

PERFORMANCE EVALUATION OF DEEPSEEK-R1 IN UNDERSTANDING AND DESIGNING Al_2O_3 POROUS CERAMICS WITH THE SACRIFICIAL BIOMASS TEMPLATE METHOD

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DeepSeek has demonstrated preliminary success in multidisciplinary applications over recent months. This paper investigates the level of understanding of DeepSeek-R1 on Al_2O_3 porous ceramics from the sacrificial biomass template method (APCBT) and provides a preliminary study of its application to porous ceramics, including wood ceramics, porous ceramics and APCBT ceramics. The study was initiated with 48 questions of increasing complexity, the purpose of which was to ascertain the readability and accuracy of DeepSeek's responses to APCBT. Based on this, the study explored the feasibility of using DeepSeek to identify and analyse the APCBT material mix ratio design, and filtration performance analysis. The results showed that DeepSeek-R1 is highly proficient in acquiring fundamental knowledge of APCBT materials, a capability validated through an interactive human-computer model, for analysing APCBT precursors, formulating preliminary material compositions, and providing feedback on filtration performance. However, it was also found that DeepSeek-R1 has limitations in understanding the complex preparation design and mechanics of APCBT and lacks the ability to synthesise and integrate interdisciplinary knowledge, sometimes resulting in arbitrary and reluctant responses. These findings emphasise the need for further improvements in the algorithmic complexity and database comprehensiveness. The paper concludes by predicting the future applicability of DeepSeek-R1 in the field of porous ceramic materials, pointing the way for subsequent research and development.

INTRODUCTION

In recent years, the rapid development of Artificial Intelligence (AI) has facilitated the development of increasingly sophisticated and generalised generative AI techniques [1, 2]. Generative AI is able to create and integrate into new data by learning from existing data such as text, images, video and music [3]. The combination of generative AI and Natural Language Processing (NLP) enables machines to understand and generate human language, which facilitates the output of the corresponding data and text [4]. This integration has greatly contributed to the further development of specialised AI technologies [5]. A prominent example of this trend is OpenAI's AI model ChatGPT [6], which, since its inception, has become an indispensable technology that has attracted a lot of attention and discussion among researchers around the globe. DeepSeek-R1 is a large model based on the Mixture of experts (MoE) architecture introduced by DeepSeek, Inc [7]. It supports 128K long contextual understanding, industry-leading math and code capabilities and reasoning at 1/100th the cost of GPT-4 Turbo (equivalent results). The total score of their academic writing skills is shown in Figure 1 and the related parameters are shown in Table 1 [8].

While controversy and discussion about the ethical considerations [9], potential biases [10], and intellectual property issues of generative AI continue [11], these have not hindered the initial use cases it has already achieved. In fact, the future of generative AI has the potential to reshape numerous traditional industries, including but not limited to healthcare, education, and engineering. In education, practitioners are working to use generative AI to create personalised lesson plans [12], facilitate brainstorming among groups of learners [13, 14], and improve their problem-solving skills. Meanwhile, many studies in the medical field have confirmed the ability of generative AI to enhance medical practice and provide public health policy recommendations [15, 16]. Boßelmann et al [17] conclude that advances in generative AI can improve the accuracy of diagnosis and treatment in epilepsy cases. Contemporary academia is tentatively exploring the application of generative AI in fields as diverse as marketing, linguistics, and hydrology [18]. This emergence is not only contributing to the transformative growth of existing industries, but also to the technological advancement of generative AI itself [19].

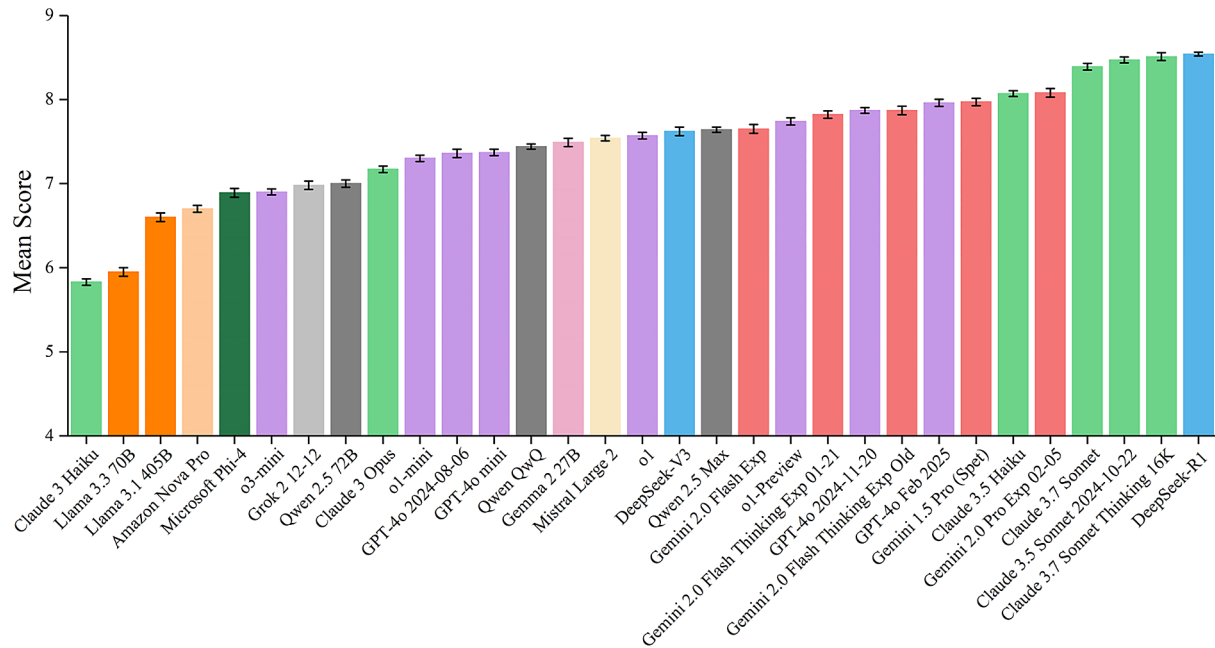


Figure 1. Writing benchmark: Overall score (zoomed with error bars).

Table 1. Details of writing benchmarks.

Model	Params	Length	Slop	Vocab	Writing
DeepSeek-R1	18×37	5272	5.3	4.4	87.11
Gpt-4o-2024-11-20	–	6642	7.2	5.6	84.59
Claude-3.7-sonnet-20250219	–	5976	4.9	5.8	84.43
Darkest-muse-v1	9	7133	5.2	5.0	84.25
Claude-3.5-sonnet-20241022	–	4710	4.3	5.7	82.98
Chatgpt-4o-latest-2024-09-03	–	6204	5.3	4.2	82.51
Gemini-2.0-flash-thinking-exp-1219	–	7476	9.3	5.9	82.46
Gemma-2-Ataraxy-v4d-9B	9	5661	11.6	6.6	81.90
Gemini-1.5-pro-002	–	4799	10.0	5.5	81.44
Gemini-2.0-flash-001	–	5692	8.2	5.5	81.41
Gemma-2-Ataraxy-9B	9	4574	14.7	7.3	81.38
DeepSeek-V3	18×37	6402	8.5	5.6	81.19

The origins of DeepSeek can be traced back to the January 5, 2024 introduction of DeepSeek LLM. In the financial field, it helped to develop the quantitative investment model AlphaSeek, with a management scale of more than 10 billion; in the field of education, the DeepSeek-solving model MathGPT covers K12 to competition-level math problems; in terms of code development, DeepSeek Coder, an intelligent programming assistant, supports 70+ programming languages, and it is building a visual-linguistic model, VLM-7B, to realise complex Diagram parsing and providing breakthroughs in dynamic scene 3D generative modelling technology.

