Structure and Properties of ZrO_2- Al_2O_3-MgO Porous Composites

Thesis booklet of the PhD dissertation

by

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Hungary, 2026

1. Abstract

Porous ceramics are composite materials that consist of a ceramic substrate and pores that are dispersed throughout the ceramic matrix. The special characteristics of porous ceramics – their low density, large surface area, and chemical inertness – have made them an increasingly popular product in the ceramics industry recently. Zirconia-based porous ceramics have emerged as potential materials for different application, owing to their mechanical durability, and adjustable porosity. Their mechanical characteristics and performance are controlled by the porosity, pore morphology and pore size distribution, which is the key to their effectiveness. Diverse techniques, including gel casting, freeze casting, and direct foaming, have been used to fabricate porous structures. Nonetheless, these approaches often encounter difficulties in attaining a balance among porosity, mechanical strength, and structural homogeneity. The intricacy and expense of these processes necessitated the exploration of more accessible and cost-effective techniques for the production of porous materials. Therefore, other techniques were developed, for example the starch consolidation casting technique, that provide a direct control of porosity during production.

This PhD research work focuses on the manufacturing, characterisation, and optimisation of novel zirconia-alumina-magnesia porous ceramics via the starch consolidation casting method, an economical and eco-friendly methodology for producing porous structures. Potato and tapioca starches were used as body and pore-forming agents, while the distilled water content was altered to improve the rheological properties of the ceramic slurries.

This PhD study assessed the influence of varying starch percentages and types on achieving the desired pore morphology. Mechanical properties are also essential in different applications; hence, this PhD research evaluated the impact of varying ratios of ceramics oxides and starches to achieve optimal mechanical strength.

To produce the porous structure, ceramic slurries were prepared with different starch type and content, zirconia-to-alumina ratios, and powder-to-water ratios; subsequently, these slurries were poured into impermeable plastic moulds and heated at 80°C for 2 hours to allow the starch to swell and gelatinize. The samples are then de-moulded and gradually pre-sintered at 1100°C. The sintering temperature is critical and influences the mechanical characteristics and pore morphology on the surface. Consequently, it is essential to investigate the impact of varying sintering temperatures and holding time. Therefore, the samples were sintered at 1400°C, 1500°C, and 1600°C for varying holding time to investigate their effects on microstructural development,

densification, and mechanical characteristics. A thorough assessment was performed to evaluate the impact of these factors (starch type and content, zirconia-to-alumina ratios, powder-to-water ratios, sintering temperatures, and sintering holding time) on the final characteristics of the ceramics, including apparent density, apparent porosity, volume shrinkage, and compressive strength. Microstructural characterization was conducted utilizing scanning electron microscopy (SEM) to investigate pore morphology and interconnectivity, X-ray diffraction (XRD) to identify phase compositions and transformations, and mercury intrusion porosimetry (MIP) to measure pore opening size distribution.

SEM and EDS analysis illustrates that in all the pre-sintered and sintered samples, large areas with a uniform distribution of alumina and zirconia grains were present. It confirms the effectiveness of the mixing procedure that was followed. The findings indicated that increasing the starch content markedly improved overall porosity, decreased density, and affected the mechanical strength of the resultant porous ceramics. A higher alumina content was associated with an increase in apparent porosity and a reduction in volume shrinkage and apparent densities. The main advantage of alumina is its ability to improve compressive strength serving as a barrier against fracture development. Pre-sintering effectively reduced the rate of shrinkage during the final sintering stage; this resulted in more controlled and predictable shrinkage, leading to better dimensional stability and reduced risk of defects in the final product. Porous ceramics with adequate mechanical strength and interconnected porosity were generated by optimizing material combinations and sintering conditions making them ideal in several fields as in bone replacement applications, catalytic systems, and energy-related applications, notably in solid oxide fuel cells, and batteries. The results of the study highlight the efficacy of starch consolidation casting as a technique for producing porous ceramics with customized characteristics. To comprehend the intricate interactions among the different variables in the experimental data, it is crucial to analyse their pairwise correlations. Pair plots serve as an effective exploratory method for visualizing distributions and correlations among numerous variables, therefore clarifying the impact of processing conditions and compositions on the prepared porous ceramics performance.

2. Knowledge gaps and the objectives of this PhD thesis

2.1 Knowledge gaps

The review of the literatures indicates the existence of these knowledge gaps.

- There is a deficiency in research being conducted on preparation of porous ZrO_2-Al_2O_3-MgO ternary composites as a bone replacement material.
- The effect of the preparation parameters (composition of ceramics, content and types of pores forming agents, combining two types of starches, content of distilled water, pre-sintering methods, sintering temperatures, and sintering holding time) on the properties of ZrO_2-Al_2O_3-MgO porous composites have not been investigated.
- The correlation between the preparation conditions and the properties of the ZrO_2-Al_2O_3-MgO composite have not been investigated.

2.2 The objectives of this PhD thesis

- Preparation and characterization of ZrO_2-Al_2O_3-MgO ternary ceramic composites, designed with the porous structures at reduced cost.
- Studying the effect of using the preparation parameters (different amount and type of starches, different amount of distilled water, different amount of Al_2O_3, pre-sintering methods, different sintering temperatures, and different sintering holding time) on the properties (apparent density, volume shrinkage, compressive strength, apparent porosity, pore morphology, pore openings size, and the produced phases) of ZrO_2-Al_2O_3-MgO porous composites.
- To explore an adequate explanation of how processing conditions, compositional variations, and pore-forming agents concurrently affect various properties.

3. Materials and Methods

3.1 Materials

The following materials were employed in this PhD research work:

- Monoclinic zirconia (67.5, 70, 72.5, 75, 77.5, 80, or 82.5 wt.% of solid ceramics),
- Magnesia (2.5 wt.% of solid ceramics),
- Alumina (15, 17.5, 20, 22.5, 25, 27.5 or 30 wt.% of solid ceramics),
- Distilled water (60, 65, 68 or 70 wt.% suspension concentration),
- Deflocculant (Dolapix CE64) (1.5 wt.% based on solid ceramics),
- Potato and tapioca starches (10, 20, or 30 wt.% based on solid ceramics).

