Electronic Supplementary Material (ESI) for Nanoscale Advances.

Ductile Cooling Phase Change Material

Pratahdeep Gogoi[a,†], Zheng Li [a,b,†], Zipeng Guo[c], Saurabh Khuje[a], Lu An[a], Yong Hu[a], Shuquan Chang[b], Chi Zhou[c], Shenqiang Ren[a,d,e,*]

[a.] Department of Mechanical and Aerospace Engineering, Research and Education in Energy Environment & Water Institute, University at Buffalo, The State University of New York, Buffalo, New York, 14260, United States
[b.] College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 210016, China
[c.] Department of Industrial System Engineering, University at Buffalo, The State University of New York, Buffalo, New York 14260, United States
[d.] Department of Chemistry, University at Buffalo, The State University of New York, Buffalo, New York, 14260, United States
[e.] Research and Education in Energy Environment & Water Institute, University at Buffalo, The State University of New York, Buffalo, New York, 14260, United States.

† P.G. and Z.L. contributed equally to this work.
* Email: shenren@buffalo.edu

Figure S1 shows the bar chart representation depicting the time for which the hydrogel composite can maintain its temperature below 0℃ and 20℃ for samples with different amount of water content. From the figure ,we can know the hydrogel with 80 wt% water have longest time maintaining under 0℃ and 20℃. Figure S2 indicate the temperature vs. time profiles representing different hydrogel composites with increasing number of layers and their effect on the overall cooling time. Meanwhile, Figure S3 depict the time for which the hydrogel composite can maintain its temperature below 0℃ and 20℃ for samples with varying number of hydrogel layers (with the constant overall sample thickness fixed). It is clear seen from the image that one layer hydrogel not only have better cooling time below 20℃(370 mins) but also 0℃(175 mins). And the time decrease with the increase of layer. When the layer get 5 layers, the time reach 0℃ and 20℃ separately is 135and 290min.

However, the situation is different when the overall thickness of hydrogel is unrestricted. Figure S4 shows the temperature vs. time profiles of the samples with varying number of hydrogel layers when the overall sample thickness is not constrained. The results indicate that the performance increases with an increase in the number of hydrogel layers. Thus, the cooling capacity of the samples increased with an increasing number of hydrogel layers and the sample with 7 hydrogel layers demonstrates the best results (20℃ for 225 mins and 0℃ for 450 mins). It is observed that the cooling capacity of the sample increased by 60 minutes for every added layer of hydrogel. Figure S5 represent the Young's modulus of hydrogel composites with 80wt.%, 85wt.%, 90wt.% and 95wt.% water content as observed during the mechanical evaluation tests. Figure S6 is the compressive stress-strain curves of samples with 5 and 7 layers of hydrogel (thickness per layer ~ 2mm) respectively as observed during the mechanical evaluation tests. Figure S7 is the bar chart of Young's modulus of samples with 5 and 7 hydrogel layers. Young's modulus of samples with different number of hydrogel layers maintaining a constant overall sample thickness is shown in the Figure S8. Figure S9 depict the time taken by the hydrogel composites infused with fumed silica to reach a temperature of 20℃ (indicative of the cooling effect, starting from -20℃) for different samples. Figure S10 reveals the Young's modulus of the hydrogel composites with 1wt.%, 2wt.% and 3wt% fumed silica. The sample with 2 wt% fumed silica have best cooling time(200 mins), however the sample with 1 wt% fumed silica have best mechanical properity(2250 kPa) via the two image. Figure S11 depict the printed hydrogel composite during the uniaxial compression test with varying amount of compression loading(from 0% to 80%). Line chart of figure S12 represent the displacement at the numbered points on the hydrogel composite in proportion to increasing amount of strain (the Strain-displacement curve).

