



Review

A review of pore-forming agents on the structures, porosities, and mechanical properties of porous ceramics

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Abstract: This review article provided a thorough examination of porous ceramic materials, concentrating on production, characteristics, and the involvement of pore-forming agents. The primary objective of this research was to evaluate the effects of various ceramic materials and pore-forming agents on the structure, porosity, and mechanical characteristics of porous ceramics. The study's scope included a thorough investigation of key sources of literature, such as academic publications, review articles, and industry reports, to provide a comprehensive understanding of porous ceramic technology. According to the literature review, the selection of ceramic material and pore-forming agents has a significant influence on the pore size distribution, porosity, and mechanical strength of porous ceramics. Various manufacturing methods, including foaming, sintering, and sol-gel procedures, were explored in terms of their influence on porous ceramic microstructure and characteristics. Furthermore, the study emphasized the need to optimize processing settings and select pore-forming agents to obtain the necessary qualities in porous ceramic materials. Overall, this review is useful for researchers, engineers, and practitioners who desire to learn more about porous ceramic manufacturing, characteristics, and applications.

Keywords: porous ceramic; pore-forming agents; fabrication methods; mechanical properties; thermal properties

1. Introduction

Ceramic materials have a long history of manufacture and treatment, yet they continue to attract the interest of researchers all around the world. Commercialization and technical advancement in ceramic materials have risen in recent years as chemical, mechanical, and thermal performance has improved [1]. A specific family of materials known as porous ceramics has high porosity, which bestows distinctive qualities including increased permeability, low density, and large surface area. These materials comprise a network of linked pores scattered across a ceramic matrix. These holes can range in size from less than 2 μm to more than 50 μm , and they can be either closed (isolated) or open (interconnected) [2]. The selection of pore-forming agents and ceramic ingredients greatly influences the final characteristics of the porous ceramics [3–10].

The requirement for materials that combine the advantages of porosity with the intrinsic qualities of ceramics, such as thermal and chemical durability, contributed to the creation of porous ceramics. Thermal insulation and filtration were the first main applications. The performance of porous ceramics has improved, and its variety of applications has increased throughout time due to materials science and engineering developments [11–17].

The development of building materials that help to lower building energy use is unquestionably of importance to society. The utilization of air conditioners for indoor cooling in both private and public buildings has become increasingly prevalent in recent years, particularly in nations characterized by warm climates, such as those in Asia. Power costs for buildings have experienced a significant increase in recent years, and this upward trend is expected to persist in the future. Anticipated projections suggest that the rise in electricity consumption for cooling is poised to become predominant in buildings by 2050, exhibiting a cumulative growth rate exceeding 75%. Moreover, the escalation in power consumption aligns with a concurrent surge in CO₂ emissions [18–20].

A large surface area is shown by porous ceramics because of their interconnected pore structure. This property is especially useful for processes like adsorption and catalysis that call for a large number of surface contacts. More active sites for chemical reactions or the adsorption of molecules are made possible by the larger surface area, which improves the effectiveness of adsorbents, catalytic converters, and other functional materials. These ceramics have a low density due to their high porosity, which makes them lightweight materials. This feature is helpful in areas like aerospace, automotive, and transportation where weight reduction is crucial without sacrificing structural integrity. While keeping the essential mechanical qualities, lightweight porous ceramics can lower the total weight of buildings and increase fuel economy. Overall, the purpose of this comprehensive review is to analyze the effects of different ceramic materials and pore-forming agents on the structure, porosity, and mechanical properties of porous ceramics.

2. Ceramic materials

Ceramic materials are frequently made from clay and other natural minerals, as well as chemically processed oxide, nitride, or carbide crystal powders, such as silicon and carbon (silicon

carbide, SiC), silicon and nitrogen (silicon nitride, Si₃N₄), and aluminium and oxygen (alumina, Al₂O₃). Ceramic materials encompass inorganic, non-metallic compounds and the resulting products derived from them, which can exhibit crystalline or partially crystalline structures.

Crystalline ceramic materials are non-metallic inorganic compounds with a structured atomic arrangement. These materials are broadly employed in numerous industrial, technical, and scientific fields because of their desired qualities, which include outstanding strength, durability, chemical inertness, and thermal resistance. Crystalline ceramics have a very organized atomic arrangement, with atoms grouped in a repeated three-dimensional lattice arrangement [21]. This regular structure contributes to their identity.

Crystalline ceramics exhibit elevated hardness, exceptional thermal and chemical resilience, minimal electrical and thermal conductivity, as well as resilience to wear and corrosion [22]. These attributes represent the desirable qualities inherent to ceramics. Commonly, these materials are manufactured either through an *in situ* reaction or by compressing powder into a cohesive mass, followed by sintering at elevated temperatures to attain the desired shape and solidity [23]. Instances of crystalline ceramic materials comprise alumina, zirconia, silicon carbide, sapphire, and ceramics with piezoelectric properties.

Ceramic-based materials are a broad and adaptable family of materials recognized for their distinct set of characteristics and many uses. These materials are made of inorganic substances, which are often non-metals. High melting point, high strength and hardness, strong oxidation and corrosion resistance, minimal thermal expansion, good stability, the capacity to operate at high temperatures, and electrical insulating qualities are some of its distinguishing characteristics [24]. These extremely desired qualities enable them to perform better in many applications than materials based on metal or polymers, particularly under difficult operating situations like higher temperatures or corrosive environments. Notwithstanding their benefits, ceramics' brittleness restricts their ability to withstand mechanical damage and creates significant challenges to their widespread technical uses [24].

Materials based on ceramics are employed in a variety of sectors, including biomedicine, electronics, automotive, aerospace, and energy. Ceramic-based materials are categorized as follows depending on their composition, qualities, and uses:

1. Oxide ceramics: these types of ceramics are primarily made of metal oxides, including silica (SiO₂), alumina (Al₂O₃), and zirconia (zirconium oxide, ZrO₂). Good chemical resistance, electrical insulation, and thermal stability are provided by oxide ceramics. They have enormous potential for use in the production of biomedical implants, thermal barriers, electrical components, and refractories [25].

2. Nitride ceramics: metal nitrides such as silicon nitride (Si₃N₄), aluminium nitride (AlN), and boron nitride (BN) make up nitride ceramics. They have excellent strength, heat conductivity, and corrosion and wear resistance. Heat sinks, cutting tools, and electronic packaging all employ nitride ceramics [25].