3.2 Preparation of porous structured ceramics

The ceramic raw ingredients first mixed in a laboratory milling machine for 5 hours. Then the ceramic and starch powders were rapidly stirred (600 rpm) in distilled water containing 1.5 wt.% of the deflocculant. The prepared slurries were poured into the prepared impermeable plastic moulds. The moulds containing the slurries was then placed in an oven and heated up to 80°C for

2 hours in order to enable the starch to swell and gelatinise. After cooling to room temperature and setting overnight the moulds opened and the ceramic bodies were de-moulded. The prepared ceramic samples were subjected to gradual pre-sintering in the laboratory furnace at temperatures of 500ºC and 1100ºC. Following pre-sintering, the samples underwent a gradual sintering process in the laboratory furnace. The gradual sintering was first conducted at temperatures of 300ºC and 500ºC for 1 hour, followed by 1400ºC (2 hours), 1500ºC (2 hours), or 1600°C (2, 3, or 4 hours), with a heating rate of 2 °C/min. Fig. 1 shows the preparation procedure of porous-structured ceramic. The following flow chart summarizes the progress on the PhD thesis, detailing the research work carried out in each study.

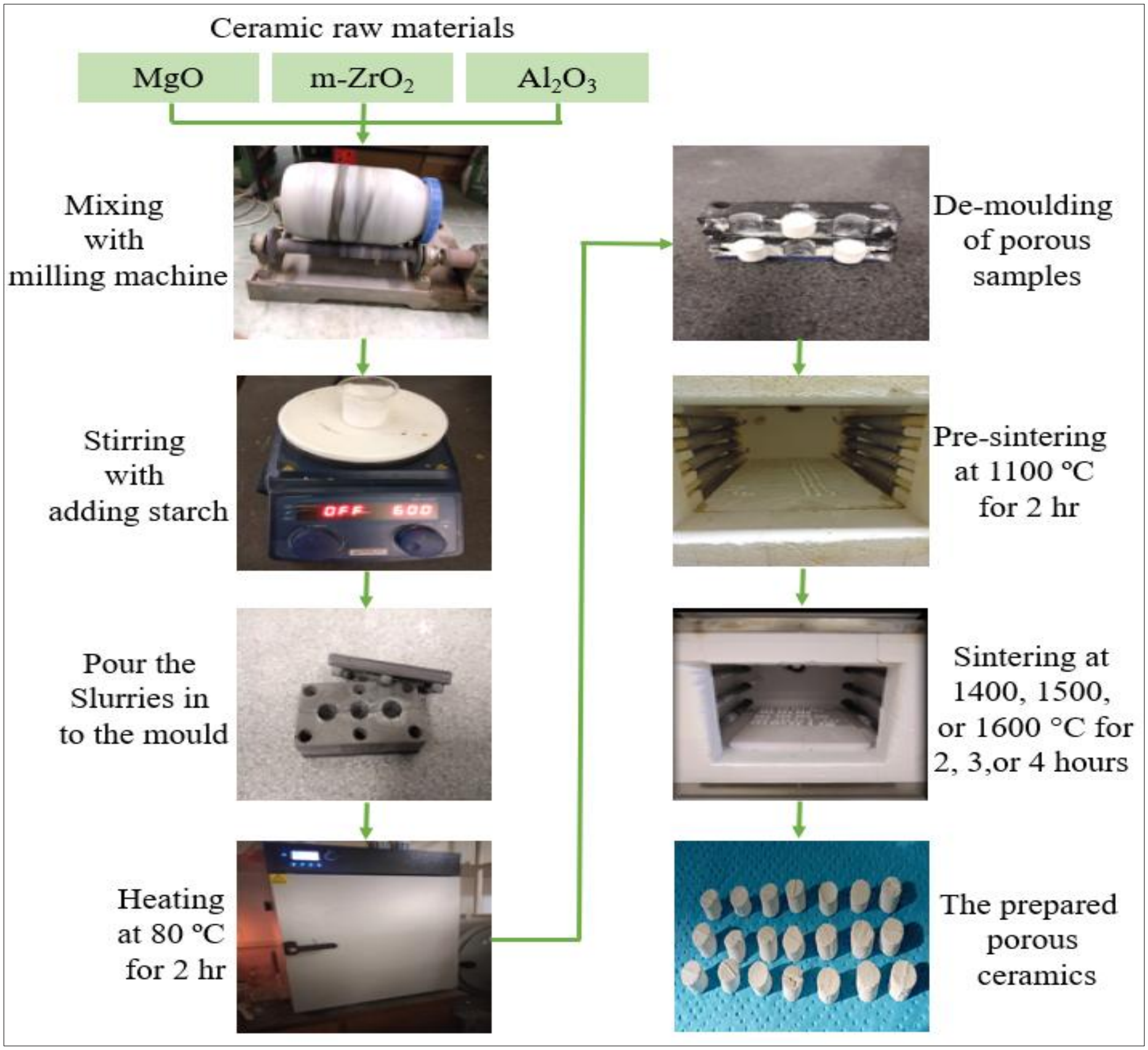
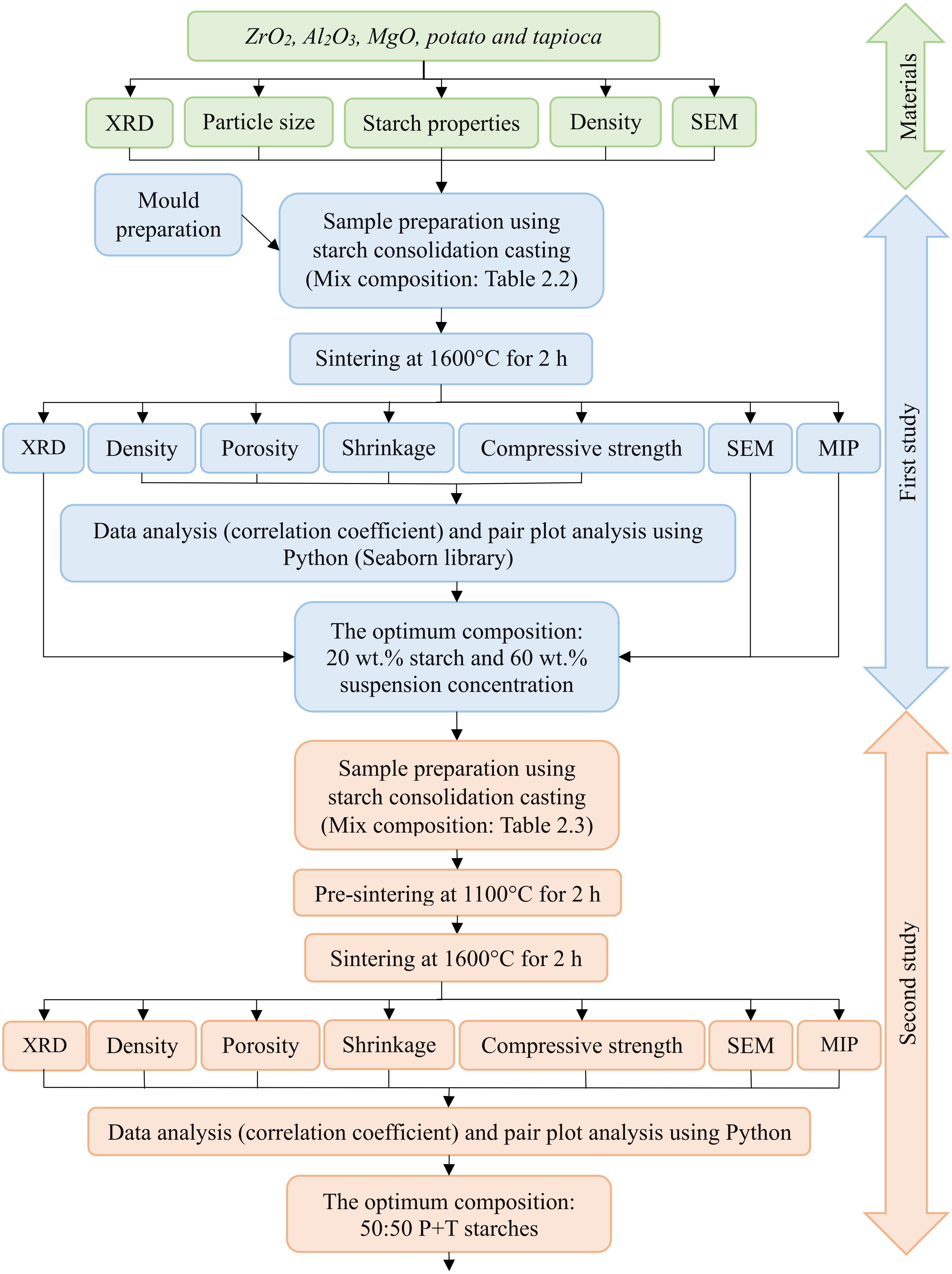
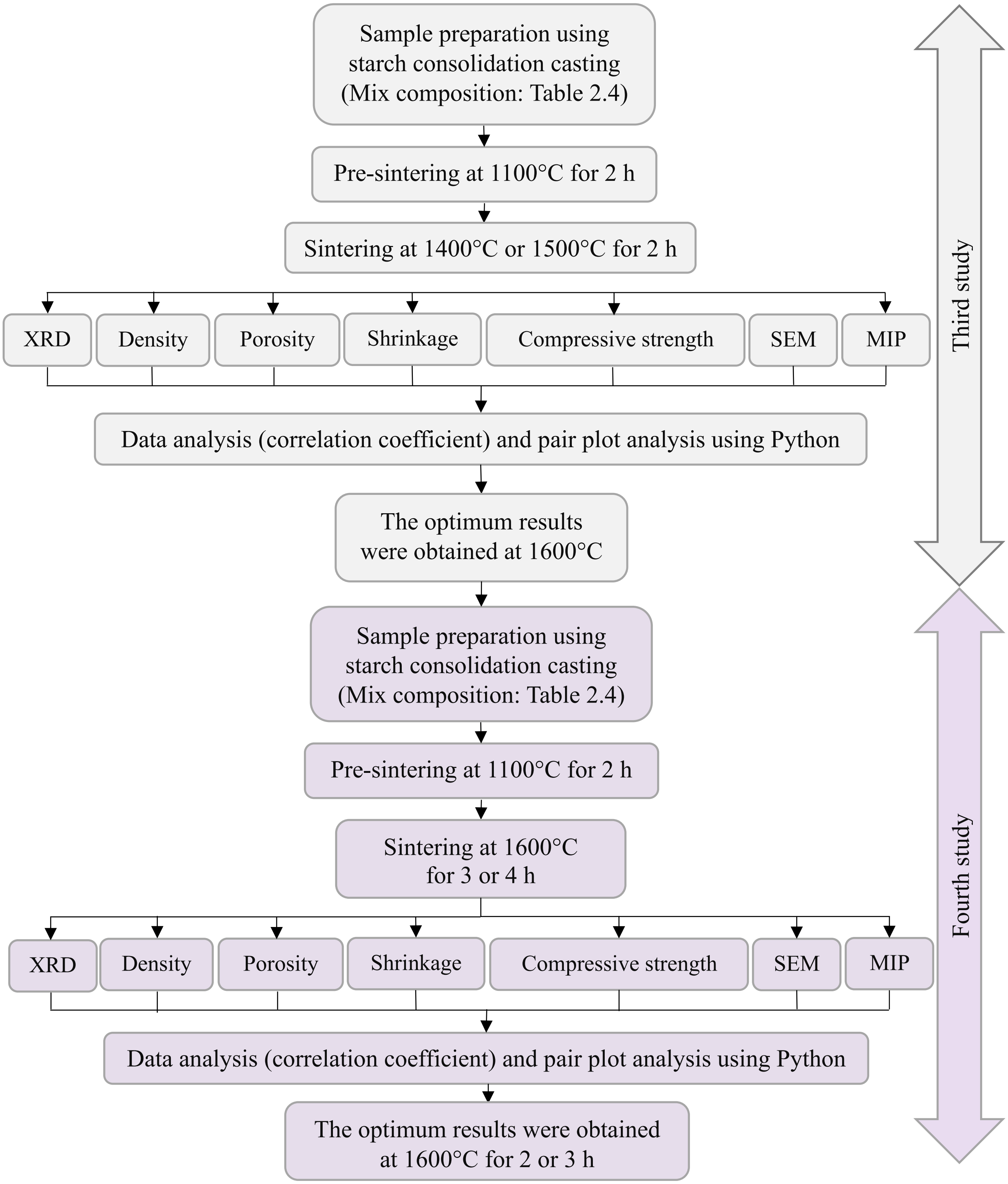


