	Electrical conductivity (S cm⁻¹)	Reference
24	MXene@ANF	160	12.07	26.31	37
25	MXene@ANF	502.9	48.1	3,000	38
26	MXene-CNF@ANF	506.7	44.6	12,700	39
27	MXene@GO	613.7	14.8	7,766	40
28	MXene@rGO	290	2.18	24	41
29	MXene-GO@MC	181.6	6.8	64	42
30	CSM	958	66.3	13,692	This work

Supplementary Table 6. Electrical conductivity of MXene, SM, CM, and CSM fibers.

Sample	Electrical conductivity (S cm ⁻¹)
MXene	9,325 ± 107
SM	11,516 ± 128
CM-I	9,683 ± 96
CM-II	10,159 ± 135
CM-III	10,818 ± 112
CSM-I	11,406 ± 125
CSM-II	12,355 ± 141
CSM-III	13,692 ± 116

Supplementary Table 7. Thickness, average EMI SE at certain frequency range, and thickness-averaged SE (SE/t) of CSM textiles and previously reported textiles woven using polymer, metal, carbon, and MXene composite fibers.

Number	Materials	Thickness (cm)	EMI SE (dB)	SE/t (dB cm ⁻¹)	Frequency (GHz)	Reference
1	PPy-POTS	0.07	24.7	353	8.2-12.4	43
2	PPy-PET	0.03	18.7	623	8.2	44
3	Al-ANF-CFF	0.6	82.63	138	8.2-12.4	45
4	Ni-PI	0.055	83	1,509	8.4-12.5	46
5	LM-PDMS-PET	0.035	72.6	2,074	8.2-12.4	47
6	Ag-cellulose	0.0188	47	2,500	2.0	48
7	G-ANF	0.2	67.86	339	8.2	49
8	rGO-PU-cotton	0.1	48.1	481	8.2-12.4	50
9	G-Al ₂ O ₃	0.087	85	977	18.0	51
10	CNT-G-PET	0.035	30	857	8.2-12.4	52
11	CNT	1	87	87	8.2-12.4	53
12	M-PU@CNT-PU	0.119	23.4	197	8.2-12.4	54
13	M-PPy-PET	0.13	90	692	8.2	55
14	M-PDA-nylon	0.08	66.5	831	8.2	56
15	M-cotton	0.033	36	1,091	8.0-12.0	57
16	MGP-T	0.05	61	1,220	8.2	36
17	M-PET	0.02	36.6	1,830	8.2	58
18	MXene@GO	0.0116	39.7	3,422	8.2-12.4	40
19	CCM	0.021	81.5	3,881	8.0	59
20	MXene@ANF	0.0213	83.4	3,915	9.0	38
21	MXene-GO@MC	0.0185	84.4	4,562	8.2-12.4	42
22	CSM	0.0108	70.3	6,509	8.2-12.4	This work

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