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CELLULOSE-METAL FOAM HYBRID PHASE CHANGE MATERIAL COMPOSITES WITH REDUCED METAL CONTENT FOR LIGHTWEIGHT HEAT STORAGE

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ABSTRACT

This work investigates whether shape stabilisation and thermal performance in phase change material (PCM) composites can be independently optimised to produce lightweight, cost-effective thermal energy storage materials. A hybrid composite comprising polyethylene glycol (PEG-1000) as the latent heat storage medium, carboxymethylated cellulose (CMC) to address leakage, and aluminium open-cell foams for thermal conductivity and mechanical reinforcement was developed. This approach aims to retain the benefits of metal foams while minimising the proportion of material not contributing to heat storage. Thermal conductivity increased with pore density (PPI), reaching ~2.2 $W \cdot m^{-1} \cdot K^{-1}$, while specific heat was mainly governed by relative density (RD). A key performance index identified 20 PPI 4-6% RD as the optimal architecture.

1. INTRODUCTION

Solid-liquid phase change materials (PCMs) are investigated for thermal energy storage due to their high energy density and temperature-specific operation. Polyethylene glycol (PEG) is attractive as its phase transition temperature can be tuned through molecular weight selection, enabling application-specific design [1]. However, implementation is limited by leakage during melting, low thermal conductivity, and insufficient mechanical strength [2]. Conventional approaches include encapsulation and metal foam incorporation. Encapsulation introduces thermal resistance and risks structural failure under volumetric expansion, while metal foams enhance conductivity and provide structural support but significantly increase mass and cost. High metal content also reduces the effective thermal energy storage capacity of the composite [3]. Recent work has explored cellulose-based matrices for shape stabilisation due to their porous structure, renewability, and compatibility with aqueous processing routes. However, cellulose alone cannot provide sufficient thermal conductivity or mechanical robustness [4]. This work addresses the gap by proposing a hybrid system where carboxymethylated cellulose (CMC) provides shape stabilisation, allowing metal foam content to be reduced while maintaining thermal performance. The objective is to determine how metal foam architecture, i.e. pore density (PPI) and relative density (RD), influences thermal conductivity, thermal energy storage, and weight.

2. METHODOLOGY

Hybrid composites were prepared using a water-based process. CMC nanofibres were dispersed and homogenised with PEG-1000 at a fixed ratio, followed by vacuum-assisted infiltration into ERG open-cell aluminium foams of varying architectures. The infiltrated structures were then freeze-dried (lyophilised) to

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produce a solid, shape-stabilised composite. Metal foam morphologies were: (i) PPI 5, 10, 20; (ii) RD 4-6%, 8-10%. This produced six distinct hybrid architectures for comparison (Fig 1). Thermophysical properties were measured using a TA FOX50 heat flow meter over a temperature range of 5-37 °C across the PCM transition temperature. Thermal conductivity, equivalent specific heat capacity, and overall weight were determined to enable comparison of gravimetric thermal performance across architectures. To evaluate overall performance, a key performance indicator was defined as in Equation 1.

$$KPI = \frac{k \cdot cp}{m_{tot}} \quad (1)$$

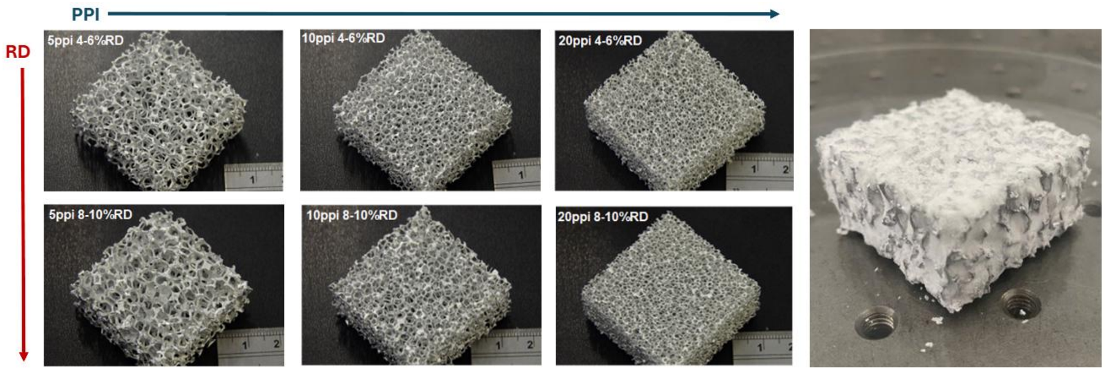

Fig. 1 Open-cell aluminium foams used (left). 5PPI 4-6% RD hybrid composite example (right)

3. RESULTS

Thermal conductivity increased consistently with PPI across all RD (Fig 2, left). The highest values were obtained for 20 PPI, reaching 2.2 $W \cdot m^{-1} \cdot K^{-1}$, i.e. an order of magnitude improvement over pristine PEG. RD had a secondary influence, with higher RD providing slightly increased conductivity due to greater solid conduction pathways. In contrast, specific heat capacity was primarily governed by RD (Fig 2, right). Low-density foams (RD 4-6%) retained higher thermal storage capacity, achieving ~40% of the PEG baseline, while higher density foams exhibited substantial reductions due to increased metal content. A minor decrease in Cp with increasing PPI was observed, attributed to reduced PCM loading efficiency in finer pore structures.