Fig. 1 The preparation procedure for porous-structured ceramic


ZrO2, Al2O3, MgO, potato and tapioca
XRD
Particle size
Starch properties
Density
SEM
Materials
Mould preparation
Sample preparation using starch consolidation casting (Mix composition: Table 2.2)
Sintering at 1600°C for 2 h
XRD
Density
Porosity
Shrinkage
Compressive strength
SEM
MIP
Data analysis (correlation coefficient) and pair plot analysis using Python (Seaborn library)
The optimum composition: 20 wt.% starch and 60 wt.% suspension concentration
First study
Sample preparation using starch consolidation casting (Mix composition: Table 2.3)
Pre-sintering at 1100°C for 2 h
Sintering at 1600°C for 2 h
XRD
Density
Porosity
Shrinkage
Compressive strength
SEM
MIP
Data analysis (correlation coefficient) and pair plot analysis using Python
The optimum composition: 50:50 P+T starches
Second study


Sample preparation using starch consolidation casting (Mix composition: Table 2.4)
Pre-sintering at 1100°C for 2 h
Sintering at 1400°C or 1500°C for 2 h
XRD
Density
Porosity
Shrinkage
Compressive strength
SEM
MIP
Data analysis (correlation coefficient) and pair plot analysis using Python
The optimum results were obtained at 1600°C
Third study
Sample preparation using starch consolidation casting (Mix composition: Table 2.4)
Pre-sintering at 1100°C for 2 h
Sintering at 1600°C for 3 or 4 h
XRD
Density
Porosity
Shrinkage
Compressive strength
SEM
MIP
Data analysis (correlation coefficient) and pair plot analysis using Python
The optimum results were obtained at 1600°C for 2 or 3 h
Fourth study

4. Claims/New scientific results

From the comprehensive experimental investigation, the following new scientific findings were obtained:

Claim 1: Preparation of innovative porous ceramic composites using cost-effective starch consolidation casting.

I have experimentally proved that innovative porous ceramic composites can be synthesized exhibiting an apparent density (2.5 - 3.2 g/cm^3), apparent porosity (~42 - 57%), pore size (~50 - 300 μm), and mechanical compressive strength (~44 - 73 MPa), utilizing zirconium dioxide (monoclinic phase, m-ZrO_2) (67.5 - 82.5 wt.% of the solid ceramic) combined with aluminium oxide (corundum phase, α-Al_2O_3) (15 - 30 wt.% of the solid ceramic) and magnesium oxide (periclase phase, c-MgO) (2.5 wt.% of the solid ceramic). ZrO_2-based porous ceramic composites were fabricated using starch consolidation casting method, employing a mixture (50:50 wt.%) of potato with tapioca starches (the swelling factor for potato starch was 41, whereas for tapioca starch it was 32) as pore and body forming agents. The ceramic slurries were produced with 20 wt.% of starches mixture and 60 wt.% of suspension concentration according to the conditions shown in Table C1.

Table C1. The mixed compositions with the sintering conditions

<table>
<tr><th colspan="6">Suspension concentration (60 wt.% based on solids)</th><th>Pre-sintering conditions</th><th>Sintering conditions</th></tr>
<tr><td colspan="4">Solids (60 wt.% of the suspension)</td><td colspan="2">Liquids (40 wt.% of the suspension)</td><td rowspan="3">500 °C (1 hour), then 1100 °C (2 hours) with 2 °C/min heating rate</td><td rowspan="3">300°C (1 hour), then 500°C (1 hour), then 1600°C (2 or 3 hours) with 2 °C/min heating rate</td></tr>
<tr><td colspan="3">Ceramics (80 wt.% of the solids)</td><td>Starches (20 wt.% of the solids)</td><td rowspan="2">Dolapix CE64 (1.5 wt.% of the liquids)</td><td rowspan="2">Distilled water (98.5 wt.% of the liquids)</td></tr>
<tr><td>m-ZrO_2 (82.5, 80, 77.5, 75, 72.5, 70, 67.5 wt. % of the ceramics)</td><td>MgO (2.5 wt.% of the ceramics)</td><td>Al_2O_3 (15, 17.5, 20, 22.5, 25, 27.5, 30 wt.% of the ceramics)</td><td>50:50 P+T</td></tr>
</table>

Where 50:50 P+T wt.% denoted to a mixture (50:50 wt.%) of potato with tapioca starches.

<u>Related publication:</u> ***Rusul Ahmed Shakir***, *Róbert Géber, Marwan T. Mezher, Tomasz Trzepieciński. (2025). Exploring influence of sintering temperature on the structure and technical characteristics of ATZ ceramic composites. Results in Engineering. Volume 28, 107139. https://doi.org/10.1016/j.rineng.2025.107139* ***(Q1)***

Claim 2: The impact of incorporating various amounts and types of starches with various amounts of distilled water on the technical properties of the produced porous ceramics.

I have statistically determined the Pearson correlation matrix (Tables C2.1 and C2.2) of the experimental data to analyse the correlation between the amounts and types of starches, the amounts of distilled water, and the properties of the produced porous m-ZrO_2-Al_2O_3-MgO ceramics. Pearson correlation matrix demonstrated that starch content (10 wt.%, 20 wt.%, and 30 wt.%) correlates with essential material (porous m-ZrO_2-Al_2O_3-MgO ceramics) properties, exhibiting a strong negative correlation with apparent density (r = -0.738 with using potato starch and r = -0.873 with using tapioca starch) and compressive strength (r = -0.761 with using potato starch and r = -0.798 with using tapioca starch). The Pearson matrix showed that the starch content has a positive correlation with apparent porosity (r = 0.819 with using potato starch and r = 0.726 with using tapioca starch) and volume shrinkage (r = 0.545 with using potato starch and r = 0.187 with using tapioca starch). The results also demonstrated a negative correlation between suspension concentration and apparent density (very weak corelation when r = -0.268 with using potato starch and r = -0.095 with using tapioca starch), apparent porosity (weak correlation when r = -0.499 with using potato starch and r = -0.472 with using tapioca starch), and volume shrinkage (strong correlation with using potato starch, r = -0.737, and very strong correlation with using tapioca starch r = -0.909). The correlation between the suspension concentration and compressive strength is weak positive (r = 0.517 with using potato starch and r = 0.516 with using tapioca starch).

Table C2.1 The correlation matrix with using potato starch

	Starch (wt.%)	Sus. (wt.%)	AD	AP	VS	σ
Starch (wt.%)	1					
Sus. (wt.%)	0	1				
AD	-0.738	-0.268	1			
AP	0.819	-0.499	-0.549	1		
VS	0.545	-0.737	-0.031	0.769	1	
σ	-0.761	0.517	0.292	-0.848	-0.842	1

Table C2.2 The correlation matrix with using tapioca starch

	Starch (wt.%)	Sus. (wt.%)	AD	AP	VS	σ
Starch (wt.%)	1					
Sus. (wt.%)	0	1				
AD	-0.873	-0.095	1			
AP	0.726	-0.472	-0.774	1		
VS	0.187	-0.909	-0.084	0.574	1	
σ	-0.798	0.516	0.639	-0.265	-0.371	1

Where AD: apparent density, AP: apparent porosity, VS: volume shrinkage, σ: compressive strength, Sus.: suspension concentration.