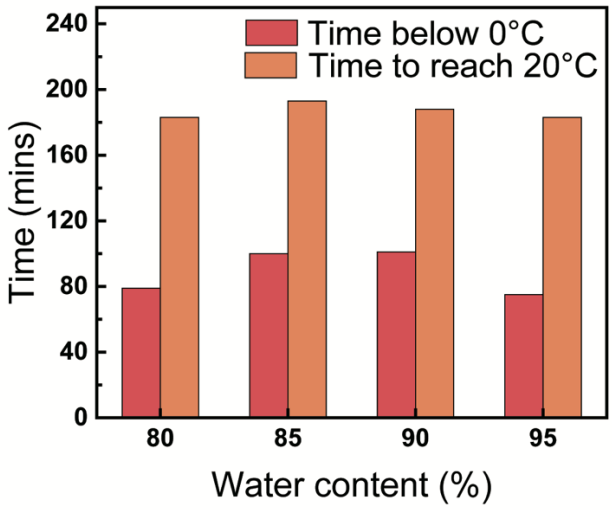

Figure S1 Bar chart representation depicting the time for which the hydrogel composite can maintain its temperature below 0℃ and 20℃ for samples with different amount of water content.

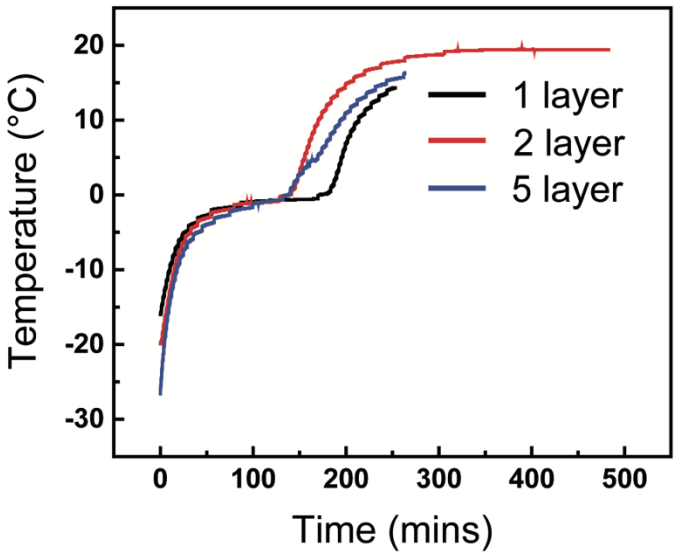

Figure S2 Temperature vs. time profiles representing different hydrogel composites with increasing number of layers and their effect on the overall cooling time

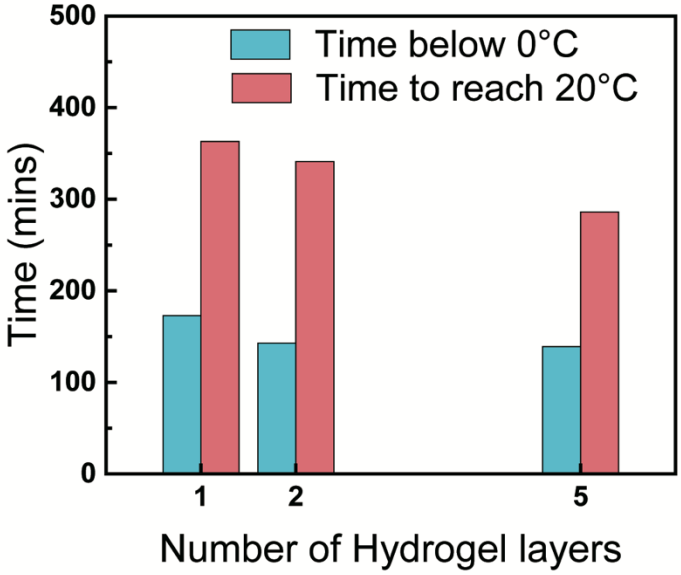

Figure S3 Bar chart depicting the time for which the hydrogel composite can maintain its temperature below 0℃ and 20℃ for samples with varying number of hydrogel layers (with the constant overall sample thickness fixed).