The KPI analysis revealed a clear optimisation trend (Table 1). While higher RD improved conductivity, the associated mass penalty reduced overall performance. The optimum was identified as 20 PPI 4-6% RD, which balanced thermal conductivity, energy storage, and composite weight. These results demonstrate that pore density (PPI) governs thermal transport, whereas relative density (RD) controls thermal storage capacity.

Table 1. Key Performance Indicator Values across Hybrid Composites

RD [%]	*PPI*	KPI_{max}	KPI_{S-L}	KPI	KPI/KPI_{CPCM}
4-6	5	0.87	0.61	0.47	3.74
4-6	10	1.23	0.86	0.65	5.23
4-6	20	1.84	1.39	1.05	8.39
8-10	5	0.57	0.47	0.36	2.91
8-10	10	0.72	0.54	0.41	3.29
8-10	20	1.08	0.81	0.63	5.06
CPCM		0.24	0.16	0.12	1.00

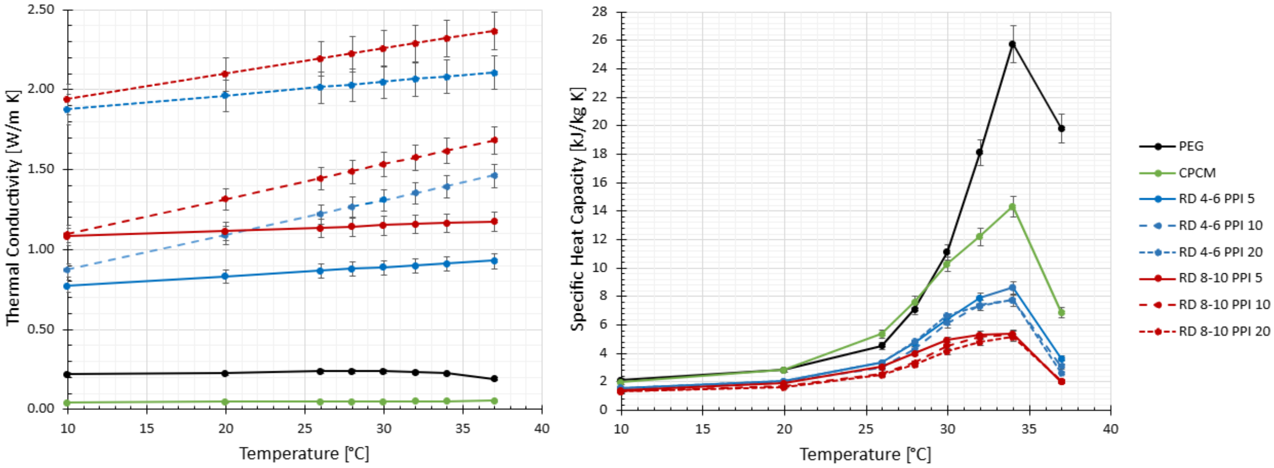

Fig. 2 Thermal conductivity (left) and specific heat capacity (right) for variable metal foam morphology hybrid composites including composite PCM without metal foam (CPCM) and bulk PEG-1000

4. CONCLUSIONS

Hybrid cellulose-metal foam PCM composites enable lightweight thermal energy storage by decoupling stabilisation and thermal transport. Thermal conductivity increased with pore density, with 20 PPI foams providing the highest enhancement. Specific heat capacity was mainly governed by relative density, with low-density foams retaining higher thermal storage capacity. Performance index analysis identified 20 PPI at 4-6% relative density as the optimal architecture. Reducing relative density from 8-10% to 4-6% caused only a modest decrease in thermal conductivity while significantly lowering composite mass, demonstrating that small conductivity losses yield substantial gains in overall performance.

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REFERENCES

[1] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev. 2009 Feb 1;13(2):318–45. doi:10.1016/j.rser.2007.10.005.

[2] Eanest Jebasingh B, Valan Arasu A. A detailed review on heat transfer rate, supercooling, thermal stability and reliability of nanoparticle dispersed organic phase change material for low-temperature applications. Mater Today Energy. 2020 Jun 1;16:100408. doi:10.1016/j.mtener.2020.100408

[3] Chen J, Yang D, Jiang J, Ma A, Song D. Research Progress of Phase Change Materials (PCMs) Embedded with Metal Foam (a Review). Procedia Mater Sci. 2014 Jan 1;8th International Conference on Porous Metals and Metallic Foams4:389–94. doi:10.1016/j.mspro.2014.07.579

[4] Le WT, Kankkunen A, Rojas OJ, Yazdani MR. Leakage-free porous cellulose-based phase change cryogels for sound and thermal insulation. Sol Energy Mater Sol Cells. 2023 Jul 1;256:112337. doi:10.1016/j.solmat.2023.112337