3. Ceramics made of carbides: ceramics made of carbides of metals include titanium (TiC), tungsten (WC), and silicon (SiC). Their remarkable chemical stability, great heat conductivity, and extraordinary hardness are well-recognised. Wear-resistant parts, cutting tools, abrasives, and shielding materials are all made of carbide ceramics [26].

4. Ceramics made of silicates: earthenware, stoneware, and porcelain are examples of ceramics made of silicate compounds. These ceramics have strong heat resistance, electrical insulation, and

aesthetic qualities. They are made of clay minerals. Pottery, dinnerware, and architectural tiles are frequently made of silicate ceramics [27].

5. Glass ceramics: materials that blend glass and crystalline phases are known as glass ceramics. It is created by carefully regulated glass crystallization of a particular composition. A harmonious combination of transparency, strength, resistance to heat shock, and flexibility may be found in glass ceramics. They are used in dental remediation, electronics, and cookware [28].

6. Composite ceramics: composite ceramics are made up of several ceramic components combined with other elements, frequently metal or fiber. The strengths of each component are utilized to provide these ceramics with improved characteristics. Fiber-reinforced ceramics, for instance, have improved toughness and fracture resistance. Uses for composite ceramics include structural, automotive, and aerospace [29].

7. Bioceramics: these materials are made especially for use in biological fields. These include alumina-zirconia composites, bioglass, and hydroxyapatite (HA). Bioceramics demonstrate mechanical qualities that are suitable for live tissue, as well as biocompatibility and bioactivity. It is utilized in tissue engineering, bone grafting, and dental implants [30].

Materials based on ceramics are crucial to the creation and use of inorganic membranes [31,32]. Table 1 contains a list of properties for comparable ceramic materials. These characteristics are unique to each ceramic substance and have a considerable impact on the application and efficiency of ceramic components.

Table 1. Comparison of different ceramic materials with their properties.

Ceramic materials	Properties	Ref.
Aluminium oxide (Al ₂ O ₃)	Density (4.04 g/cm ³), flexural strength (~12 to ~33 MPa), elastic modulus (140–180 GPa), compressive strength (65.27 MPa), hardness (1440 kg/mm ²), fracture toughness (1.13 MPa·m ^{1/2}), thermal conductivity (15.4–35 W/mK), affordable cost, relatively abundant, and environmentally conscious.	[33–38]
Aluminium nitride (AlN)	Density (2.67–3.20 g/cm ³), thermal conductivity (171–174 W/mK), flexural strength (306.3–332.4 MPa), bending strength (456.6 MPa), fracture toughness (4.47 MPa·m ^{1/2}), high hardness, and its stability is solely preserved within a high-temperature environment under inert conditions.	[39–41]
Silicon carbide (SiC)	Density (3.21 g/cm ³), electrical resistivity (9.0 × 10 ⁻² –3.9 × 10 ¹ Ω·cm), thermal conductivity (2.3–31.4 W/mK), flexural strengths (8.1–32.9 MPa), flexural strength (592 MPa), hardness (28.3 GPa), elastic modulus (461 GPa), and fracture toughness (3.6 MPa·m ^{1/2}).	[42–45]
Silicon nitride (Si ₃ N ₄)	Density (2.689–5.221 g/cm ³), thermal conductivity (90 W/mK), flexural strength (861.34–953 MPa), and fracture toughness (3.6–10.64 MPa·m ^{1/2}).	[46–49]
Zirconia (ZrO ₂)	Flexural strength (162.40–285.04 MPa), fracture toughness (5.4–6.7 MPa·m ^{1/2}), elastic modulus (100–250 GPa), tensile strength (330 MPa), high-temperature resistance, wear resistance, and corrosion resistance.	[50–53]
Titanium carbide (TiC)	Density (4.91 g/cm ³), electrical resistivity (68 μΩ·cm), Young's modulus (410–510 GPa), flexural strength (24–390 MPa), melting temperature (3067 °C), boiling temperature (4820 °C), and thermal conductivity (21 W/mK).	[54]
Silicon dioxide or silica (SiO ₂)	Density (2.31 g/cm ³), compressive strength (65.27 MPa), thermal conductivity (0.066 W/mK), tensile strength (110 MPa), fracture toughness (5.21 MPa), hardness (575.5 HV), and crushing strength (565 MPa).	[55–58]
Mullite (Al ₆ Si ₂ O ₁₃)	Density (0.30–0.70 g/cm ³), compression strength (1.41–16.30 MPa), thermal conductivity (0.083–0.305 W/mK), and the mechanical performance is comparatively modest.	[59,60]
Lead zirconate titanate or PZT	Good dielectric and piezoelectric characteristics, optical absorption, and high-power handling capacity.	[61–65]
Magnesium oxide (MgO)	Hardness (8.25 GPa), fracture toughness (2.01 MPa·m ^{1/2}), Young's modulus (286 GPa), thermal conductivity (48.4 W/mK), and compressive strength (173.72–244.87 MPa).	[66–68]

3. Fabrication of ceramic products

Ceramic materials may be manufactured using a variety of procedures. Ceramic materials may be formed into a variety of shapes, including cylindrical fibers, tubes, and flat surfaces. Additionally, ceramic materials can go through four steps of treatment: material preparation, manufacturing, sintering, and finishing. Wet forming, dry forming, gel casting, thixotropic casting, direct foaming, and freeze casting are some of the procedures used to treat ceramic materials.

The gel casting process represents an inventive approach to producing porous ceramics. Through the free radical polymerization of organic monomers and cross-linking agents catalyzed by initiators, a three-dimensional crosslinked polymer forms, allowing the ceramic powder to maintain its shape. Figure 1 below shows the stages of the gel casting method. During sintering, the disintegration and volatilization of the polymer subsequently lead to the generation of pores. Porous structures can be created devoid of pore-forming agents, a technique applied across a range of ceramic material systems [69]. Yu et al. generated porous Si₃N₄ ceramics by augmenting the

monomer concentration (comprising acrylamide and N,N'-methylene bisacrylamide) within a ceramic suspension, without the incorporation of any organic additives, during the casting process of an acrylamide-based gel [70]. Gel casting should be done in safe and optimal conditions. Nonetheless, within industrial manufacturing, employing a protective atmosphere not only complicates control but also escalates production expenses. The appropriate amount of polymer can minimize the surface-splitting characteristic of the airborne green body while enhancing the fluidity of the suspension [71].

