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Research article

Correlations between porosity, thermal conductivity, and mechanical strength in bi-layered ceramics with varying carbon black contents

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Abstract: This paper focuses on the correlations between porosity, thermal conductivity, and mechanical strength in bi-layered ceramics with varying carbon black (CB) contents. Dense/porous bi-layered ceramics were synthesized via a solid-state reaction using feldspar, silica, and kaolinite powders, with CB incorporated into the porous bottom layer at 1–5 wt.% as a pore-forming agent, while the dense top layer remained CB-free. All specimens were fabricated under identical processing conditions, which involved uniaxial pressing at 20 MPa and sintering at 1175 °C for 3 h. A non-linear relationship was established between the CB content and the material properties. The optimum composition, 3 wt.% CB, exhibited the highest porosity (9.16%), the lowest thermal conductivity (1.483 W/m·K), and the maximum flexural strength (49.73 MPa), thus representing the best compromise between insulation efficiency and mechanical strength. At lower CB contents (1–2 wt.%), insufficient pore development limited the reduction in thermal conductivity, whereas excessive CB loadings (4–5 wt.%) produced diminished porosity and corresponding decreases in strength. These results highlight that controlled CB burnout during sintering governs pore evolution in a manner that optimizes phonon scattering and stress redistribution. Overall, this study demonstrates that precise control of pore-former content is critical to tailor multifunctional properties in bi-layered ceramics and establishes a design guideline for developing lightweight ceramic systems with superior thermal and structural performances.

Keywords: bi-layered ceramics; porosity; thermal conductivity; flexural strength; carbon black

1. Introduction

In recent years, porous ceramics have attracted growing attention due to their capability to serve in multifunctional roles that require both thermal insulation and mechanical resilience. These materials are particularly advantageous in applications such as thermal barrier systems, structural supports in aerospace, and energy-efficient construction materials, where it is vital to reduce the thermal conductivity while maintaining sufficient strength. Among the design innovations, bi-layered ceramic structures comprised of a dense substrate and a porous surface layer have emerged as a strategic configuration to fulfil these competing demands. The dense layer provides structural integrity, while the porous layer enhances the thermal insulation and reduces the material weight [1]. However, engineering this dual functionality remains a significant challenge because increasing the porosity to reduce the thermal conductivity typically compromises the mechanical strength of ceramics. This trade-off is mainly due to the creation of stress concentration sites and the reduction of load-bearing cross-sectional areas [2].

A promising method to introduce and control the porosity is the use of pore-forming agents (PFAs) such as carbon black (CB). Upon thermal decomposition during sintering, CB leaves behind a network of pores that can be tailored in terms of size, distribution, and interconnectivity. The effectiveness of this approach is highly dependent on the amount and dispersion of CB in the ceramic matrix. Moderate CB additions have been reported to enhance the thermal insulation by forming open and interconnected pores that effectively scatter phonons, thereby disrupting the heat transfer pathways [3]. Simultaneously, these pores can also improve the fracture resistance of ceramics by either arresting or deflecting cracks. However, an excessive CB content may lead to undesirable effects such as particle agglomeration, pore coalescence, and localized densification, all of which degrade both the thermal and mechanical performances due to structural inhomogeneity and shrinkage mismatch [4–6].

Although prior research has investigated the role of PFAs in porous ceramics, most studies have either concentrated on monolithic structures or focused on independently optimizing either the thermal or the mechanical properties. There remains a critical gap in understanding how CB content simultaneously influences both the thermal conductivity and the flexural strength in bi-layered architectures. Moreover, limited attention has been given to the interaction between the porous and dense layers, particularly in terms of interfacial bonding and thermal-mechanical mismatch factors that are crucial for long-term performance under service conditions [7,8]. The development of advanced ceramic systems that can maintain structural coherence while providing effective thermal insulation calls for a systematic investigation into the processing–microstructure–property relationships of bi-layered configurations modified with CB.

To address this gap, the present study aims to investigate the influence of the CB content on the thermomechanical performance of dense/porous bi-layered ceramics. Specifically, it seeks to evaluate how incremental additions of CB affect pore development during sintering, and how the resulting microstructure governs the dual performance parameters of thermal conductivity and flexural strength. The first objective is to investigate the relationship between CB induced porosity and the resulting thermal conductivity and flexural strength, thereby identifying the CB concentration that achieves the lowest thermal conductivity without compromising the strength. The second objective is to determine the critical threshold of the CB content that provides the best balance between thermal insulation and mechanical performance, thereby offering guidance for the design of multifunctional ceramic systems.