In this context, the purpose of this paper is to evaluate the application of DeepSeek on Al_2O_3 porous ceramics from Alumina Porous Ceramic Biomass Template (APCBT) [20] and to conduct preliminary application tests to provide a basis and reference for the future application of DeepSeek in the field of porous ceramics. APCBT are ceramics prepared based on wood ceramics

[21, 22], biomass-based porous ceramics [23], and the sacrificial template method [24]. To date, there are a large number of research results related to these three directions on Google Scholar, but the technology is still evolving and still faces challenges in filtration, preparation cost, and sustainability. This provides an ideal scenario for the application of DeepSeek-R1: the large number of works highlights the need for research, while the large number of existing studies demonstrates the abundance of data. In this study, DeepSeek-R1's deep thinking and networked search were used to investigate a combination of test scenarios for the classification of three ceramic materials for the APCBT – wood ceramics, porous ceramics, and ceramics prepared by the template method. The questions varied in difficulty and were designed to assess DeepSeek-R1's comprehension of APCBT. Based on this, the feasibility of using DeepSeek-R1 for the pore identification, precursor ration design, and filtration performance calculations was also explored.

Comprehension of APCBT

This study examined DeepSeek-R1's level of understanding of APCBT using a question, answer, and assessment research method.

Methodology

DeepSeek-R1 received a total of 48 questions about APCBT, including wood ceramics, porous ceramics, and the sacrificial biomass template method. None of these questions were pre-arranged and most were based on answers provided by DeepSeek-R1. Figure 2 indicates that if the information provided seems insufficient, unclear, or illogical, additional queries are made so that the AI outputs a more detailed explanation. Table 2 lists all the questions.

Providing insufficient, unclear or absurd information is provided for a more detailed explanation, as shown in Figure 2. All the questions are listed. They then progressively increase in difficulty and complexity, i.e., advanced questions, with details progressively elaborated

upon and inquiries deepening into more specialised areas, eventually encompassing interdisciplinary knowledge. These advanced questions are highlighted in three areas: the understanding of theoretical formulations, elucidation of the trajectory of technological advances, and mastery of the direction of development in the question.

The questions posed in Table 2 were answered by DeepSeek-R1. In this paper, we first evaluate DeepSeek-R1's responses for steganography and readability, and then provide a technical overview to check for errors in the responses.

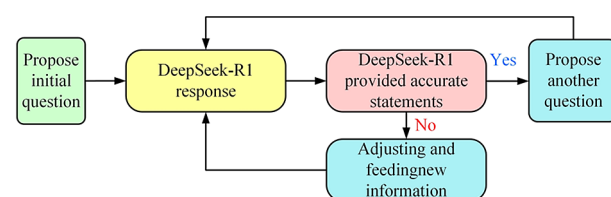


Figure 2. The query method of DeepSeek-R1.

Table 2. Questions input into DeepSeek-R1.

Initial questions	Advanced questions
1. What are wood ceramics?	4. Are wood ceramics environmentally friendly materials?
2. What are the structural characteristics of wood ceramics?	5. How does the lignin content affect the pore formation of wood ceramics?
3. What are the raw material requirements for wood ceramics as a filtration material?	6. Where were the first wood ceramics developed?
	7. How stable is the filtration efficiency of wood ceramics?
	8. How does the temperature affect the filtration efficiency of wood ceramics?
	9. How does the pore structure affect the filtration performance of wood ceramics?
	10. How does the fibre content affect the filtration efficiency of wood ceramics?
	11. How to improve the high temperature filtration stability of wood ceramics?
	12. Do wood ceramics have a thermoelectric effect?
	13. What is the electrical conductivity of wood ceramics compared to porous ceramics?
	14. How to determine the permeability-pressure drop curve of wood ceramics and its model?
	15. How does the addition of activated carbon affect the long-term filtration performance of wood ceramics?
	16. How to maintain the filtration performance of wood ceramics during recycling?
17. What are porous ceramics?	20. How to prepare high-strength porous ceramics? What are the key process parameters to be controlled?
18. What are the main components of porous ceramics?	21. Who first proposed the pore structure design theory of porous ceramics? What is the core principle?
19. How does the durability of porous ceramics compare with that of conventional dense ceramics?	22. Does high porosity lead to a significant decrease in the mechanical strength of porous ceramics? Why?
	23. How does the surface coating technology affect the filtration performance of porous ceramics? What are the commonly used coating materials?
	24. Are porous ceramics self-healing? How to improve their self-repair performance through material design?

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Table 2. Questions input into DeepSeek-R1. (Continue)

Initial questions	Advanced questions
	25. How to prepare conductive porous ceramics? What are the advantages of conductive porous ceramics over metallic porous materials?
	26. Is the modulus of elasticity of porous ceramics lower than that of dense ceramics? How is their mechanical behaviour affected by the pore structure?
	27. What is the potential of porous ceramics for 3D printing? What are the special features of the pore structure design?
	28. How to realise the self-cleaning function of porous ceramics? What is its technical mechanism?
	29. What are the differences in the pore distribution and properties of porous ceramics by different pore-forming agents (e.g., starch, polymer particles)?
	30. Is the size effect of porous ceramics significant? What problems may be faced in the application of large size samples?
	31. How can the pore size gradient design of porous ceramics optimise the balance between their filtration efficiency and permeability?
	32. What is the theoretical basis for the design of porous ceramic materials? Please list the key formulas or models.
33. What ceramics are prepared by the sacrificial template method?	36. Based on the assumption of uniformity of pore structure, how to derive the bending strength calculation model of sacrificial template ceramics?
34. What are the main raw materials and additives for ceramics prepared by the sacrificial template method?	37. What is the material cost of the sacrificial template method? How can the cost be significantly reduced by optimising the template material?
35. What are the important applications of ceramics prepared by the sacrificial template method?	38. Is it possible to use natural porous materials (e.g., wood, plant fibres) as sacrificial templates to prepare ceramics? What are the mechanisms and potential problems?
	39. What are the advantages of the sacrificial template method in the 3D printing of complex structural ceramics? How to avoid pore collapse during sintering?
	40. What is the core design theory of ceramics prepared by the sacrificial template method? What are the key technological breakthroughs in its development?
	41. What are the successful application cases of sacrificial template ceramics? How to solve the problem of shrinkage cracking during sintering?
	42. Can biodegradable polymers be used to replace traditional template materials for ceramic preparations? What are the technical bottlenecks?
	43. What is the high temperature and corrosion resistance of sacrificial template ceramics? How to improve its structural stability under a high temperature environment?
	44. What is the fatigue performance of sacrificial template ceramics under cyclic loading? How does its failure mechanism differ from that of dense ceramics?
	45. Can industrial solid wastes (e.g., fly ash, rice husk ash) be used as sacrificial templates or ceramic raw materials? How to balance the dosage of solid waste and the strength of ceramics?
	46. What are the advantages and disadvantages of sacrificial template ceramics compared with traditional foamed ceramics?
	47. What is the current record of the highest compressive strength of ceramics prepared by the sacrificial mouldboard method? What is the source of the data?
	48. How to optimise the synergistic relationship between the pore distribution and mechanical properties of sacrificial template ceramics through the template gradient design?