Related publications:

1. ***Rusul Ahmed Shakir****, Róbert Géber. (2023). Structure and properties of ZrO_2-Al_2O_3-MgO porous ceramic for biomedical applications. Results in Engineering. 18, 101104. https://doi.org/10.1016/j.rineng.2023.101104* ***(Q1)***
2. ***Rusul Ahmed Shakir****, Róbert Géber. (2024). POROSITY AND PORE MORPHOLOGY CHARACTERISTICS OF ZIRCONIA-ALUMINA BIOCERAMICS. POLLACK PERIODICA, An International Journal for Engineering and Information Sciences. 19, 3, 107 - 114. DOI:10.1556/606.2024.01099* ***(Q3)***

Claim 3: The influence of Al_2O_3 content in the properties of porous structured composites.

I have statistically determined the Pearson correlation matrix of the experimental data to analyse the correlation between the Al_2O_3 content (15, 17.5, 20, 22.5, 25, 27.5, and 30 wt.%), and the properties of the produced porous m-ZrO_2-Al_2O_3-MgO ceramics. The Pearson correlation matrix (Tables C3.1 - C3.3) established that Al_2O_3 content has a very strong negative correlation (r = -0.80 to -1.00) with apparent density and volume shrinkage, while concurrently exhibiting a very strong positive correlation (r = 0.80 to 1.00) with apparent porosity and compressive strength.

Table C3.1 Pearson correlation matrix for the experimental data using tapioca starch

	Al_2O_3 (wt.%)	AD	AP	VS	σ
Al_2O_3 (wt.%)	1				
AD	-0.9664	1			
AP	0.9871	-0.9691	1		
VS	-0.9886	0.1482	-0.1582	1	
σ	0.8794	0.7101	-0.8979	-0.3591	1

Table C3.2 Pearson correlation matrix for the experimental data using potato starch

	Al_2O_3 wt.%	AD	AP	VS	σ
Al_2O_3 (wt.%)	1				
AD	-0.9728	1			
AP	0.9905	-0.9493	1		
VS	-0.9368	0.1439	-0.1509	1	
σ	0.8579	0.7661	-0.8253	-0.3905	1

Table C3.3 Pearson correlation matrix for the experimental data using potato + tapioca starch

	Al_2O_3 (wt.%)	AD	AP	VS	σ
Al_2O_3 (wt.%)	1				
AD	-0.9858	1			
AP	0.9863	-0.9891	1		
VS	-0.9828	0.1546	-0.1679	1	
σ	0.9208	0.7071	-0.9346	-0.3266	1

Related publication: ***Rusul Ahmed Shakir****, Róbert Géber, Marwan T. Mezher, Tomasz Trzepiecinski, Ferenc Móricz. (2024). Effect of Alumina Proportion on the Microstructure and Technical and Mechanical Characteristics of Zirconia-Based Porous Ceramics. Journal of Composites Science. 517. https://doi.org/10.3390/jcs8120517* ***(Q1)***

Claim 4: Improvement of the pore size by utilizing 50:50 wt.% potato and tapioca starches together

I experimentally proved by using scanning electron microscopy (Fig. C4.1) and mercury intrusion porosimetry (Fig. C4.2) methods that using a combined starch composition (50:50 wt.% potato with tapioca starches together), as a body and pore forming agent, produces larger pore diameters (exceeding 200 µm) with larger pore openings (throat) in the produced porous m-ZrO_2-Al_2O_3-MgO ceramics compared to those made with individual starch types. The enlarged pores result from the interaction of the two starches, facilitating the development of larger and more interconnected pores.

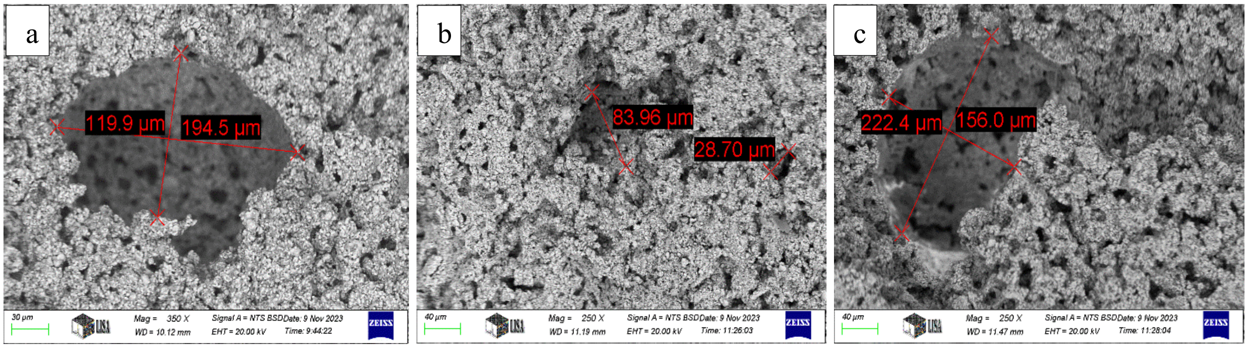


Fig. C4.1 SEM micrographs of porous ceramics (67.5 wt.% ZrO_2, 2.5 wt.% MgO, and 30 wt.% Al_2O_3) after sintering, (a) using potato starch, (b) using tapioca starch, and (c) using 50:50 wt.% tapioca + potato

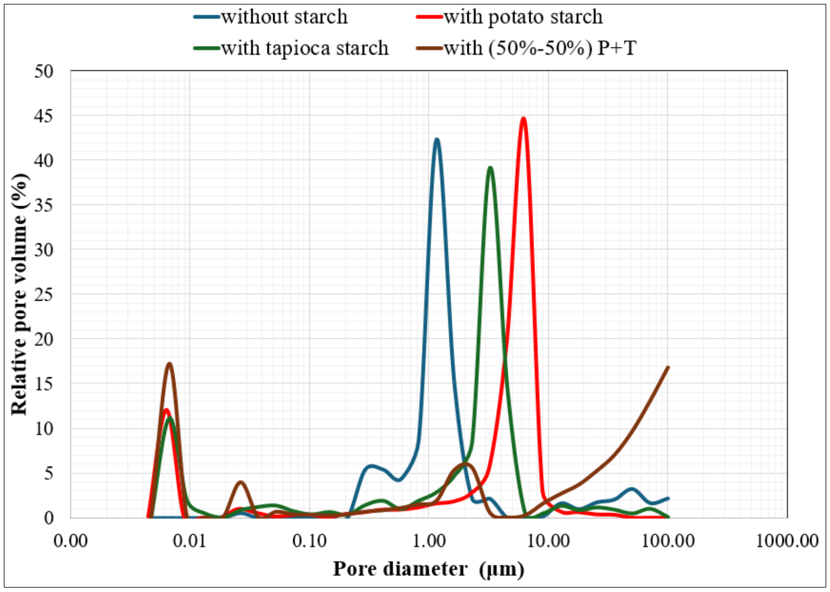


Fig. C4.2 The pore size distribution via relative pore volume

<u>Related publication:</u> ***Rusul Ahmed Shakir****, Róbert Géber, Marwan T. Mezher, Tomasz Trzepiecinski, Ferenc Móricz. (2024). Effect of Alumina Proportion on the Microstructure and Technical and Mechanical Characteristics of Zirconia-Based Porous Ceramics. Journal of Composites Science. 517. https://doi.org/10.3390/jcs8120517* ***(Q1)***

Claim 5: Progressive pre-sintering reduces the rate of shrinkage and mitigate thermal stresses.