The present study establishes correlations between porosity, thermal conductivity, and mechanical strength across a CB content range of 1–5 wt.% to systematically investigate these correlations and to identify the optimum CB concentration that achieves the lowest thermal conductivity without compromising the structural integrity. By clarifying the interplay between pore evolution and property response, this work provides a processing guideline for the rational design of multifunctional bi-layered ceramics tailored for energy-efficient and mechanically demanding applications.

2. Materials and methods

2.1. Raw materials

Feldspar, silica, and kaolinite clay powders were selected as the primary constituents to synthesize the bi-layered ceramics. Analytical grade CB was employed as a sacrificial pore-forming agent and was incorporated into the porous layer at varying concentrations of 1, 2, 3, 4, and 5 wt.% relative to the total matrix composition. The CB powder had an average particle size of 30–50 nm. The mixing process involved thoroughly blending the weighed CB with the raw material mixture (kaolinite clay, silica, and feldspar) to ensure homogeneity. A ball milling process was employed to achieve a uniform dispersion of CB particles within the ceramic matrix. Ball milling was performed at a rotational speed of 300 rpm for 3 h. The formulation strategy was guided by previous studies which demonstrated effective porosity control in layered ceramics via CB addition [9].

2.2. Sample preparation

The dense/porous bi-layered green compacts were prepared by sequentially loading two distinct powder layers into a 13 mm stainless steel die: the upper porous layer contained CB, while the lower dense layer was CB-free. Each bi-layered specimen was uniaxially pressed at 20 MPa for 60 s using a hydraulic press. This sequential compaction method ensured distinct interfaces and structural uniformity, as validated in prior fabrication approaches for dual-layer ceramics [9].

2.3. Sintering temperature

The green samples were sintered in a programmable muffle furnace at a fixed temperature of 1175 °C for 3 h, with a constant heating rate of 5 °C/min. Furnace cooling was employed to bring the specimens to ambient temperature. This sintering regime was selected based on the prior optimization of phase development and the densification of feldspar-based ceramics [10].

2.4. Porosity and density measurement

The apparent porosity and bulk density were determined via the Archimedes method following ASTM C373. This method is widely used in ceramic studies to evaluate the open porosity and structural compactness [9,10].

2.5. Thermal conductivity

Thermal conductivity measurements were performed at room temperature using a Hot Disk TPS 2500S system operating in the transient plane source (TPS) mode. A Kapton-insulated sensor was placed between two identical sample halves, and a constant power input of 50 mW was applied. This non-destructive technique provides the high-accuracy thermal characterization of porous ceramics.

2.6. Flexural strength test

The flexural strength was evaluated using a three-point bending test on an Instron 3365 universal testing machine in accordance with ASTM C1161. Rectangular bar specimens (75 × 10 × 5 mm) were tested with a span length of 30 mm and a crosshead speed of 1.0 mm/min. Five samples per composition were tested to ensure statistical reproducibility. This test configuration has been extensively adopted to characterize layered and porous ceramics [10].

3. Results and discussion

3.1. Effect of CB content on porosity and thermal conductivity

The relationship between the CB content and the resulting porosity and thermal conductivity of dense/porous bi-layered ceramics is shown in Figure 1. As the CB content increased from 1 to 3 wt.%, the average porosity rose steadily, and reached a peak of 9.16% at 3 wt.%. Beyond this point, the porosity declined to 6.13% and 6.79% at 4 and 5 wt.%, respectively. A corresponding trend was observed for the thermal conductivity: it decreased from 1.566 W/m·K at 2 wt.% to a minimum of 1.483 W/m·K at 3 wt.%, then slightly increased to 1.555 and 1.557 W/m·K at 4 and 5 wt.%, respectively. The porosity peaked at 3 wt% CB (9.16%) because this content ensured sufficient burnout and a uniform distribution of particles. Beyond this threshold, excessive CB agglomerated, leading to coalesced pores and localized densification during sintering. This reduced the effective porosity despite the higher CB addition [4,5].