RESULTS AND DISCUSSION

The responses generated by DeepSeek-R1 contain 292 paragraphs with 647 sentences and 18,545 words. To ensure the originality of these responses, we performed a plagiarism check using Turnitin, available at <https://www.turnitin.com/>. The analysis showed a very low similarity index of 10.25 %, which is fully in line with the strict requirement set by most academic institutions to keep similarity below 20 %.

As shown in Figure 3a, the similarity of publications in each paragraph generally conforms to the characteristics of a normal distribution, with a maximum similarity that can be controlled at 11 %, and it is noteworthy that no source contributes more than 1 % to the overall similarity. Confirmation of authenticity and the plagiarised nature of non-DeepSeek responses. This result indicates the proficiency of DeepSeek-R1 in producing plagiarism-free content. It is consistent with the observations conducted by Gao et al [25], Cai et al [26], and Ling et al [27] that summaries generated by generative AIs do not trigger any alerts in plagiarism detection models, which demonstrates the robustness of DeepSeek-R1 in generating original content.

The assessment of the response readability was conducted using the Check Plagiarism tool, which can be accessed at <https://www.check-plagiarism.com/>. The results of the evaluation showed that the average readability level of DeepSeek-R1's responses was 10, indicating a suboptimal performance. Although the latest version of DeepSeek-R1 has improved the readability

over the previous version of DeepSeek-V3, the ideal readability level is generally best kept below level 8. Figure 3b illustrates the Rix readability distribution for 647 sentences. The readability distribution of DeepSeek-R1-generated passages is very close to a normal distribution, with 201 passages having readability scores equal to or greater than 11. A certain level of domain-specific knowledge is required to fully understand these passages.

All DeepSeek-R1 answers were reviewed individually. Most of the answers were correct, clear, and error-free, demonstrating the power of DeepSeek-R1 for information gathering and reprocessing. However, there were cases of ambiguous, incorrect, or erroneous representations on some questions that required deeper knowledge, as shown in Tables 3 and 4, respectively. Table 3 shows that DeepSeek-R1 often gives casual answers to vague, controversial topics or undisclosed technical details. Although DeepSeek-R1 can better understand text-based conclusions, its treatment of formulas and theories is often formulaic and rigid, failing to address the core issues and sometimes even misquoted as shown in Table 4. In addition, DeepSeek-R1 has a limited ability to update information, resulting in outdated information and conclusions. At the same time, DeepSeek-R1 has a poor ability to track the trajectory of technology development and usually provides irrelevant answers. The "Remarks" column in Tables 3 and 4, which includes conversations with DeepSeek-R1, contains comments and corrections that are relevant to the authors.

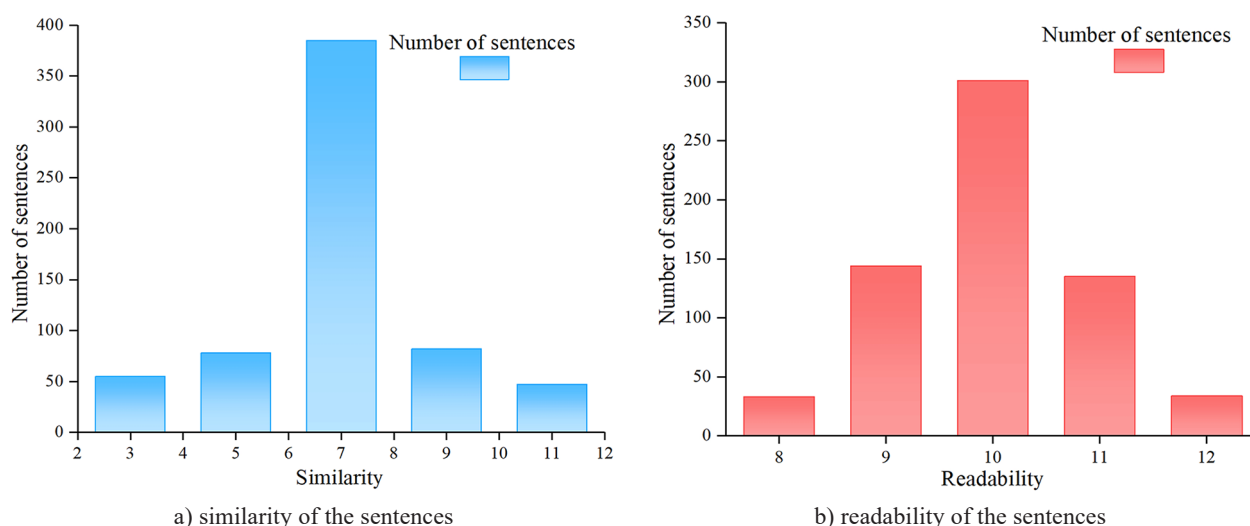


Figure 3. Similarity and readability of the sentences answered by DeepSeek-R1.

Table 3. Ambiguous statements by DeepSeek-R1.