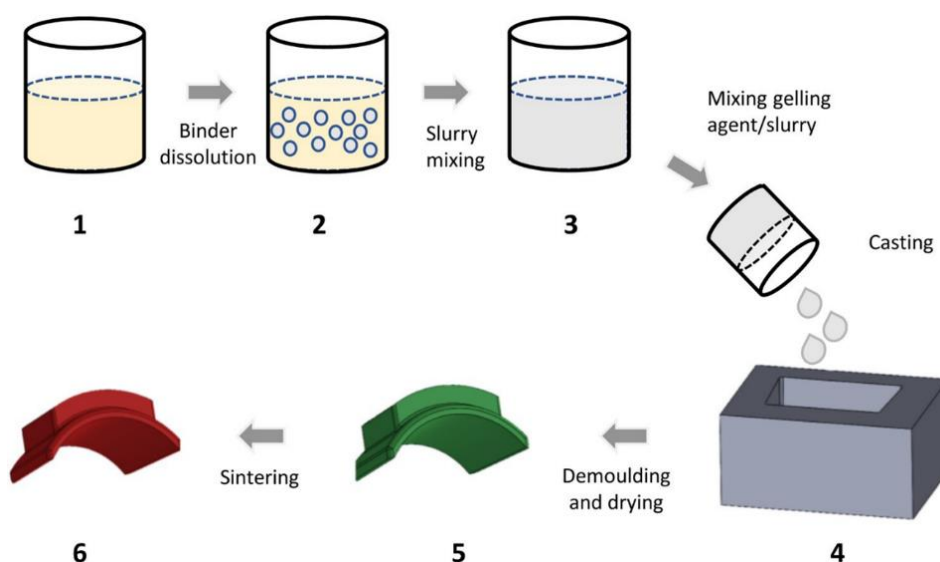


Figure 1. Stages of the gel casting method (Reproduced from Ref. [72] with permission).

Gel casting, a simple and trustworthy technology using *in situ* polymerization with natural monomers, is used to create porous ceramics with complicated forms and long-lasting foams [73–75]. Nevertheless, industrial gel casting poses challenges due to the toxicity associated with organic monomers [76]. Direct foaming produces porous ceramics by introducing air into the solution via a froth stabilizer and then drying and firing. Figure 2 below shows the schematic illustration of the direct foaming technique. Nevertheless, porous ceramics produced through direct foaming are susceptible to breakage owing to their weak mechanical properties [77]. Most porous ceramics featuring intricate shapes and high porosity are currently manufactured utilizing high-temperature foaming methods. In this manufacturing procedure, a foaming agent is mixed into the green body before being sintered at higher temperatures [78]. The gas created by the foaming agent rises and is either retained or expelled from the ceramic, resulting in porosity.

High-temperature foaming has been gaining popularity because it makes it possible to prepare porous ceramics that have substantially closed porosity. For instance, a porous ceramic exhibiting a porosity of 69% and a relatively high compressive strength of approximately 7 MPa underwent sintering at 980 °C [79]. At 1140 °C, a porous ceramic is formed with a small density of the bulk of 0.39 g/cm³ and a suitable flexural modulus of 2.4 MPa [80]. Nevertheless, the manufacturing cost associated with high-temperature foaming tends to surpass that of other methods, owing to its higher sintering temperature and longer heating time.

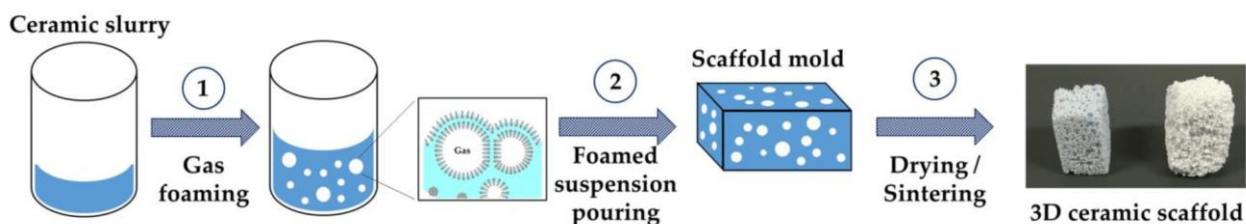


Figure 2. Schematic illustration of the direct foaming technique (Reproduced from Ref. [81] with permission).

4. Porous ceramics

Porous ceramics are material composites made up of a ceramic substrate and gases scattered within the matrix's porous structure [82–87]. It possesses the advantages of conventional ceramics, such as resistance to extreme temperatures, corrosion, and oxidation, as well as being lightweight, having a significant area of surface, and having a low coefficient of thermal conductivity [88–91]. Porous ceramics provide remarkable porosity, heat resistance, and sound absorbing qualities, among other benefits. These types of ceramics are essential in high-temperature production insulation [92] and high temperature purification [93], and they are also extensively applied in catalyst transporters, sound insulation, gas-sensitive substances, and biological materials [94–96]. Porous ceramics rely heavily on their porous structure to achieve their efficacy. The pore structure is crucial in the study of porosity ceramic materials and causes problems that can lead to inconsistencies and flaws in the finished product, such as uneven pore distribution, unwanted pore size, and trouble regulating pore production during manufacturing [83,94,97–99].

The advantageous properties of porous ceramics, including filtration and separation, thermal insulation, catalysis, biomedical applications, and acoustic applications, render them applicable across various industries. Furthermore, the utilization of these porous ceramics has seen an increase in artificial bone and tooth root materials, sensitive components, and sound-absorbing materials [9,100,101]. Figure 3 below shows how zirconia ceramics are used in biomedical applications for contemporary bone replacement and repair. Because of its exceptional strength, durability, and biocompatibility, it may be used in a range of medical implants, such as dental implants, hip and knee replacements, and other orthopedic applications [102]. The porosity in ceramic materials is controllable to a certain extent, allowing for a diverse range of pore sizes and distributions. This porosity can be customized or adjusted to fulfill specific requirements, such as the desired permeability, mechanical strength, and thermal or chemical resistance. Various techniques can be employed to produce porous ceramics with different morphologies and pore size distributions. Examples include firing polymer sponges impregnated with a ceramic slurry [103–105], solid-state sintering [106–108], sol-gel methods [109–113], replicating polymer foams through impregnation, and gel casting processes [114–117].