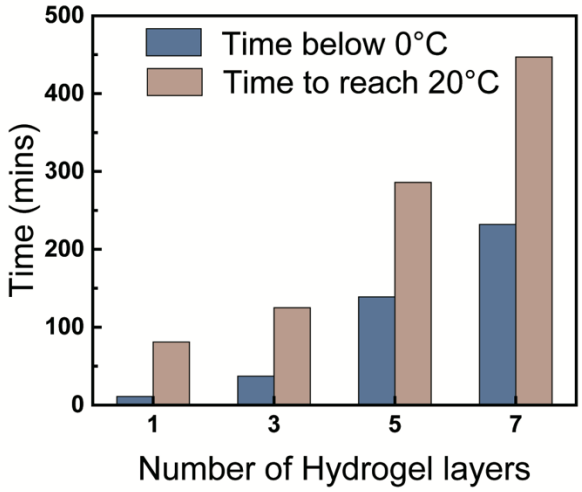

Figure S4 Bar chart representation of the time for which the hydrogel composite can maintain its temperature below 0℃ and 20℃ for samples with different number of hydrogel layers (with unrestricted overall sample thickness).

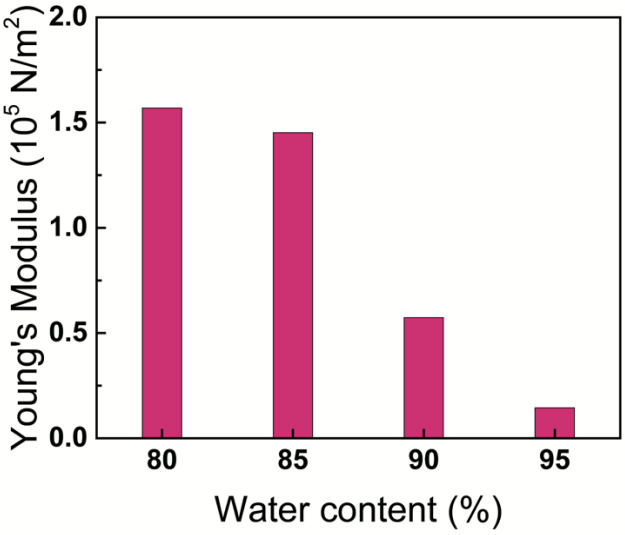

Figure S5 Representation of the Young's modulus of hydrogel composites with 80wt.%, 85wt.%, 90wt.% and 95wt.% water content as observed during the mechanical evaluation tests.

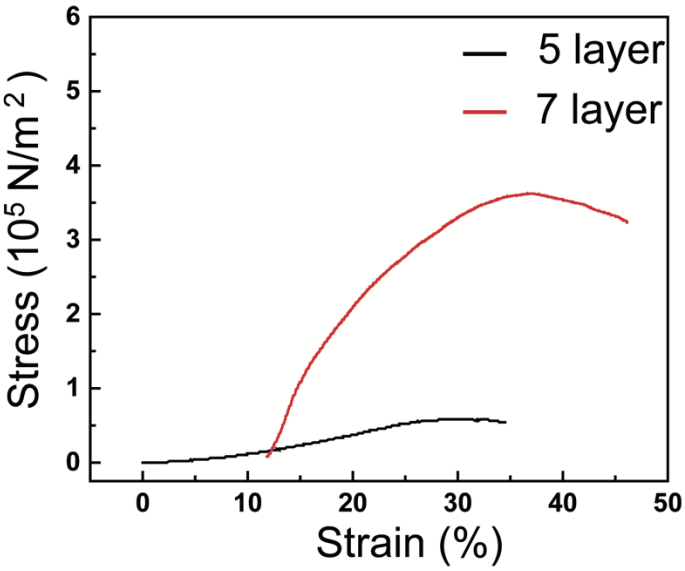

Figure S6 Compressive stress-strain curves of samples with 5 and 7 layers of hydrogel (thickness per layer ~ 2mm) respectively as observed during the mechanical evaluation tests.