Question	DeepSeek-R1's statements	Remarks
16. How to maintain the filtration performance of wood ceramics during recycling?	Maintaining the filtration performance of wood ceramics during recycling requires the optimisation of a balance of process parameters, with a focus on maintaining the stability of active sites and pore connectivity on the surface of the material. Selective cleaning or low-temperature regeneration treatments can restore the retention capacity to a certain extent, but the recycling program needs to be designed with specific contaminant types in mind.	The maintenance of the filtration performance during wood-ceramic recycling relies on the pyrolysis temperature control and chemical attack minimisation, with an emphasis on maintaining the inherent porosity (20-200 μm) of the carbonised wood skeleton and the density of the oxygen-containing functional groups on the surface. A two-stage regeneration process is suggested: first thermal oxidation at 400-500 $^{\circ}\text{C}$ in an inert atmosphere to remove organic clogging, followed by the restoration of the surface active sites by a dilute acid treatment (e.g., 0.1 M HNO_3), which can result in a BET specific surface area recovery of $85 \pm 3 \%$ of the initial value [28-30].
27. What is the potential of porous ceramics for 3D printing? What are the special features of the pore structure design?	3D printing offers new ideas for customised pore networks in porous ceramics, with the potential for the digital construction of gradient pores and biomimetic structures. The printing process can realise the directional arrangement of macroporous-mesoporous multilevel structures through the interlayer stacking strategy and the composite use of pore-forming agents, but the contradiction between precision and shrinkage still needs to be coordinated.	DLP/SLS-based 3D printing technology demonstrates controllable pore structure advantages in porous ceramic preparation. By co-mixing pore-forming agents (e.g., PMMA microspheres) with a ceramic slurry, combined with print path planning, customised gradient structures with pore diameters ranging from 50-500 μm and porosities ranging from 40-80% can be achieved. Key features include: anisotropic pore arrangement (interlayer pore orientation angle $\leq 15^{\circ}$), and integrated moulding of curved runners, but it faces technical bottlenecks such as interlayer interfacial defects (approximately an 18-22 % reduction in the compressive strength) and non-uniformity in the sintering shrinkage (anisotropic shrinkage 2-8 %) [31-35].
28. How to realise the self-cleaning function of porous ceramics? What is its technical mechanism?	The self-cleaning function of porous ceramics usually relies on the synergistic effect of the surface modification and micro- and nanostructures, such as the composite design of photocatalytic coatings and superhydrophobic surfaces. The technological mechanism involves the dual paths of physical adsorption inhibition and chemical decomposition enhancement, but the long-term stability is constrained by the bonding strength between the surface-modified layer and the substrate.	The self-cleaning function of porous ceramics is realised by surface nano-modification, and typical methods include: (i) sol-gel loading of the TiO_2 photocatalytic layer (thickness of 50-100 nm, grain size of 10-20 nm), which can degrade pollutants by generating $\cdot\text{OH}$ radicals using UV excitation; and (ii) construction of micro- and nano-hierarchical structured superhydrophobic surfaces (contact angle $> 150^{\circ}$) by CVD. The mechanism involves photocatalytic oxidation (quantum efficiency ≥ 0.25) synergised with Cassie-Baxter states, but there is a problem of coating flaking due to photocorrosion after long-term use (the contact angle drops to $130^{\circ} \pm 5^{\circ}$ after 50 cycles) [36, 37].
29. What are the differences in the pore distribution and properties of porous ceramics by different pore-forming agents (e.g., starch, polymer particles)?	The type of pore-forming agent significantly affects the pore morphology and mechanical properties of the ceramics, with starch-based pore-forming agents forming a closed-pore structure and polymer templates being more conducive to the generation of connected pores. Differences in particle size distribution and thermal decomposition properties lead to significant changes in the pore wall roughness and grain boundary strength after sintering.	The type of pore-forming agent has a significant effect on the pore structure: starch undergoes swelling-carbonisation during sintering (weight loss rate 70-80 %), forming irregular pores (pore size distribution of 20-50 μm) with predominantly closed pores (closure rate $> 60 \%$), which results in a reduction in the flexural strength to 45-60 MPa; whereas the thermal decomposition of PMMA spherical templates ($T_d = 300\text{-}400^{\circ}\text{C}$) produces connected open pores (pore connectivity. The thermal decomposition of PMMA spherical templates ($T_d = 300\text{-}400^{\circ}\text{C}$) produces connected pores (pore connectivity $> 85 \%$) with controllable pore diameters in the range of 10-200 μm , corresponding to bending strengths of 80-110 MPa. The pore-forming agent particle size distribution (span value < 1.2) directly influences the critical defect size and the Weibull modulus ($m = 8\text{-}12$) [28, 29, 38].

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Table 3. Ambiguous statements by DeepSeek-R1. (Continue)

Question	DeepSeek-R1's statements	Remarks
36. Based on the assumption of uniformity of the pore structure, how to derive the bending strength calculation model of sacrificial template ceramics?	Strength models based on ideal pore distribution are usually parameterised using the modified Gibson-Ashby equation with the introduction of pore orientation factors and wall thickness variation coefficients. The model needs to verify the reasonableness of the assumptions by reconstructing the real pore network by micro-CT, and the residual stress distribution is the main source of error.	The flexural strength model based on the assumption of pore uniformity can be expressed as $\sigma_f = \sigma_0 (1 - \phi)^n \exp(-kC_v)$, where σ_0 is the densified ceramic strength, ϕ is the porosity, $n = 1.5-2.0$ is the empirical exponent, C_v is the coefficient of variation of pore volume, and $k = 0.8-1.2$ is the stress concentration factor. The model needs to be corrected by combining the real pore distribution reconstructed by μ -CT (Voronoi tessellation analysis), and the spatial correlation between the local strain concentration and the maximum pore size ($d_{\max} > 200 \mu\text{m}$) is verified by the DIC technique, and the prediction error can be controlled within $\pm 15 \%$ [32, 39].
37. What is the material cost of the sacrificial template method? How can the cost be significantly reduced by optimising the template material?	The cost of sacrificial templates depends on the complexity of the template preparation and sintering efficiency, and the substitution of natural polymers for traditional polymers can reduce the raw material cost. The economics can be further optimised by template reuse technology or the <i>in situ</i> generation strategy, but the template strength needs to be balanced with the stability of the pore-making effect.	The cost of the sacrificial template method is mainly composed of template materials (35-50 % of the total cost) and the energy consumption for removal (20-30 % of the total cost). The use of biomass templates (e.g., rice husk, cellulose) can reduce the feedstock cost by 60-70 %, and the combination of gradient pyrolysis process (heating rate $\leq 5 \text{ }^\circ\text{C}/\text{min}$) can reduce the removal energy consumption by 40 %. Further optimisation requires the maximisation of the template efficiency per unit volume (pore/template volume ratio > 5) through template topology optimisation (finite element pore simulation), but needs to balance the contradiction between the template removal rate ($> 98 \%$) and the matrix densification degree (relative density $> 92 \%$) [38, 40, 41].
38. Is it possible to use natural porous materials (e.g., wood, plant fibres) as sacrificial templates to prepare ceramics? What are the mechanisms and potential problems?	Natural porous materials have unique structural biomimetic advantages as biotemplates, and the mechanism involves the carbon skeleton generated by lignin pyrolysis to guide the ceramic phase deposition. The main challenges are to address crack propagation due to the difference in the coefficients of thermal expansion of the organic-inorganic phases and the uncontrollable sintering shrinkage of the biostructures.	The preparation mechanism of wood-derived ceramics involves the lignin pyrolytic carbon skeleton (500-800 $^\circ\text{C}$ cleavage) guiding the sol-gel penetration of oxide precursors (e.g., TEOS) to form a β -SiC/SiO ₂ complex-phase structure by sintering. The main problems include: (i) anisotropic shrinkage of the cellulose (6-8 % in the axial direction vs. 15-20 % in the radial direction) leading to cracks; and (ii) metal impurities (K, Ca content $> 1 \text{ wt.}\%$) causing abnormal grain growth. Solutions include pre-impregnation with boric acid (to reduce the melt viscosity) and pulsed current sintering (to suppress elemental segregation) [30, 38, 40].
44. What is the fatigue performance of sacrificial template ceramics under cyclic loading? How does its failure mechanism differ from that of dense ceramics?	The fatigue failure of sacrificial template ceramics under cyclic loading is characterised by progressive pore consolidation, which is different from the sudden brittle fracture of dense ceramics. Its damage evolution is dominated by the stress concentration in the maximally connected pores, and the crack extension path is regulated by the pore topology, but the fatigue life prediction model has not been perfected.	Fatigue failure of sacrificial template ceramics shows three stages: (i) microcracks sprout in the pore necks within 10^3 cycles ($\Delta K^{\text{th}} \approx 1.5 \text{ MPa } \sqrt{\text{m}}$); (ii) crack bridging and branching occur in 10^3 - 10^5 cycles ($da/dN = 10^{-8}$ - 10^{-6} m/cycle); and (iii) the final fracture is caused by the critical stress intensity of the largest pore clusters (equivalent diameters $> 50 \mu\text{m}$) factor ($K_{\text{IC}} \approx 2.8 \text{ MPa } \sqrt{\text{m}}$) controls. The fatigue life dispersion ($\text{COV} = 25\text{-}35 \%$) is significantly larger compared to dense ceramics (sudden fracture, steeply decreasing S-N curve) and requires the modified Paris formula: $da/dN = C(\Delta K)^m / (1 - \phi)^p$, where $p = 2.3\text{-}3.1$ is the pore sensitivity index [32, 39].