Figure 3. Diagram illustrating the latest uses of zirconia nanosystems (Reproduced from Ref. [102] with permission).

Porous ceramics exhibit distinctive properties that render them advantageous in various applications. High porosity is one such notable feature, with porous ceramics possessing a significant number of interconnected pores that facilitate the flow of gases and liquids. This heightened porosity contributes to the effectiveness of processes, such as filtration, absorption, and adsorption [113]. Porous ceramic materials are widely used in a variety of technologies, including thermal insulation systems, filtration membranes [9,118,119], bone tissue engineering [120–124], ceramic preform fabrication [125–127], and more. The utilization of porous ceramics in these applications is attributed to the synergistic interplay between the unique properties of ceramics and the development of the pore network [128].

For instance, mullite porous ceramics have gained widespread use in energy recovery, metal smelting, and the chemical industry owing to their exceptional qualities, including a high melting point, resistance to acid and alkali corrosion, substantial porosity, favorable mechanical properties, high-temperature resistance, and low thermal conductivity [129–134]. Figure 4 below displays the typical bi-layered samples seen from the top and side views by stereomicroscopy. This sample appears to be a standard arrangement of solid components encircled by four concentric rings with varying widths. Radial filaments bind the compact and ring components together, creating a structurally sound and appropriate arrangement. Concentric rings and radial filaments that enlarge with distance from the dense core connect to generate open pores in the shape of isosceles trapezoids [135].

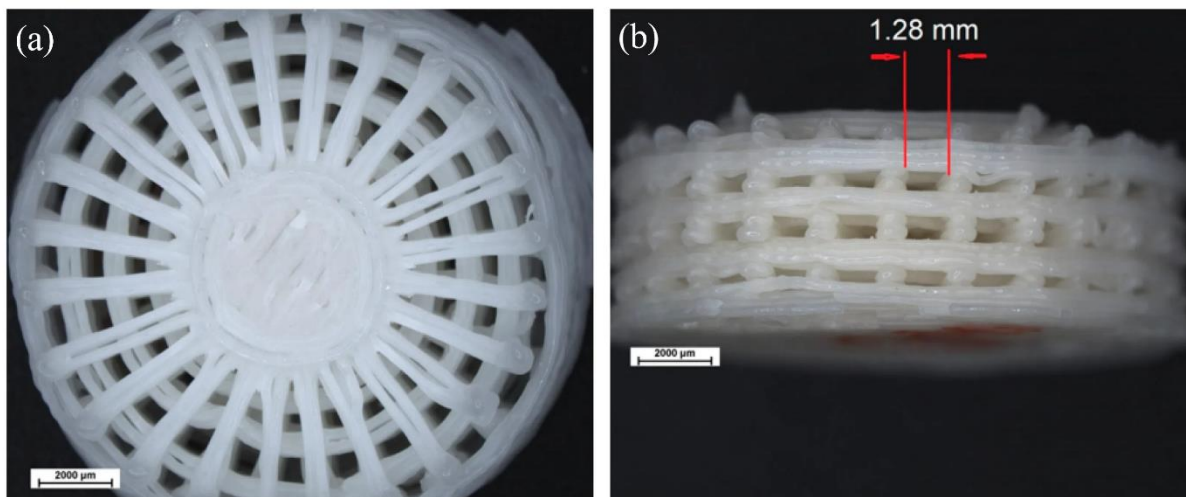


Figure 4. Typical bi-layered samples seen from the (a) top and (b) side by stereomicroscopy (Reproduced from Ref. [135] with permission).

Furthermore, porous ceramics commonly demonstrate exceptional thermal resistance, rendering them well-suited for applications in high-temperature settings. The thermal conductivity of porous ceramics is influenced by factors, such as composition, pore size and distribution, porosity, and the method of manufacturing [136–138]. Their capability to endure extreme heat, thermal shock, and thermal cycling without substantial degradation is crucial in industries like aerospace, automotive, and energy. Despite their porosity, porous ceramics maintain a relatively low density, resulting in a lightweight material. The mechanical strength of porous ceramics is determined by the critical crack size, where pores serve as the primary source of cracks [128]. Furthermore, porous ceramics are resistant to a variety of substances, including acids, bases, and organic solvents. This chemical stability qualifies them for application in harsh situations such as chemical processing, water treatment, and the pharmaceutical sector.

4.1. Categorization of porous ceramics

Porous ceramics are traditionally classified according to pore size, with three major categories: macroporosity (pores larger than 50 nm), mesoporosity (pores between 2 and 50 nm), and microporosity (pores less than 2 nm) [127]. The variety of uses for various texture characterization techniques in pore size research is shown in Figure 5, where each technique has a certain length range of applicability. Methods utilizing mercury intrusion porosimetry are commonly employed to assess the distribution of pore sizes. This methodology cannot establish the distribution of pore sizes of closed porosity; however, alternate methods, such as optical and technological examination of cleaned cross-sections, can be used for this purpose. The distribution of pore sizes illustrates the pore volume relative to pore size and is typically expressed as a percentage or derivative [2].

However, because various nations have varying rules governing the use of porous materials, this categorization criteria are not followed internationally [139]. Microporous ceramics feature very small holes, often less than 2 nm in diameter, and are widely utilized in gas separation, membrane technology, and as adsorbents for gases and liquids. Mesoporous ceramics have medium-sized pores,

often ranging from 2 to 50 nm, and are used in applications, such as molecular filters, adsorbents, and drug delivery systems, whereas macroporous ceramics have large holes, more than 50 nm. Microporous ceramics are commonly used in filtering, catalyst support, and structural applications [2]. Consequently, porous ceramics can be categorized according to distinct features, such as the chemical composition of the initial ceramic material, percentage of porosity, physical condition of the product, and refractoriness in relation to service temperature, purpose, and application area [140].