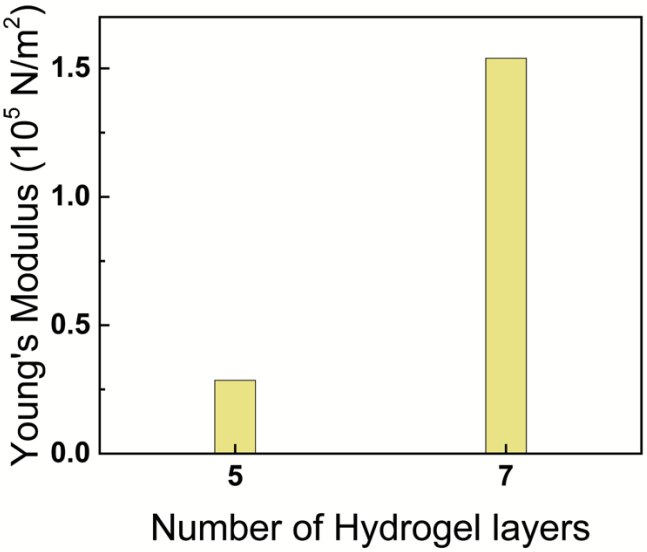

Figure S7 Bar chart representation of Young's modulus of samples with 5 and 7 hydrogel layers as observed during the mechanical evaluation tests.

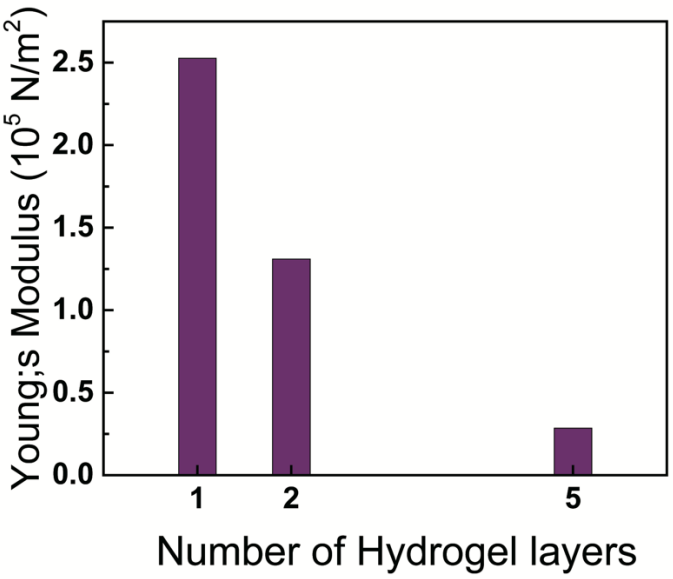

Figure S8 Young's modulus of samples with different number of hydrogel layers maintaining a constant overall sample thickness as observed during the mechanical evaluation tests.