Table 4. Incorrect or inaccurate statements given by DeepSeek-R1.

Question	DeepSeek-R1's statements	Remarks
6. Where were the first wood ceramics developed?	First synthesised by the American Ceramic Society in the 1960s by carbonising plant soil simulants.	The first wood-based ceramics (also known as “biomorphic ceramics”) were developed in Japan in the early 1990s. A team of researchers at Kyoto University carbonised a wood template through a controlled pyrolysis process, converting its natural cellulose structure into a porous carbon precursor, which was subsequently infiltrated with silicon or metal oxides to form a ceramic composite. The technique utilises the inherent multistage pore structure of wood and successfully replicates its microscopic characteristics [28].
7. How stable is the filtration efficiency of wood ceramics?	Its filtration efficiency is due to the imbalance of surface charge caused by hydroxyl pyrolysis, and the decay rate reaches 80 %/h after 100 °C.	The stability of the filtration efficiency of wood ceramics depends on the integrity of its structure under operating conditions. It has been shown that its efficiency decay is less than 5 % below 600 °C due to the presence of a rigid carbon-silicon carbide network; however, oxidative pore closure above 800 °C leads to performance degradation. In long-term use, the cycling of humidity and particulate loading triggers micro-cracking and localised clogging, which degrades the efficiency by 10-15 % [29].
11. How to improve the high temperature filtration stability of wood ceramics?	The addition of calcium oxide nanoparticles induces a phase transition in cellulose to form a calcite synergistic structure with lignin.	Strategies to enhance the high-temperature filtration stability of wood-based ceramics include (1) introducing refractory coatings (e.g., SiC nanolayers prepared by chemical vapour-phase infiltration) to inhibit oxidation, (2) doping zirconia to enhance thermal shock resistance, and (3) optimising the pyrolysis rate of the carbonisation stage (2-5°C/min) with a gradient sintering process (2 h of holding time at 1350 °C) to improve the pore wall crystallinity and reduce the thermal deformation [28, 30, 38, 42].
13. What is the electrical conductivity of wood ceramics compared to porous ceramics?	Carbonised lignin produces graphene-like conductive channels with conductivity up to 10^2 S/m, which is six orders of magnitude higher than porous ceramics.	The lignoceramics exhibited high electrical conductivity (10^2 - 10^3 S/m) due to the residual carbon-based conductive network, which was significantly better than that of conventional porous ceramics (10^{-10} - 10^{-6} S/m). The connected carbon skeleton formed by lignin carbonisation provides percolation channels, whereas oxide-based porous ceramics need to be doped with conductive phases (e.g., metal particles) in order to be electrically conductive [37].
20. How to prepare high-strength porous ceramics? What are the key process parameters to be controlled?	Microwave plasma sintering was used with the key parameters of power density > 5 kW/mm ³ and helium partial pressure $\leq 10^{-3}$ Pa.	The preparation of high-strength porous ceramics requires the foam gel injection moulding method, and the key process parameters include: (1) slurry rheology control (45-55 vol.% solids, 1-2 Pa-s viscosity); (2) pore-forming agent particle size distribution (20-200 μ m); (3) bimodal particle grading (70 % coarse particles + 30 % fine particles); (4) sintering regime (heating rate $\leq 3^\circ\text{C}/\text{min}$, peak 1600-1700 °C). Pressure-assisted sintering (10-20 MPa) promotes the formation of inter-particle necks and enhances the strength [31, 39, 43].
22. Does high porosity lead to a significant decrease in the mechanical strength of porous ceramics? Why?	At porosity > 60 %, the micropores triggered the dislocation pinning effect and the Vickers hardness inversely increased by 12 %.	High porosity (> 60 %) usually leads to an exponential decrease in the mechanical strength ($\sigma \propto (1 - P)^n$, $n = 4-6$), with pores acting as stress concentration points to initiate brittle fracture. However, the loss of strength can be mitigated by the pore structure design: oriented laminar pores (e.g., freeze-cast Al_2O_3) reduce the strength by only 40 % at 75 % porosity; the addition of fibre-reinforced phases, such as SiC whiskers, bridges the pores and inhibits crack propagation [38, 39].
24. Are porous ceramics self-healing? How to improve its self-repair performance through material design?	Dependent on the flow of B_2O_3 glass phase at high temperature to realise self-healing, doping 10 wt.% Na_2SiO_3 can reduce the healing temperature to 400 °C.	Porous ceramics are not self-healing due to the brittle nature of covalent bonding, but can be realised through the material design: (1) the encapsulation of self-healing agents (e.g., Si/SiO ₂ microcapsules), and oxidation of the crack to generate a glassy phase to fill the defects; (2) the design of oxygen-deficient phases (e.g., non-chemically stoichiometric SiAlON), and the realisation of finite repair by migration of the glassy phase at > 1200 °C [44].