These results indicate that the addition of CB facilitates pore formation through thermal decomposition during sintering. The evolving pore network effectively reduces the thermal conductivity due to the insulating effect of entrapped air, which disrupts the phonon transport. The minimum thermal conductivity at 3 wt.% CB coincides with the maximum porosity, thus confirming the critical role of well-distributed, open pores in thermal insulation. This behavior is consistent with the findings of Liu et al. who highlighted that open and interconnected pores are more effective in disrupting the heat flow compared to closed or isolated voids [11]. Similarly, Li et al. reported that porous mullite–silica ceramics with multistage pore structures exhibited significantly lower thermal conductivity due to enhanced phonon scattering [12].

However, the slight decline in porosity and rebound in thermal conductivity at higher CB contents (≥ 4 wt.%) may be attributed to the agglomeration of the CB particles and incomplete burnout during sintering. Excess CB tends to cluster, resulting in either localized pore collapse or densification of certain regions, which compromises the overall porosity and continuity of the insulating network. This phenomenon has also been observed in porous alumina ceramics processed with carbon-based pore-forming agents, where excessive CB loading led to irregular pore morphology and a reduced performance [4,5].

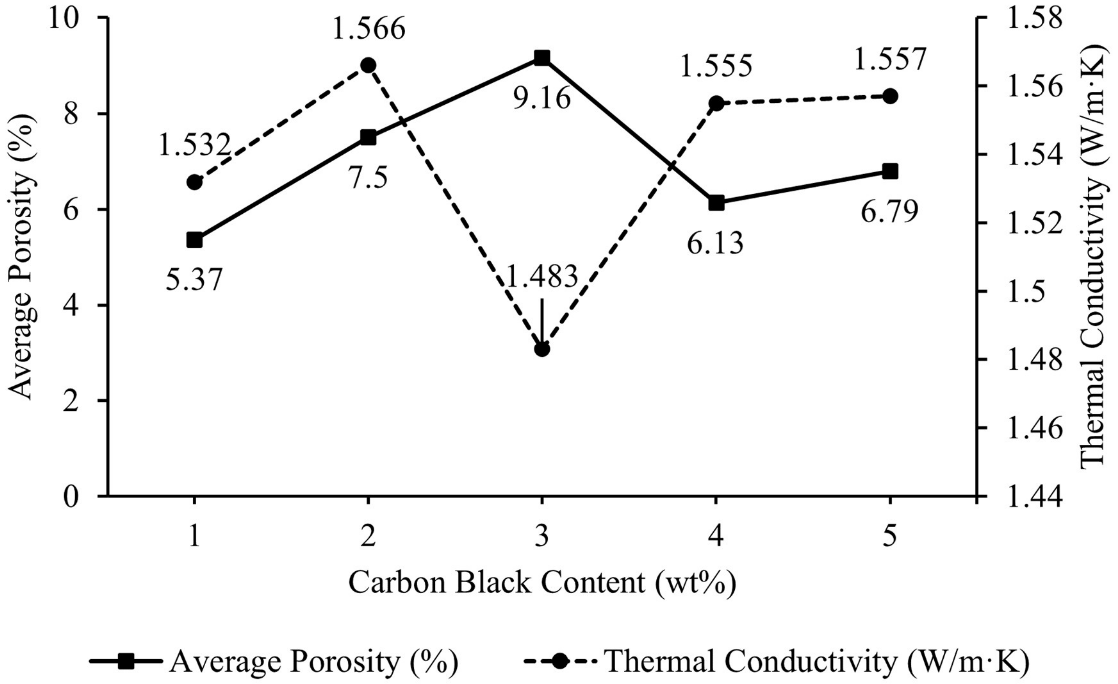

Figure 1. Effect of the CB content on the porosity and thermal conductivity of dense/porous bi-layered ceramics.

Additionally, for titanium carbide (TiC) ceramics, Nguyen et al. demonstrated that a moderate CB content improves the thermal insulation due to microstructural refinement; however, excessive amounts can introduce structural defects [13]. Likewise, for TiB_2–silicon carbine (SiC) systems, Popov et al. showed that optimized carbonaceous additives significantly reduced the thermal conductivity, whereas higher loadings impaired the ceramic's integrity [6]. The current study aligns with these findings and emphasizes the need for a precise control of the CB content to ensure an optimal porosity and thermal behavior.