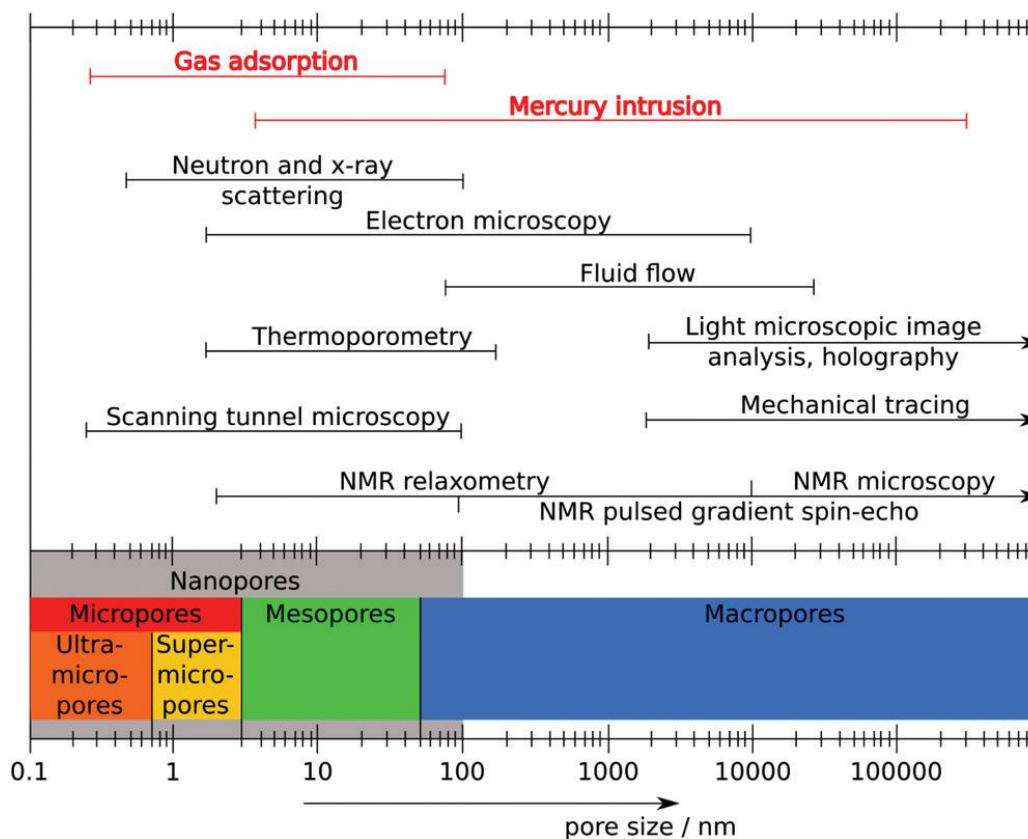


Figure 5. The pore size of a material determines whether it is macroporous, mesoporous, or microporous (Reproduced from Ref. [141] with permission).

5. Pore-forming agents

Based on Colombo P and Eom JH et al., several methods for producing porous ceramics have been documented. Pore-forming agents, in this instance, have demonstrated the ability to achieve significant degrees of porosity, as they naturally burn during the heating process to the firing temperature, creating a gap in the ceramic material [142,143]. The structure of these gaps will be determined by the pore-forming agent used and may thus be regulated by adjusting the absorption content and distribution of particle sizes.

Pore-forming agents, such as starch [144–149], graphite [150–154], lycopodium [155], sucrose [154,156–158], polymethyl methacrylate [159–164], polypropylene [160,165,166] and carbon black [167–172] have all been studied. Although starch is the most used pore-forming substance, it is rarely used when large holes are required, most likely due to its biological basis and

accessibility, the difficulties in maintaining the shape of the pores formed by starch combustion, and the tiny size of the particles. Various starch kinds are widely manufactured, ranging from 5 to 50 μm [173].

Polypropylene (PP) and polymethyl methacrylate (PMMA) are the primary porogen compounds used. PP was chosen because of its large-scale manufacturing and low cost, making it economically desirable for industrial applications [165]. A previous study on the thermal breakdown of PP found that it decays rapidly and completely, yielding a wide range of aromatic hydrocarbons [174–176]. There were no harmful gas pollutants recorded for PP [177–179]. PMMA was commonly utilized in ceramics as a porogen because it has a correct compromise of thermal characteristics that are suited for the specified purpose [135,163,180]. PMMA breaks down almost completely into monomers and fires at a very fast and steady rate [181,182].

Besides, the application of carbon black is wide due to its highly engineered nature. It is frequently employed as a filtration or strengthening agent in rubber, plastic, and other polymeric products. Carbon black has the potential to be used as a porous material in different applications, including ceramic applications. The pore-forming agent carbon black was used by [169] to create porous alumina ceramics with controlled porosity, and the compressive strength of the ceramic was significantly increased. Furthermore, carbon black particles penetrate the pores between the particles of ceramic as the carbon black content increases from 0 to 5 wt.%, resulting in a drop in conductivity but an improvement in mechanical characteristics [183]. Carbon black's ability to create a variety of pore sizes and distributions is one of the main benefits of using it as a porogen. Furthermore, carbon black can be safely used in porous ceramics due to its inertness and non-toxicity. Liu J et al. reported that burnt specimens were made porous by using carbon black with different carbon black contents, which was used as a porogen to produce their total porosity, closed porosity, and bulk density [168].

The structure, porosity, and mechanical characteristics of porous ceramics are greatly influenced by the pore-forming agent selection and the pore-formation technique. First, the structure of pore size and distribution in the ceramic matrix are largely dependent on the kind and size of the pore-forming agent. Larger polymer particles often result in larger holes, whereas smaller, more uniform pores are typically produced by finer particles or gas-release agents [184]. The connection of these pores is also significantly influenced by the process by which they originate. For instance, the loss of organic substances often causes linked holes to develop, which raises fluid permeability and mechanical stiffness.

Besides, the amount of pore-forming agent added to the ceramic combination has a significant impact on the end product's total porosity [185]. Increased porosity from greater amounts of these compounds can enhance characteristics like permeability and thermal insulation. Nevertheless, mechanical strength is sometimes sacrificed in favor of this higher porosity [185]. The kind of pore-forming chemical that is utilized also affects the morphology and shape of pores [186]. Although fibrous materials like cellulose make elongated holes, which might have varying effects on mechanical characteristics, spherical polymer particles usually produce circular pores, which provide a homogeneous pore shape [187].

In addition, the mechanical characteristics of ceramics are directly impacted by porosity. Normally, ceramic materials lose mechanical strength as their porosity increases [160]. However, by improving the distribution and shape of pores, this negative effect can be mitigated. For instance, a balance between porosity and mechanical strength can be achieved by combining appropriate pore-forming agents with non-oxide ceramics, for example, silicon carbide [188]. As porosity increases, so does the modulus of elasticity, or stiffness, of porous ceramics. To make sure the

material still satisfies the necessary mechanical performance requirements, this decrease must be carefully controlled. Furthermore, pores may serve as a stress concentrator, which increases the risk of fracture formation and progression under load. However, a carefully constructed pore structure can withstand fracture and boost ceramics' overall durability [189]. Porous ceramics may be strengthened further to boost their fracture resistance by the incorporation of strengthening processes, such as phase transition in zirconia, which will render them more dependable and long-lasting for a range of applications [190].