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Table 4. Incorrect or inaccurate statements given by DeepSeek-R1. (Continue)

Question	DeepSeek-R1's statements	Remarks
35. What are the important applications of ceramics prepared by the sacrificial template method?	Used to prepare topological insulator ceramic films with template decomposition generating pores that bind Majorana fermions.	The ceramics prepared by the sacrificial template method have outstanding applications in catalytic carriers (TiO ₂ foam photocatalysis), bone scaffolds (β -TCP, 300-500 μ m interpenetrating pores), and permeable membranes (gradient Al ₂ O ₃ /mullite gas separation), etc., with the ability to replicate the precise pore structure to achieve zigzag degree tuning from 1.5 to 3.0 and the 15-150 m ² /g specific surface area design [45, 46].
42. Can biodegradable polymers be used to replace traditional template materials for ceramic preparation? What are the technical bottlenecks?	PLA templates need supercritical CO ₂ pre-treatment, otherwise residual carbon leads to stress corrosion cracks at the ceramic grain boundaries.	Biodegradable polymers (e.g., PLA, starch) replacing traditional templates have technical bottlenecks: (1) decomposition products (CO ₂ /H ₂ O) generate uncontrollable pores; (2) low residual carbon rate (< 5 %, compared to synthetic polymers up to 30-50 %) weakening the role of the carbon templates; and (3) a mismatch of rheological properties during slurry mixing. Improvement directions include the use of PLA-phenolic resin composite templates and temperature-controlled pyrolysis in a reducing atmosphere to maintain the pore morphology [47, 48].

Preliminary applications

The most central technological advantage of porous ceramics lies in their tuneable pore topology and cross-scale mechanical-functional synergy. For a long time, research has focused on porosity, pore size distribution and their quantitative correlation with the macroscopic properties of materials. However, traditional characterisation methods (e.g., SEM image analysis) still lack effective means to capture the dynamic response of 3D pore networks, a problem that is particularly prominent in high-temperature/stress coupling environments. While DeepSeek-R1 demonstrates limited fundamental theory and the current state of research in porous ceramics, the overall accuracy of its response is considered acceptable. This section will continue to explore the application of DeepSeek-R1 to fit the ratio design, and filtration analysis.

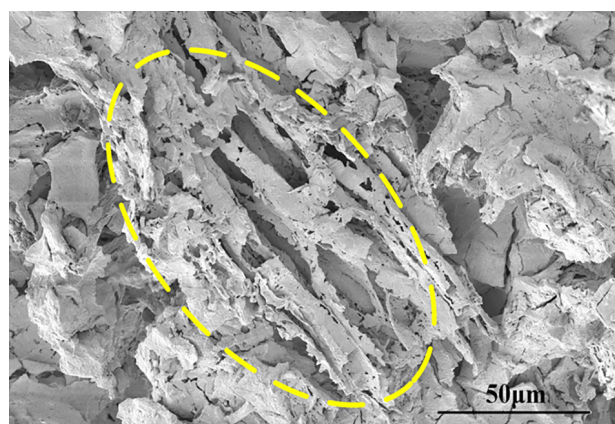
Image identification

The classical pore classification of APCBT is shown in Figure 4, and different pore types occur in

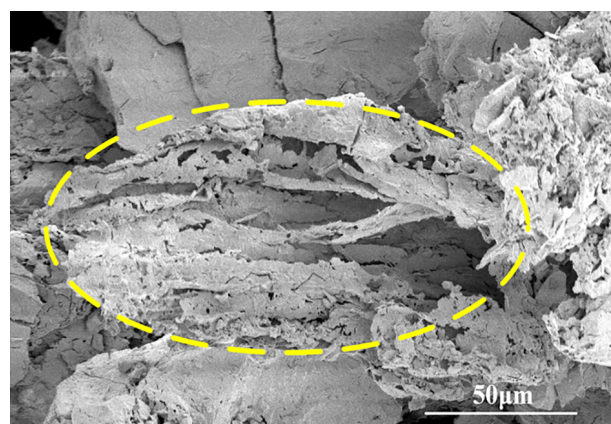
different preparation schemes [20]. Using DeepSeek-R1, an accurate pore analysis can be performed by human-computer interaction method as follows:

Step 1: DeepSeek-R1 has the function of uploading images or files with strong human-computer interaction. In the DeepSeek-R1 interface, the user uploaded six representative porous APCBT images in Figure 4 in turn, which embody the porous nature of APCBT. Subsequently, the user presented that these six images are typical porous APCBT images. The question "What is the difference between the pores in these six images?" was asked. DeepSeek-R1 demonstrated its ability to accurately identify these images and provide an accurate relative qualitative analysis of the pore size, pore type and distribution for each image.

Step 2: Building on Step 1, this study continues to analyse the distribution of the pores. First, Figure 5a was imported into DeepSeek-R1, where



a) tubular pores



b) tubular pores

Figure 4. Typical pore forms of APCBT. (Continue on next page)