I established that the pre-sintering processing of the porous m-ZrO_2-Al_2O_3-MgO ceramic composites significantly improved the structural and mechanical properties of the final sintered prepared composites. By allowing partial densification and particle rearrangement prior to high-temperature sintering, the pre-sintering process effectively decreased the shrinkage rates, leading to minimal surface cracking, as shown by SEM analysis (Fig. C5.1). Consequently, the samples (for example: 77.5 wt.% m-ZrO_2 - 20 wt.% Al_2O_3 - 2.5 wt.% MgO shown in Fig. C5.2) that pre-sintered (at 500°C for 1 hour and then at 1100°C for 2 hours with a heating rate of 2 °C/min) and then sintered (at 300°C and 500°C for 1 hour and then at 1600°C for 2 hours with a heating rate of 2 °C/min) have higher compressive strength (46.1 MPa with using 20 wt.% of 50:50 wt.% of potato and tapioca starches) as compared with the samples (with the same composition) that sintered without pre-sintering process (8.2 MPa with using 20 wt.% of 50:50 wt.% of potato and tapioca starches).

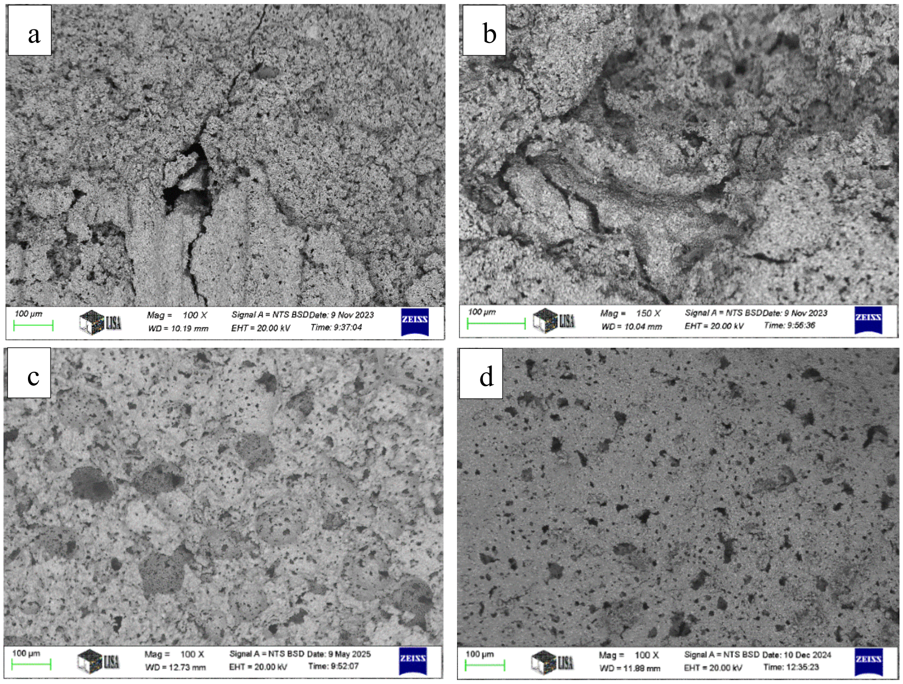


Fig. C5.1 SEM micrographs of sintered porous ceramics (67.5 wt.% m-ZrO_2, 2.5 wt.% MgO, and 30 wt.% Al_2O_3): (a) and (b) without pre-sintering, (c) and (d) with pre-sintering

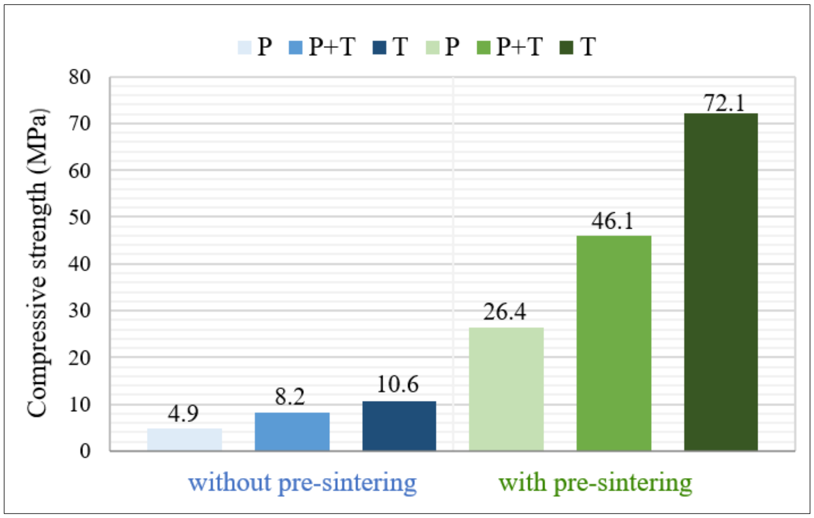


Fig. C5.2 Compressive strength of the samples

<u>Related publications:</u>

1. ***Rusul Ahmed Shakir***, *Róbert Géber, Marwan T. Mezher, Tomasz Trzepiecinski, Ferenc Móricz. (2024). Effect of Alumina Proportion on the Microstructure and Technical and Mechanical Characteristics of Zirconia-Based Porous Ceramics. Journal of Composites Science. 517. https://doi.org/10.3390/jcs8120517* ***(Q1)***
2. ***Rusul Ahmed Shakir***, *Róbert Géber. (2023). Structure and properties of ZrO_2-Al_2O_3-MgO porous ceramic for biomedical applications. Results in Engineering. 18, 101104. https://doi.org/10.1016/j.rineng.2023.101104* ***(Q1)***

Claim 6: Impact of sintering temperature on the surface pore morphology of the produced porous ceramics.