6. Characterization of porous ceramics

Table 2 below shows the porosity (open and closed), bulk density, and water absorption characteristics of burnt bodies of ceramic from different references. The results revealed that the pore-forming agent content may readily regulate the open porosity of the burned ceramic underlayer. The value rises as the quantity of the pore-forming agent increases, demonstrating a nearly linear connection. This discovery is in agreement with the results published by [191]. These researchers discovered that the apparent porosity and bulk density of the ceramic body were independent of the pore container size when graphite was used as the pore container. Liu R et al. studied the influence of different diameters of PMMA microspheres on the characteristics of porous yttria-stabilized zirconia ceramics [192].

Table 2. Comparison of porosity, bulk density, and water absorption in ceramic bodies.

Pore-forming agent (PFA)	PFA content (wt.%)	Open porosity (%)	Closed porosity (%)	Bulk density (g/cm ³)	Water absorption (%)	Ref.
PMMA	0–25	19.90–0.90	7.90–9.77	1.73–2.17	0.41–11.54	[135]
PP	0–25	22.96–3.12	7.59–9.55	1.63–2.12	1.47–14.11	[135]
Sawdust	0–15	17.53–0.90	8.13–9.77	1.90–2.17	0.41–9.23	[194]
PMMA	5–20	70.23–61.82	-	1.37–1.06	-	[193]
Cellulose fibers and pumice powder	5 and 10	3.9–0.3	-	2.35–2.36	0.1–1.7	[195]
Sodium dodecyl sulfate (SDS)	0–5	80.9–68.8	-	0.46–0.69	-	[196]
Soluble starch	0–8	7.57–11.91	6.47–8.55	2–3	-	[197]

Porogenic chemicals have the tendency to raise open porosity and decrease the number of closed pores in the sintering disc. The last factor may be attributed to increased pore connectivity. Consequently, the surface accessible in the porous layer expands, which might be advantageous for applications that demand the implantation of these voids. According to Liu R et al., below 20% PMMA incorporation, pores are mostly blocked, establishing a 20% PMMA relative permeability. Surprisingly, the data suggest a relative permeability of 10 to 15 wt.% PMMA incorporation [192].

Based on Chen A et al., Figure 6 depicts as various magnesium aluminium spinel hollow spheres (MASHSs) as pore-forming agent were added, changes were seen in porous ceramics' bulk density and apparent porosity [193]. Samples with a greater MASHSs concentration (HS0-HS10) showed thinner CA₆ plates, which means that the sample matrix saw less local volume expansion. The sample with reduced MASHSs concentration (HS20), on the other hand, has thicker CA₆ grains, which causes the sample matrix's local volume expansion to increase. Additionally, when fewer

MASHs are added, the sintering neck between two MASHS particles shrinks, which is inadequate to provide a strong link between the particles. Consequently, the sample's porosity is increased, as seen in Figure 6. Additionally, a larger degree of pore connection brought about by increased porosity enhances the sample's permeability and thermal insulation capabilities. All things considered, the microstructural study indicated that the inclusion of MASHs may result in the creation of thinner CA₆ plates, lower the sintering neck, and raise porosity and pore connectivity—all of which would improve the sample's physical characteristics [193].

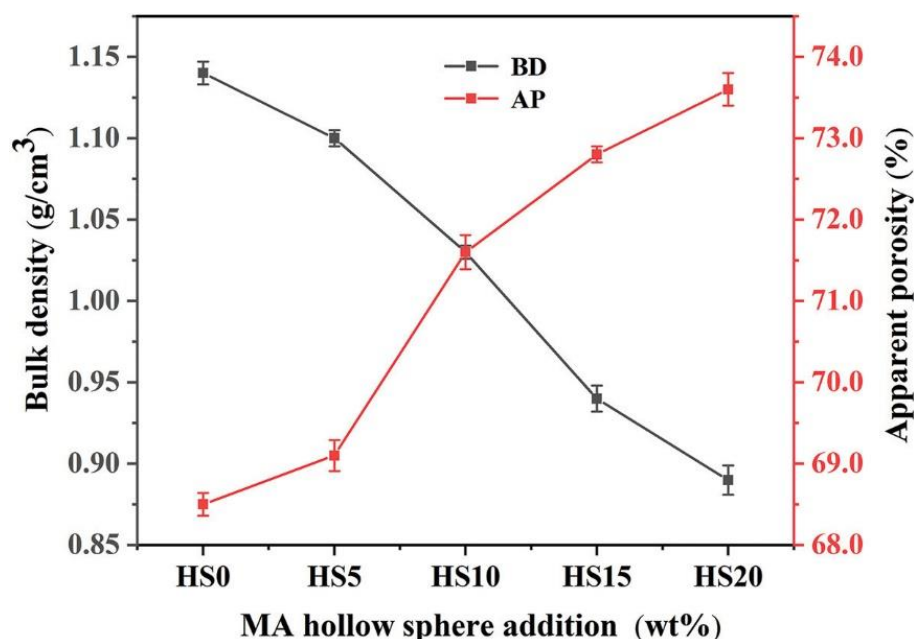


Figure 6. Adding various MASHS caused changes to the bulk density and apparent porosity of porous ceramics (Reproduced from Ref. [193] with permission).

Besides, based on Mahnicka-Goremikina et al., Figure 7 illustrates the Apparent porosity and water uptake of porous mullite ceramic modification with nano-WO₃ [161]. Lower apparent porosity of about $40 \pm 2\%$ and water absorption of approximately $25 \pm 1\%$ are seen in sample A1, which has a greater bulk density. Because yttria-stabilized zirconia (YSZ) (8 mol% Y₂O₃) influences the creation of a liquid phase that reduces porosity, this is the cause. Furthermore, samples A2, A3, and A4 exhibit porosity exceeding $63 \pm 1\%$ and water absorption of around $40 \pm 1\%$ [161]. Figure 6 indicates that comparably substantial water uptake values were achieved, well beyond the typical water absorption of stoneware constructed from porcelain tiles. As a result, mechanical strength was tested to assess the effect of porosity on the mechanical characteristics of ceramics.