3.2. Effect of CB on porosity and flexural strength

The relationship between the CB content, porosity, and flexural strength in dense/porous bi-layered ceramics is illustrated in Figure 2. This dual-axis analysis demonstrates a non-linear correlation between the CB content (1–5 wt.%) and the resulting structural performance. The findings reveal a critical balance point, thus highlighting the role of CB in tailoring the porous microstructure to optimize the thermal and mechanical functionality in dense/porous bi-layered ceramics.

At 1 wt.% CB, a relatively dense structure forms with limited porosity (5.37%) and a flexural strength of 36.72 MPa. The low porosity suggests minimal CB decomposition, resulting in fewer pores and enhanced grain packing, which, in turn, supports a decent mechanical performance. However, the limited porosity restricts the functional benefits of the porous layer in terms of the thermal insulation and energy dissipation.

As the CB content increases to 2 wt.%, the porosity rises to 7.50% and the flexural strength improves to 41.34 MPa. This simultaneous enhancement indicates that moderate CB loading allows effective pore formation without introducing significant structural defects. At this stage, the microstructure likely contains well-dispersed, isolated pores that reduce internal sintering stress and deflect the crack propagation paths, thereby enhancing the toughness.

The peak performance was recorded at 3 wt.% CB, where the porosity reached 9.16% and the flexural strength attained its maximum value of 49.73 MPa. This optimal concentration reflects a synergistic microstructure, where pore formation is balanced with sufficient grain contact and interfacial integrity. The interconnected yet uniformly distributed pores not only contribute to the thermal insulation, but also assist in dissipating mechanical stress. Similar trends have been reported by Celik et al., who demonstrated that optimal CB loading in porous alumina systems yields a favorable combination of pore control and mechanical stability [4].

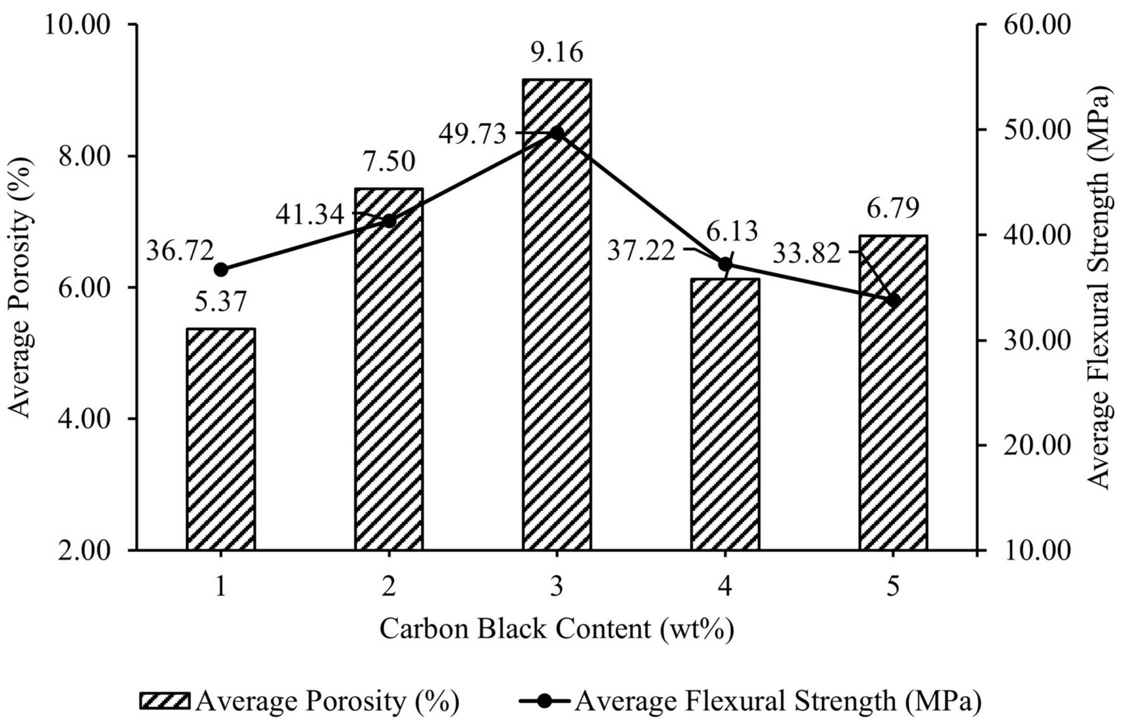

Figure 2. Relationship between average porosity and flexural strength of dense/porous bi-layered ceramics as a function of the CB content.