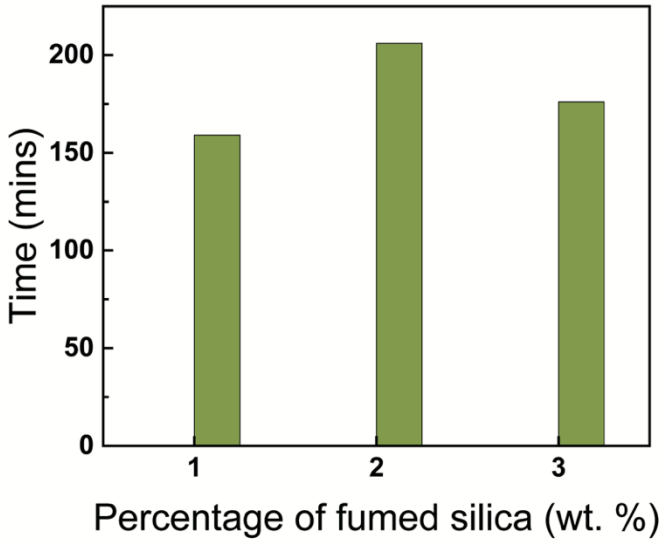

Figure S9 Bar chart depicting the time taken by the hydrogel composites infused with fumed silica to reach a temperature of 20℃ (indicative of the cooling effect, starting from -20℃) for different samples.

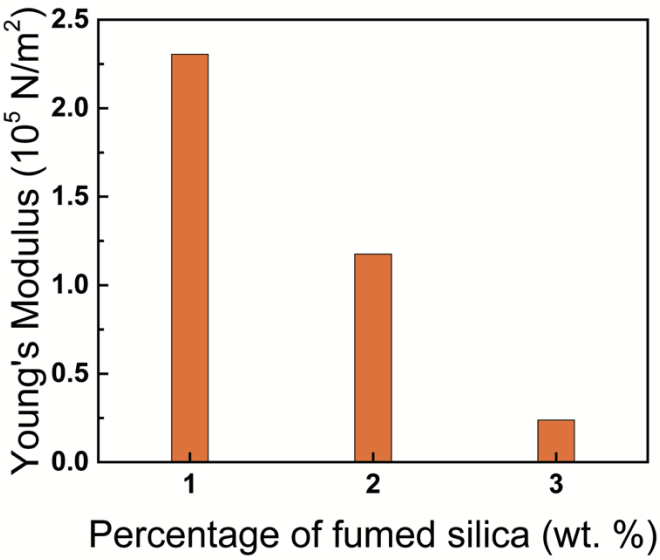

Figure S10 Young's modulus of the hydrogel composites with 1wt.%, 2wt.% and 3wt% fumed silica as observed during the mechanical evaluation tests.

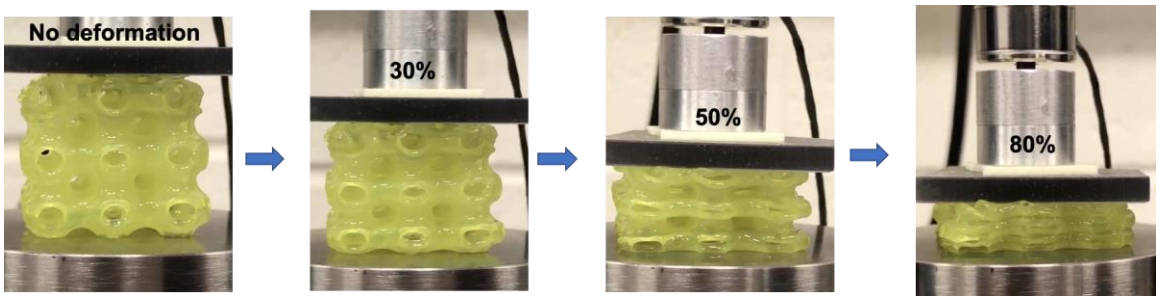

Figure S11 Images depicting the printed hydrogel composite during the uniaxial compression test with varying amount of compression loading.