Ceramic materials have different characteristics based on elements like pore-forming agents and sintering temperatures. Identifying the link between these characteristics is critical for optimizing material qualities for applications. Ceramic materials are synthesised utilising various pore-forming agents, such as starch, PMMA, CB, polyurethane, and dolomite show varied levels of control on pore size and distribution.

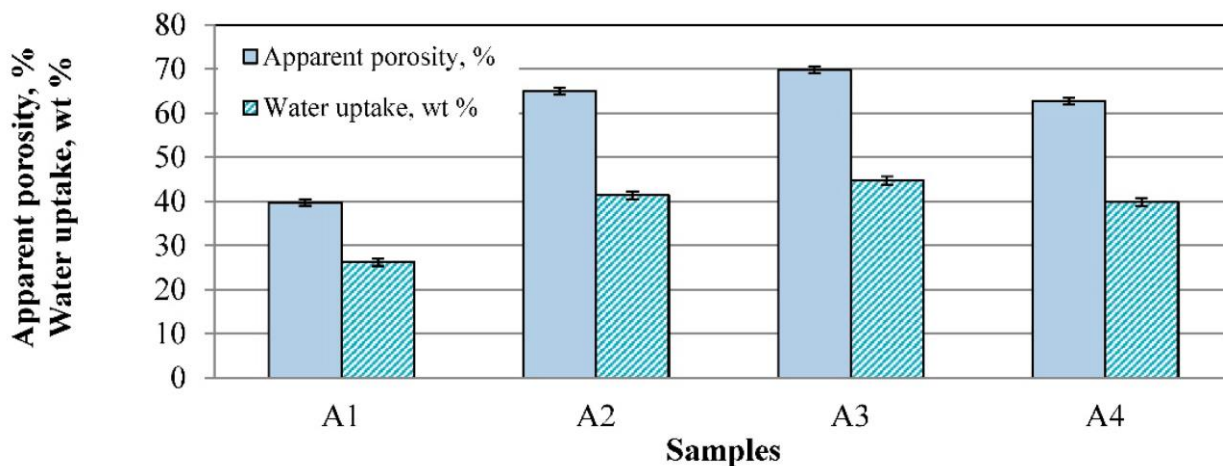


Figure 7. Apparent porosity and water uptake of porous mullite ceramic modification with nano-WO₃ (Reproduced from Ref. [161] with permission).

The sintering temperature considerably impacts the finished characteristics of the ceramic material. Elevated sintering temperatures typically result in a more compact structure characterized by decreased porosity. However, they may also promote grain growth and diminish mechanical strength. Reduced sintering temperatures, conducive to heightened porosity, could compromise mechanical characteristics while offering advantages in terms of energy efficiency and shorter processing duration [198].

Ceramic materials exhibiting finer pore sizes and reduced porosity typically exhibit enhanced mechanical strength, albeit at the expense of thermal insulation properties. On the other hand, materials with larger pores and higher porosity generally exhibit lower mechanical strength but offer superior thermal insulation properties [199]. The selection of the pore-forming agent and sintering temperature are critical in adjusting these variables to fulfill the requirements of a specific application.

The most immediate factor affecting a porous ceramic's mechanical performance is its porosity. The findings for compressive strength as a function of Si sludge replacement as pore forming agent quantity are displayed in Figure 8. Si01 has the maximum strength of 3.82 MPa, and as the quantity of Si sludge increases, the compressive strength declines till it reaches 2.11 MPa for the Si10 sample [200]. Microstructural features like pore size distribution, shape, and open-closed pore ratio have a significant impact on the mechanical properties of porous ceramics. Based on the creation of macropores resulting from an increasing quantity of Si sludge replacement, it was observed in this study that the porosity rose and the compressive strength dropped [200].

Since convection and radiation processes are only efficient at high temperatures, conduction is widely thought to play a key role in heat transmission [201]. The capacity of the material to withstand heat transfer through photon scattering by imperfections, such as order and pore faults, grain boundaries, or hopping vacancies, is essentially what controls reduced thermal conductivity [189]. It was successfully demonstrated that when air holes obstruct heat transmission, they significantly affect a material's thermal conductivity.

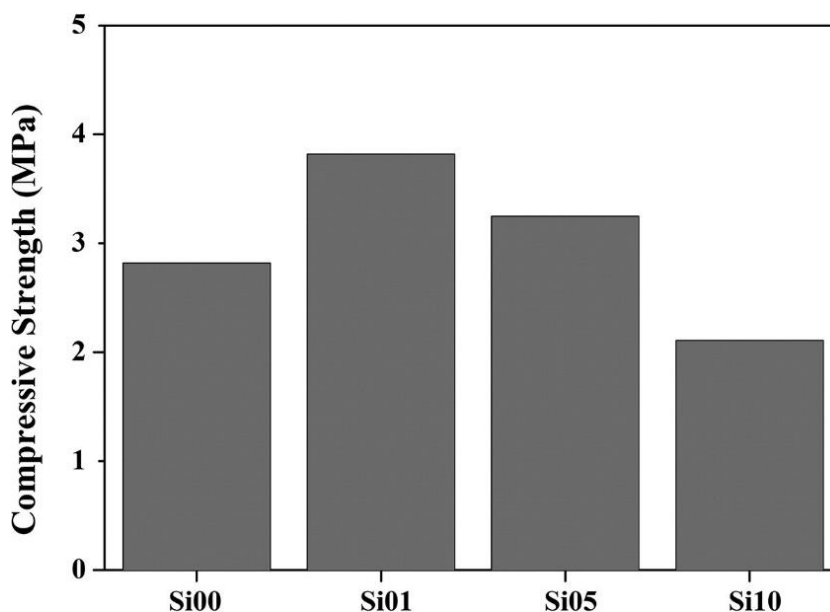


Figure 8. Porous ceramics with different replacement of Si sludge and their compressive strength. (Reproduced from Ref. [200] with permission).