The performance deteriorates beyond this threshold. At 4 wt.% CB, the porosity unexpectedly dropped to 6.13% and the strength declined to 37.22 MPa, thus suggesting either pore collapse or coalescence due to agglomerated CB particles and localized densification. At 5 wt.%, the porosity marginally increased to 6.79%, but the strength fell further to 33.82 MPa. This behavior is consistent with Fang et al. [5] and Fu et al. [14], who reported that excessive pore-forming agents can cause microstructural inhomogeneity, large voids, and grain sintering disruption, thus ultimately weakening the ceramic matrix.

Although the porosity is generally associated with a reduction in mechanical strength due to the creation of stress concentration sites and a decrease in the load-bearing area, the present results demonstrate an exception at 3 wt.% CB. At this composition, the uniformly dispersed pores acted as effective crack arrestors. Microcracks were deflected around the pores rather than propagating linearly, which increased the fracture surface area and raised the energy required for failure. This crack-deflection mechanism, combined with an improved grain boundary integrity during sintering, explains the enhancement in flexural strength despite a higher porosity level.

Moreover, the interface compatibility between porous and dense layers becomes critical at high CB levels. An increased shrinkage mismatch and interfacial stress may lead to debonding and crack initiation, as noted by [15] in multilayer ceramics. These results emphasize the importance of controlling the pore-former dispersion and content to preserve the interlayer coherence and structural integrity. In conclusion, the incorporation of CB exhibits a threshold-dependent effect on the thermomechanical performance of dense/porous bi-layered ceramics. The optimal concentration of 3 wt.% offers the best compromise between porosity-induced insulation and enhanced mechanical strength, thus serving as a benchmark for future porous ceramic designs.

3.3. Effect of CB on thermal conductivity and flexural strength

The integration of CB into dense/porous bi-layered ceramic systems significantly modulates both the thermal conductivity and the mechanical strength, thus underlining a critical design trade-off between insulation performance and structural integrity. Figure 3 illustrates the concurrent trends of thermal conductivity and flexural strength across a CB content range of 1–5 wt.%, thus revealing a non-linear and inverse relationship.