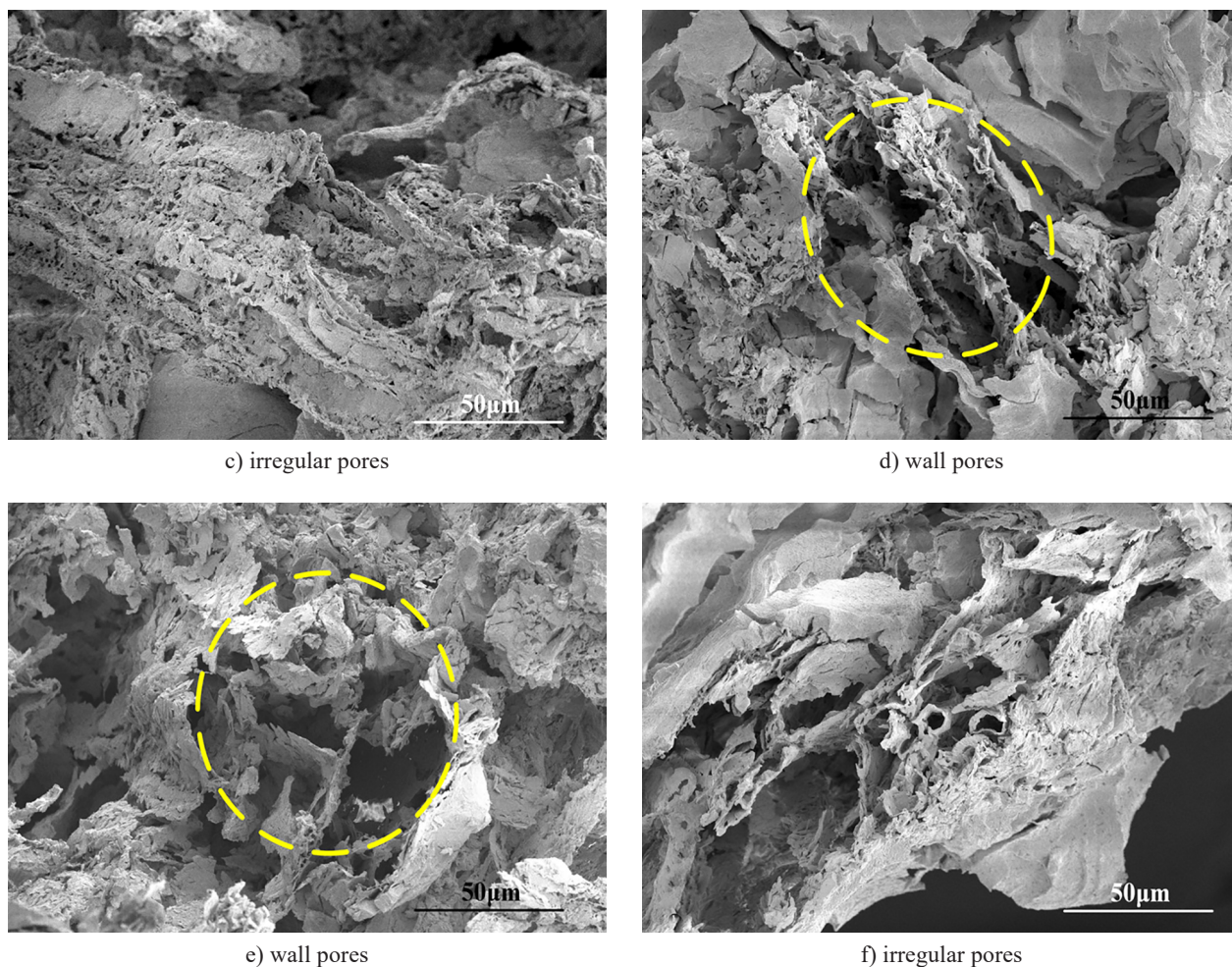


Figure 4. Typical pore forms of APCBT.

the labelled lines graphically define “pores”, a task undertaken manually by the authors. Subsequently, a question was posed to DeepSeek-R1: “How many pores similar to Figure 5a are there? Can we locate the pores based on the pore types in the above figure?” DeepSeek-R1 is equipped with image recognition and coded learning capabilities to locate references and characterise the pores using textual descriptions, as shown

in Figure 5. The authors located the labelled pores based on the simulated coordinates of DeepSeek-R1, as shown in Figure 5b, and almost all of the pores were characterised (wall pores in red circles, tubular holes in yellow circle). DeepSeek-R1 can analyse the pore distribution in Figure 4a-4f based on the scale, as shown in Figure 6. This result is approximately the same as the calculation of the pores after the binarisation of the SEM images.

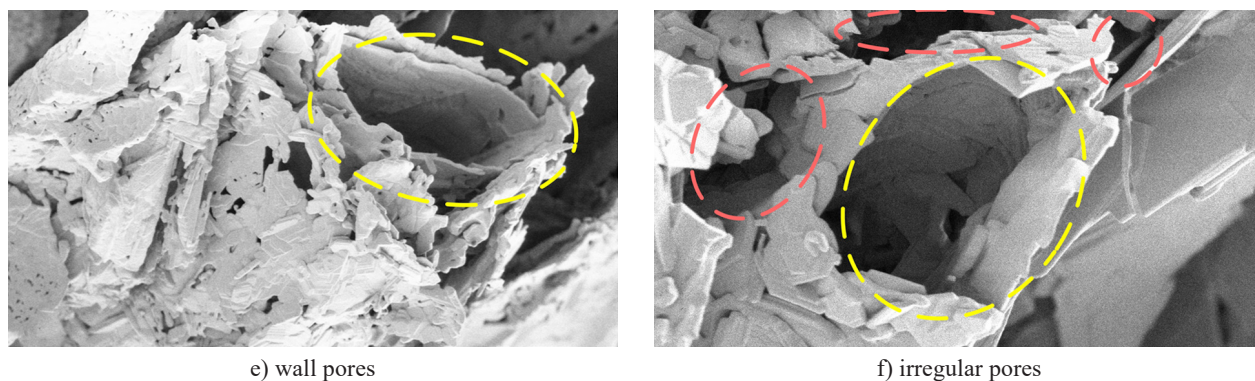


Figure 5. Pore identification.

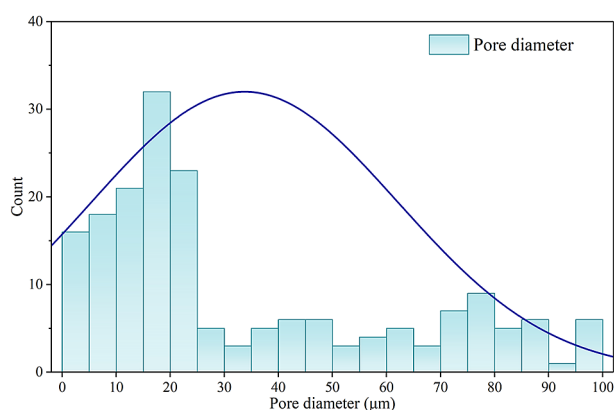


Figure 6. Distribution of the pore diameters.

Mix design support and filtration performance

As a typical filtration material, the filtration performance of porous ceramic materials is highly tuneable. This multi-factor tunability provides a favourable application scenario for DeepSeek-R1. Based on the training model, the authors corrected inaccuracies and errors and went on to ask: “Please provide various material ratios and fill rate indices for APCBT with a filtration efficiency of 85 %”. In response, Figure 7 shows a precursor blend ratio design option provided by DeepSeek-R1.

Given that filtration efficiency is not only related to the material ratios and filler rates, but also to the specifics of the porous ceramic firing process (e.g., firing temperature and duration), the biotemplate curing methodology, and the operator’s level of experience, it is not possible to directly falsify the answer to this question. Based on the existing relevant standards and literature, it can be inferred that the mixing ratios of these precursor materials have considerable credibility and validity. This can provide guidance to researchers and engineers for the initial preparation of porous ceramic precursors. Based on the feedback from this DeepSeek-R1 reaction, the precursor mixing ratios as well as other parameters can be adjusted according to laboratory conditions to obtain a compliant precursor mixing design.

Experimental predictions were made using DeepSeek-R1 in a variety of ways, including with the porosity and pore size distribution, ceramic matrix composition, pore-forming agent content, and sintering process parameters. The prediction results are shown visually

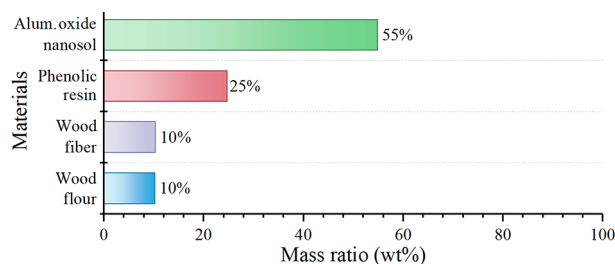


Figure 7. DeepSeek-R1 designed APCBT precursor ratios.

in Table 5, where the rectangular zones indicate the expected performance metrics obtained from this systematic predictive analysis. Experimental validation of this particular structural design was carried out by measuring the filtration efficiency, pore uniformity and structural stability. These measurements are also labelled in the graphs, indicating a high degree of agreement with the predicted results.

Table 5. APCBT filtration efficiency as analysed by DeepSeek-R1.