Using SEM and MIP, I have experimentally proved that the sintering temperature has a multiple influence on the pore structure of the produced porous m-ZrO_2-Al_2O_3-MgO ceramics. SEM observations (Fig. C6.1) indicate that samples sintered at 1600 °C have larger pores than those sintered at 1400 °C and 1500 °C, suggesting improved pore coalescence at higher temperatures. Conversely, MIP (Fig. C6.2) indicates that the pore openings (throats) decrease in size as the sintering temperature increases, with main openings (throats) sizes reducing from about 0.53 µm and 3.81 µm at 1400 °C to around 0.38 µm and 1.12 µm at 1600 °C. During sintering and because of densification, the ceramic matrix (on the surface of the pores) shrinks toward the entire part of the samples, leading to an increase in the size of the surface's larger pores and a reduction in the opening (throat) that connected between them. With increasing sintering temperature, the shrinkage of ceramics (on the surface of the pores) toward the entire body increase, leading to increase the pore size while reduce the pore openings.

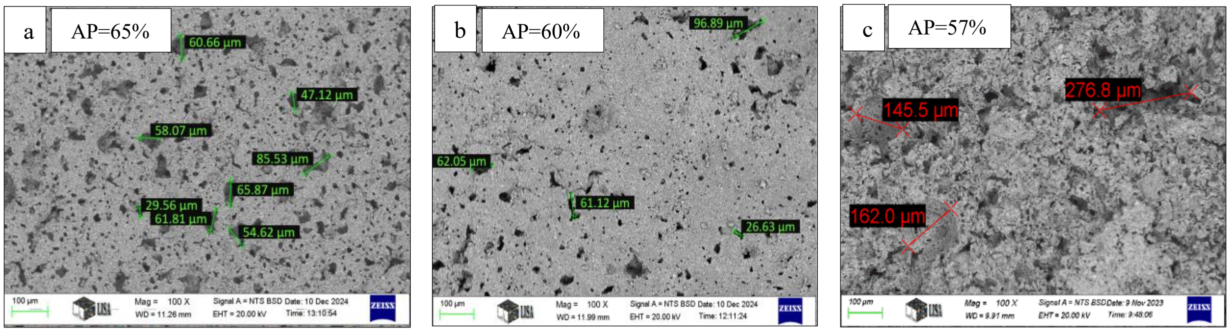


Fig. C6.1 SEM micrographs for porous ceramics (67.5 wt.% m-ZrO_2, 2.5 wt.% MgO, and 30 wt.% Al_2O_3) sintered at: 1400°C (a), 1500°C (b), and 1600°C (c), where AP: apparent porosity

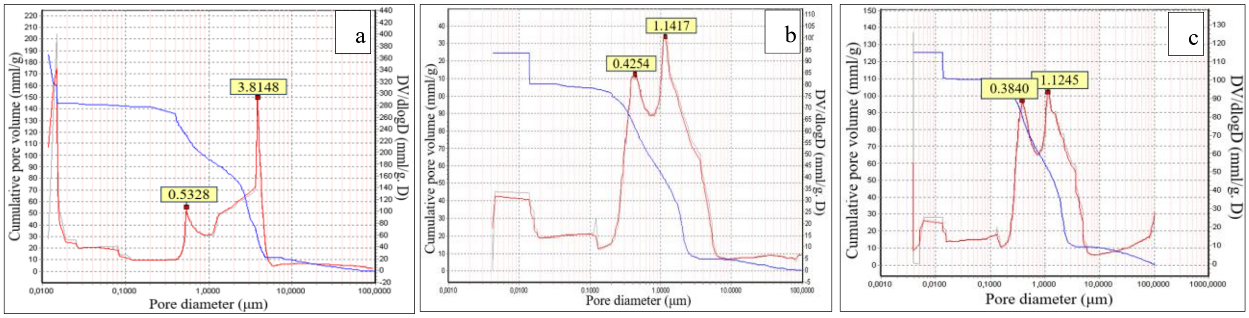


Fig. C6.2 Pore size distribution of porous ceramics (67.5 wt.% m-ZrO_2, 2.5 wt.% MgO, and 30 wt.% Al_2O_3) sintered at: 1400°C (a), 1500°C (b), and 1600°C (c)

Related publication: ***Rusul Ahmed Shakir****, Róbert Géber, Marwan T. Mezher, Tomasz Trzepieciński. (2025). Exploring influence of sintering temperature on the structure and technical characteristics of ATZ ceramic composites. Results in Engineering. Volume 28, 107139. https://doi.org/10.1016/j.rineng.2025.107139* ***(Q1)***

Claim 7: Impact of sintering holding time on the microstructural characteristics of the produced porous ceramics.

A. I established that among the three-sintering holding time (2, 3 or 4 hours), the porous ceramics (Table C7.1) sintered at 1600°C for 3 hours demonstrated the highest compressive strength (48 - 73 MPa) (Fig. C7.1) with (3.2 - 2.7 g/cm^3) apparent density and (42 - 48 %) apparent porosity.

Table C7.1 Mix compositions

Suspension concentration (60 wt.% based on solids)					
Solids (60 wt.% of the suspension)				**Liquids** (40 wt.% of the suspension)	
Ceramics (80 wt.% of the solids)			**Starches** (20 wt.% of the solids)	**Dolapix CE64** (1.5 wt.% of the liquids)	**Distilled water** (98.5 wt.% of the liquids)
m-ZrO_2 (82.5, 80, 77.5, 75, 72.5, 70, 67.5 wt. % of the ceramics)	**MgO** (2.5 wt.% of the ceramics)	**Al_2O_3** (15, 17.5, 20, 22.5, 25, 27.5, 30 wt.% of the ceramics)	**50:50 P+T**		

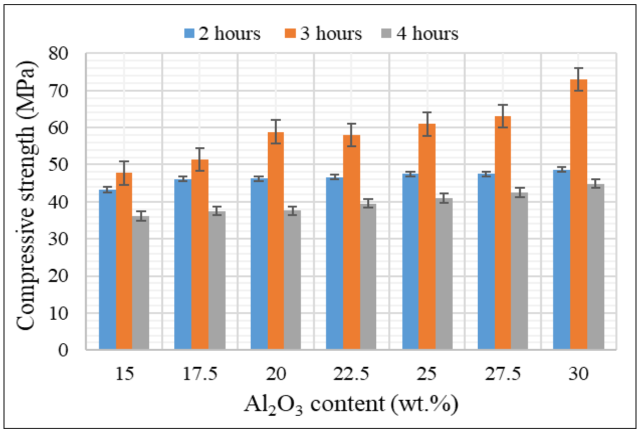


Fig. C 7 Compressive strength at different sintering holding time

B. I have statistically determined the Pearson correlation matrix (Table 7.2) of the experimental data to determine the correlation between the sintering holding times and the properties of the prepared porous (ZrO_2-Al_2O_3-MgO) ceramics. Pearson correlation matrix demonstrated that the sintering holding time (2, 3, or 4 hours) correlates with essential composite (porous m-ZrO_2-Al_2O_3-MgO ceramics) properties, exhibiting a strong positive correlation with apparent density (r = 0.7887) and volume shrinkage (r = 0.8688). Additionally, there is a very strong negative correlation with apparent porosity (r = -0.9177). The results also demonstrate that there is a weak negative correlation (r = -0.2947) between the sintering holding time and the compressive strength of the prepared porous structures.