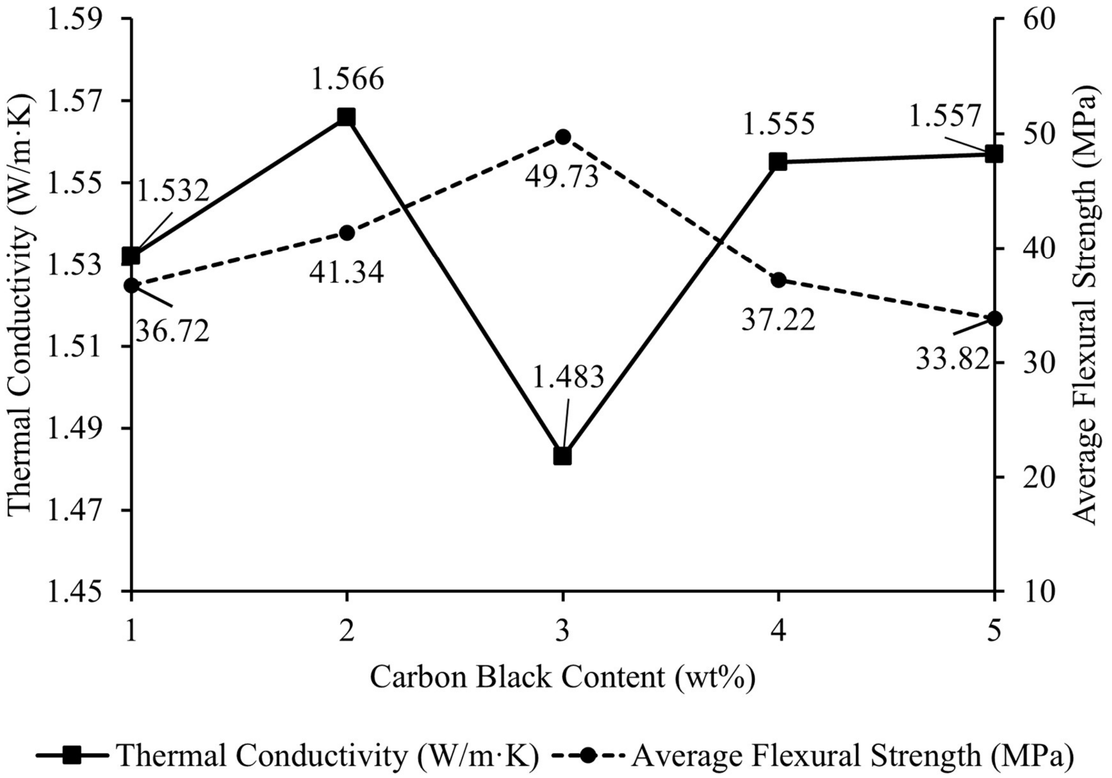

Figure 3. Correlation between the CB content, thermal conductivity, and flexural strength.

Initially, the thermal conductivity increased from 1.532 W/m·K at 1 wt.% CB to 1.566 W/m·K at 2 wt.%. This is attributed to an enhanced grain connectivity and a reduced interfacial resistance within the dense ceramic phase, which facilitates phonon transport. However, at 3 wt.% CB, the conductivity dropped significantly to 1.483 W/m·K, which is the lowest recorded value, thus indicating that pore formation induced by CB burnout reached an effective threshold. Beyond this, the thermal conductivity rose again at 4 and 5 wt.% CB, and reached 1.555 and 1.557 W/m·K, respectively. This partial recovery likely results from pore coalescence or densification during sintering, which reinstates some degree of thermal continuity [11,12].

In contrast, the flexural strength had inverse trends. It increased from 36.72 MPa at 1 wt.% CB to a peak of 49.73 MPa at 3 wt.%, thus indicating that this composition strikes an optimal balance between porosity and mechanical reinforcement. The microstructure at this loading likely exhibits refined grain boundaries and uniformly distributed pores that enhance the crack deflection and energy dissipation. However, at 4 and 5 wt.%, the strength sharply dropped to 37.22 and 33.82 MPa, respectively, thus suggesting that an excessive CB content leads to either pore clustering or microstructural discontinuities that undermine the load-bearing capability [6,13].

These findings confirm that 3 wt.% CB acts as a transition point where the dual functionality of the composite is maximized, thus delivering the lowest thermal conductivity and the highest mechanical strength. Such an inverse correlation is consistent with the classical porosity–property paradigm in ceramics: porosity impedes the heat flow through phonon scattering but, when optimally engineered, may also contribute to the fracture resistance by disrupting the crack propagation paths [11,16].

The synergy between the dense and porous layers in the bi-layered structure further amplifies this effect. The dense layer stabilizes the mechanical performance, while the porous layer, formed through CB burnout, disrupts thermal transport. This hierarchical configuration mirrors the design of advanced ceramic systems such as random ceramics, where layered structures improve the thermal shock resistance and mechanical endurance [17].

From an engineering perspective, targeted CB loading around 3 wt.% offers a strategic balance suitable for multifunctional applications. Lower loadings may favor structural use cases, while compositions at or above 3 wt.% prioritize thermal insulation. Nonetheless, maintaining sintering control is vital, as the burnout dynamics of CB determine the final pore morphology, which, in turn, governs both heat and stress pathways.

4. Conclusions

This study highlights the critical role of the CB content in governing the porosity, thermal conductivity, and flexural strength of dense/porous bi-layered ceramics. Through systematic variation of CB loading from 1 to 5 wt.%, a non-linear trend was established, which revealed that 3 wt.% CB yielded an optimal microstructure with the highest porosity (9.16%), lowest thermal conductivity (1.483 W/m·K), and peak flexural strength (49.73 MPa). The results confirm that well-distributed, interconnected pores formed at this concentration enhance phonon scattering while facilitating crack deflection, thus enabling a synergistic balance between insulation and mechanical performance. In contrast, both lower and higher CB contents resulted in suboptimal properties due to either insufficient pore formation or structural degradation from agglomeration and pore coalescence. These findings underscore the importance of precise control over pore-former content and microstructural engineering to design multifunctional ceramic systems for advanced applications requiring both thermal regulation and mechanical integrity.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Mohamed Lokman Jalaluddin: conceptualization, methodology, investigation, data curation, writing–original draft; Umar Al-Amani Azlan: supervision, project administration, validation, writing–review and editing, funding acquisition; Mohd Warikh Abd Rashid: formal analysis, resources, visualization, writing–review and editing; Muchlis: software, data curation, validation, writing–review and editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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