The findings of thermal diffusivity (κ) and thermal conductivity (λ) with variations in the quantity of Si sludge replacement are displayed in Figure 9. In the 25–800 °C temperature range, the low thermal conductivity of 1.0 W/mK or less was demonstrated by all specimens with Si sludge replacement. It is noteworthy that the thermal conductivity drops at all temperatures with a rise in Si sludge replacement, with Si10 having the lowest thermal conductivity (0.2–0.6 W/mK). These numbers suggest that the sample possesses the properties of a resistive and microporous material [200]. Additionally, there is a tendency for thermal diffusivity to decrease as Si sludge replacement increases. This is because there is more Si sludge replacement, which causes an increase in porosity. When it comes to high porosity porous ceramics, the heat capacity per unit volume (C) diminishes because the pores' heat capacity is minimal in comparison to the solid's, which in turn reduces thermal conductivity and thermal diffusion [200].

Choosing pore-forming agents and optimizing sintering conditions are crucial stages in customizing the characteristics of ceramic materials to suit applications. Through meticulous consideration of variables like pore size, porosity, mechanical strength, and thermal conductivity, one can engineer ceramic materials with performance attributes optimized for diverse industrial and technological uses. Table 3 presents a comprehensive analysis of ceramic materials based on important properties.

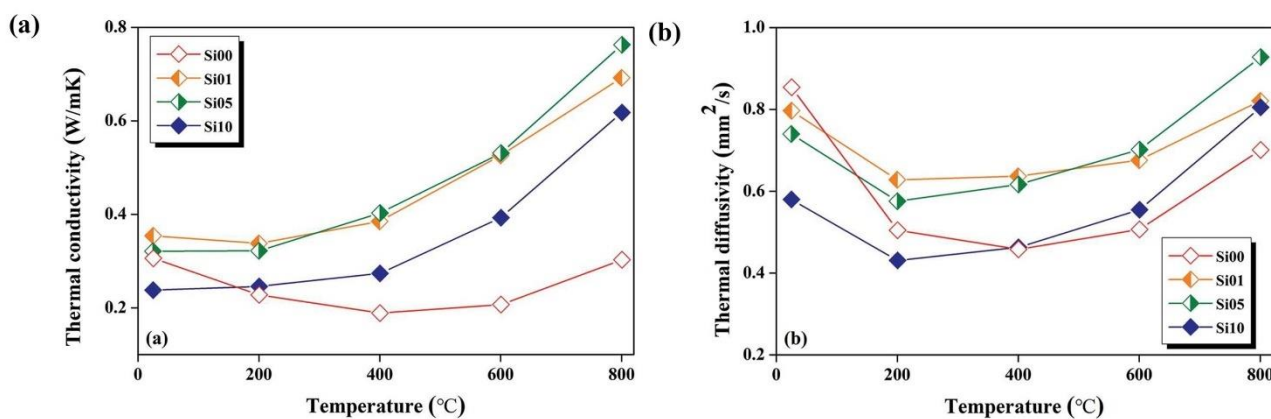


Figure 9. (a) Thermal conductivity and (b) thermal diffusivity of porous ceramics with different replacement of Si sludge (Reproduced from Ref. [200] with permission).

Table 3. Comprehensive analysis of ceramic materials based on important properties.

PFA	PFA content (wt.%)	Sintering temperature (°C)	Pore size (μm)	Porosity (%)	Mechanical strength (MPa)	Thermal conductivity (W/mK)	Ref.
YSZ fiber ($\text{Y}_2\text{Si}_2\text{O}_7$)	0–30	1550	40–380	93.5–92.7	0.99–1.36	0.107–0.097	[202]
Dolomite	20	800–1000	0.4–2.5	46.3	49.4	-	[203]
Carbon black (CB)	5–30 vol%	925–1030	-	38.48–59.81	~150	-	[169]
MASHs	32.41	1500–1700	Approximately 5	67.2–71.9	6.1–17.1	0.18–0.38	[204]
Starch	0–50	950	0.3–0.5	61.2–80	2.83–0.46	0.2388–0.09776	[205]
Soluble starch	0–8	1500	40–50	35.59–11.8	47.75–226.52	7.44–12.23	[197]
Polyurethane	2	1050–1250	189.92–119.49	63.2–85.3	19.43–0.99	0.089–0.088	[206]
PMMA	26.5–50 vol%	1100	-	60.2 \pm 0.6	12.7–81.1	14.2–3.6	[207]

7. Conclusions

In conclusion, the special qualities of porous ceramics have made them invaluable for a wide range of applications, including industrial, biomedical engineering, environmental protection, and more. This work has thoroughly investigated the ways in which the structure, porosity, and mechanical characteristics of porous ceramics are influenced by the selection of the pore-forming agent and ceramic material. The ultimate properties of this material are determined by the interaction between the pore-forming agent and the ceramic substance. A variety of ceramic bases, including silicon carbide and alumina, have different advantages, and the kind and number of pore-forming agents influence the distribution, size, and total porosity of pores. While inorganic agents permit regulated pore form and size, organic agents usually produce interconnected pores that are advantageous for filtering.

Reduction in mechanical strength due to high porosity is a common issue that may be solved by optimizing the pore structure and utilizing reinforcing techniques. These enhanced qualities are used in filtration, catalysis, energy storage, and biological applications, demonstrating the flexibility and

versatility of porous ceramics. To enhance performance and broaden the applications of porous ceramics, future studies and developments will concentrate on cutting-edge manufacturing methods, novel materials, and environmentally friendly procedures. The development of hybrid materials with improved characteristics is another potential benefit of integrating porous ceramics with other cutting-edge technologies. To sum up, customized design and optimization of porous ceramics are necessary to satisfy the requirements of a variety of contemporary applications, and further development in this area will continue to have a major influence and be extremely useful for a variety of purposes.

Use of AI tools declaration

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

Author contributions

Mohamed Lokman Jalaluddin: served as the main author of the paper, responsible for the conceptualization, literature review, and manuscript writing; Umar Al-Amani Azlan: acted as the main supervisor of the research project, providing guidance and expertise in the field of ceramics; Mohd Warikh Abd Rashid: co-supervised the project, contributing his knowledge and experience in ceramics; Norfauzi Tamin: participated as a co-member of the project, bringing in expertise in materials engineering and assisting with data analysis; Mohamad Najmi Masri: contributed as a co-member of the project, leveraging his background in advanced materials to support the research and manuscript preparation. All authors have read and approved the final manuscript.

Acknowledgments

The authors extend their appreciation to the Skim Zamalah Universiti Teknikal Malaysia Melaka (UTeM) for funding this research work.

Conflict of interest

The authors declare that they have no conflicts of interest.

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