Wood flour (wt. %)	Wood fibre (wt. %)	Filtration efficiency (%)
25	75	80.21
35	65	85.35
50	50	88.67
65	35	90.26
75	25	85.26

In addition, the filtration efficiency of APCBT when varying the mass ratio of wood fibre to wood flour was also evaluated using DeepSeek-R1, and the results are shown in Figure 8. Several existing test methods can be used to quantify the filtration performance [49-53], and DeepSeek-R1 provides a real-time pore size optimisation strategy by analytically simulating these quantification methods.

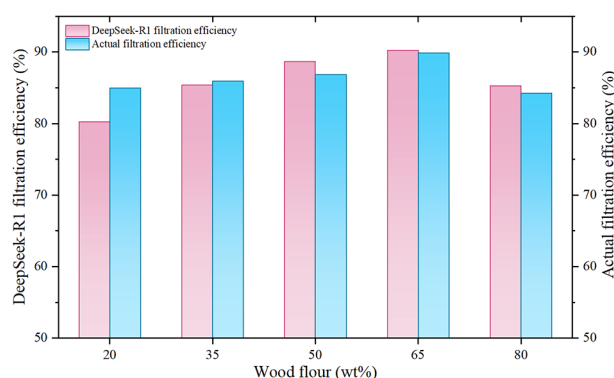


Figure 8. Comparative analysis of the predicted and actual outcomes in APCBT.

In exploring the mechanisms by which the structure of porous ceramics affects the filtration efficiency, the authors posed a key question to DeepSeek-R1: “What are the technological ways to optimise the filtration efficacy of porous ceramics?” Possible options include: tuning the ratio of porosity to the pore size distribution; introducing functional additives (e.g., nano-coatings, gradient-structured materials); using sintering aids (e.g., dispersants and pore orienting agents); optimising the sintering process parameters to promote pore connectivity; and constructing three-dimensional through-pore structures by adjusting the pore-making agent content.

The filtration performance of porous ceramics is limited by a number of key parameters, such as low porosity ($< 0.25\%$), high content of sintering aids and functional phase materials. In their quest to improve the dynamic filtration efficiency, scholars have noted the energy bottleneck of the high-temperature sintering process, as well as the technological limitations of conventional pore-forming agents in terms of pore size uniformity and structural stability [54-56].

Nanocoating technologies for pore surface modification are well established, and the efficacy of gradient-structured materials is being systematically evaluated due to their hierarchical filtration properties. While emerging technologies (e.g., biomimetic structural design) may not be fully covered by the existing schemes, they still provide an important theoretical basis for optimising the performance of porous ceramics [57].

In the experimental validation phase, eight filtration performance characterisation schemes were obtained with DeepSeek-R1. Although some of these schemes (e.g., zeta potential testing) were weakly correlated with the core filtration parameters, mainstream methods including permeate flux testing, retention analysis, and pressure drop assessment were employed. For the study of porous structure evolution, the model recommended seven characterisation techniques: pressed mercury, gas adsorption analysis, X-ray tomography, scanning electron microscopy, and micro-CT, which form a standardised test system for pore structure evolution.

Deficiencies in the compressive strength and DeepSeek-R1 analysis

As shown in Figure 9, based on the error analysis of the DeepSeek-R1 model prediction results, it was found that the model-predicted compressive strength of APCBT porous ceramics significantly produced large errors with the experimental measurements. This systematic error may stem from the fact that the model does not adequately consider the mechanism of alumina microstructure evolution triggered by the increase of the wood flour ratio. As the amount of wood powder increases, the elevated CO/CO_2 gas flux from the pyrolysis of the pore-forming agent leads to (1) accelerated migration of alumina

particles during sintering, resulting in the formation of localized high-density agglomerates, and (2) increased tortuosity of the pore channels, which contributes to a shift in stress distribution from homogeneous load-bearing to a multistage dissipation pattern [58, 59]. This microstructural synergistic effect resulted in an anomalous increase in the actual compressive strength, which was predicted by the existing model based on the linear regression relationship of the porosity-strength only, without incorporating the non-linear correction terms for particle agglomeration and stress redistribution. It is recommended that the prediction accuracy of complex sintering behaviour be improved in the subsequent model optimisation.

CONCLUSION AND OUTLOOK

DeepSeek-R1 demonstrates the potential to revolutionise the traditional materials research and development paradigm through its multimodal AI algorithm fusion. This study focuses on the technical understanding and innovative application of this model in the optimisation of porous ceramic filtration systems, and constructs a new paradigm of material design based on intelligent algorithms, focusing on gradient pore ceramics and 3D connected pore structures. Experimental data show that DeepSeek-R1 can not only effectively avoid the risk of patent similarity of technical solutions (similarity index is less than 11 %), but also demonstrate the ability to generate innovative process solutions that meet the requirements of technical specifications. However, the study also reveals the limitations of the model in analysing complex material constitutive relationships and providing cutting-edge technological details.

Overall, DeepSeek-R1 demonstrates significant value in porous ceramics, with core functionality covering the quantitative analysis of the pore structure, optimisation of material formulations, and real-time evaluation of production energy consumption. However, the following key limitations exist:

- The model's response to issues involving undisclosed patented technologies, novel pore-making processes, or academic controversies is technologically reserved, and a fuzzification strategy is often used. When analysing the cross-scale structure-property correlation of the porous ceramics shown in Figure 4, the model's knowledge of the intersection of sintering dynamics and pore topology is superficial, making it difficult to construct an in-depth theoretical model.
- The output content has redundant information, lacks mathematical descriptions of key process parameters, and has a lag of 3-5 years in tracking the technological trajectory.
- When combined with SEM image analysis, the model can realise an intelligent quantification of the pore structure and permeability prediction, and provide real-time process optimisation suggestions.

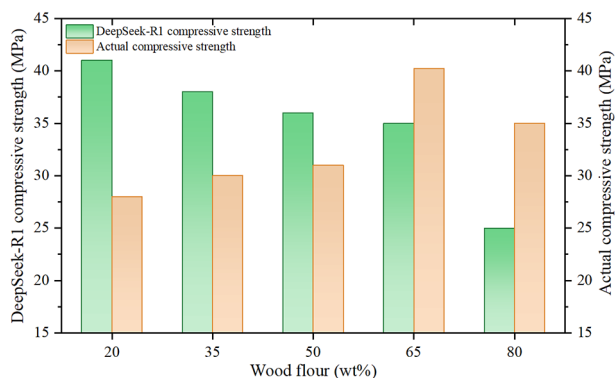


Figure 9. Compressive strength of APCBT.

In response to the technological upgrading needs of the porous ceramics industry, this study proposes the following intelligent research and development directions:

- a) Performance parameter correlation analysis: using DeepSeek-R1 to mine the implicit correlation laws between the filtration efficiency, permeation flux and parameters such as the porosity and pore size distribution.
- b) Cross-scale structural design: optimise the gradient pore size design based on the model, and develop a bionic pore structure with adaptive filtration characteristics.
- c) Intelligent detection of manufacturing defects: integrating machine vision technology to realise the online identification of sintering defects and traceability of process parameters.
- d) Service life prediction: constructing structural degradation models for porous ceramics under complex working conditions and evaluating their sustainable filtration cycles.

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