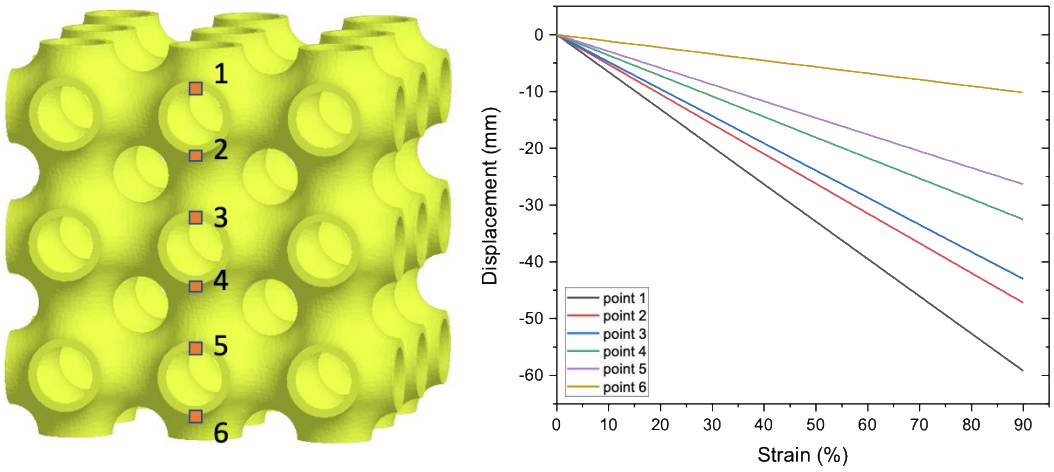

Figure S12 Line chart representation indicative of the displacement at the numbered points on the hydrogel composite in proportion to increasing amount of strain (the Strain-displacement curve).

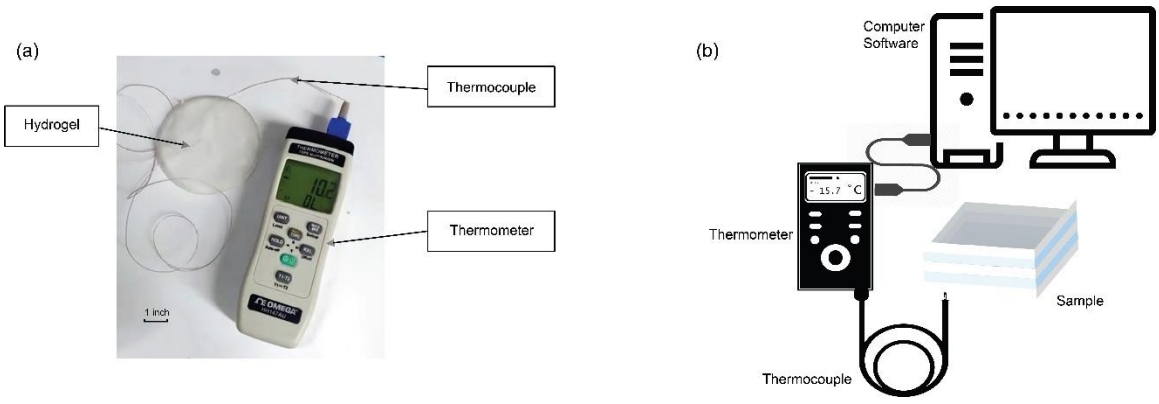

Figure S13 Schematic of the set up used to perform thermal analysis of the samples

Table S1: Quantity of chemicals used for Sol A and Sol B (85 wt.% water content)

Sol A				Sol B		
AAM (wt.%)	Sodium Alginate (wt.%)	H_2O (wt.%)	TEMED (wt.%)	MBAA solution (wt.%)	APS solution (wt.%)	$CaSO_4$ solution (wt.%)
14.95	2.5	82.5	0.05	31.4	52.3	16.3

Table S2: Dimensions of the samples used for mechanical testing

Criteria	Value	Height (mm)	Width (mm)	Thickness (mm)
Water content	80 wt.%	20	20	7
	85 wt.%	20	20	8

	90 wt.%	20	20	8
	95 wt.%	20	13	6
Number of hydrogel layers	5	15.1	15.9	14.9
	7	27.2	29.8	28.1
Number of hydrogel layers (constant overall sample thickness)	1	20	17	15
	2	20	20	15
	5	15.1	15.9	14.9
Fumed Silica Content	1 wt.%	20	20	8
	2 wt.%	25	20	8
	3 wt.%	20	17	9