Tables C7.2 The Pearson correlation matrix of the experimental data.

	Al_2O_3 (wt.%)	ST (hours)	AD	AP	VS	σ
Al_2O_3 (wt.%)	1					
ST (hours)	0	1				
AD	-0.5374	0.7887	1			
AP	0.3301	-0.9177	-0.8477	1		
VS	-0.4343	0.8688	0.9122	-0.9411	1	
σ	0.4141	-0.2947	-0.6424	0.2429	-0.4221	1

List of Publications

International Journal articles

1. **Rusul Ahmed Shakir**, Róbert Géber, Marwan T. Mezher, Tomasz Trzepieciński. (2025). Exploring influence of sintering temperature on the structure and technical characteristics of ATZ ceramic composites. Results in Engineering. Volume 28, 107139. https://doi.org/10.1016/j.rineng.2025.107139 **(Q1)**

2. **Rusul Ahmed Shakir,** Róbert Géber, Marwan T. Mezher, Tomasz Trzepiecinski, Ferenc Móricz. (2024). Effect of Alumina Proportion on the Microstructure and Technical and Mechanical Characteristics of Zirconia-Based Porous Ceramics. Journal of Composites Science. 517. https://doi.org/10.3390/jcs8120517 **(Q1)**
3. **Rusul Ahmed Shakir**, Róbert Géber. (2023). Structure and properties of ZrO_2-Al_2O_3-MgO porous ceramic for biomedical applications. Results in Engineering. 18, 101104. https://doi.org/10.1016/j.rineng.2023.101104 **(Q1)**
4. **Rusul Ahmed Shakir**, Róbert Géber. (2025). ZIRCONIA-ALUMINA CERAMICS: A STUDY OF THEIR PROPERTIES. POLLACK PERIODICA, An International Journal for Engineering and Information Sciences. DOI: 10.1556/606.2025.01253 **(Q3)**
5. **Rusul Ahmed Shakir**, Róbert Géber. (2024). POROSITY AND PORE MORPHOLOGY CHARACTERISTICS OF ZIRCONIA-ALUMINA BIOCERAMICS. POLLACK PERIODICA, An International Journal for Engineering and Information Sciences. 19, 3, 107 - 114. DOI:10.1556/606.2024.01099 **(Q3)**

Paper published in conference proceeding:

- **Rusul Ahmed Shakir**, Róbert Géber. (2022). STARCH CONSOLIDATION CASTING METHOD FOR PREPARATION OF ZrO_2-Al_2O_3-MgO POROUS STRUCTURE. Multidiszciplináris tudományok. 12. kötet. (2022) 4 sz. pp. 232-241. https://doi.org/10.35925/j.multi.2022.4.25

Papers published in Almanach:

1. **Rusul Ahmed Shakir.** (2024). Exploring the behaviour of starch swelling in starch consolidation casting method for the production of porous structured ceramics. Almanach 2024-1.kötet/1.volume. 125. ISSN 2939-7294
2. **Rusul Ahmed Shakir.** (2023). Preparation of ZrO_2 based porous composite using potato starch as a pore- and body-forming agents. Almanach. 2023-1.kötet/1.volume. 8. ISSN 2939-7294.
3. **Rusul Ahmed Shakir**. (2022). Preparation of ZrO_2-Based Porous Structure via the Utilization of Starch as a Pore-Forming Agent. Almanach. 2022-1.kötet/1.volume. 51. ISSN 2939-7294.

Conference presentations

1. **Rusul Ahmed Shakir.** (2024) Structure and Characteristics of Porous Ceramic Composites Based on ZrO_2. Oral presentation. MAGYAR TUDOMÁNY ÜNNEPE, “KERÁMIA- ÉS

SZILIKÁTIPARI KUTATÁSOK A MISKOLCI EGYETEMEN" CÍMŰ RENDEZVÉNYÉRE. Hungary, 2024 November 5th.

2. **Rusul Ahmed Shakir.** (2023) Structure and Properties of ZrO_2-Al_2O_3-MgO Porous Ceramics for Biomedical Applications. Oral presentation. A MAGYAR TUDOMÁNYOS AKADÉMIA, MAGYAR TUDOMÁNY ÜNNEPE, "KERÁMIA- ÉS SZILIKÁTIPARI KUTATÁSOK A MISKOLCI EGYETEMEN" CÍMŰ RENDEZVÉNYÉRE, Hungary, 2023 November 8th.

Other publications

1. M.T. Mezher, A. Pereira, **Rusul Ahmed Shakir,** T. Trzepieciński. (2024). Application of machine learning and neural network models based on experimental evaluation of dissimilar resistance spot-welded joints between grade 2 titanium alloy and AISI 304 stainless steel. Heliyon, 10(24), e40898.
   doi: https://doi.org/10.1016/j.heliyon.2024.e40898 **(Q1)**
2. M.T. Mezher & **Rusul Ahmed Shakir**. (2023). Modelling and evaluation of the post-hardness and forming limit diagram in the single point incremental hole flanging (SPIHF) process using ANN, FEM and experimental. Results in Engineering, 20, 101613.
   doi: https://doi.org/10.1016/j.rineng.2023.101613 **(Q1)**
3. O.S. Barrak, O.F. Taresh, M.M. Hamzah, & **Rusul Ahmed Shakir**. (2023). An investigation of joining polyamide (PA) to stainless steel AISI 316L by hot press process. Journal of Techniques, 5(1), 114–121. doi: https://doi.org/10.51173/jt.v5i1.1280
4. **Rusul Ahmed Shakir,** M.T. Mezher, & R. Geber. (2022). Synthesis and characterization of erbium doped lead zirconate titanate thin films. Revue Des Composites Et Des Matériaux Avancés, 32(3), 111–116. doi: https://doi.org/10.18280/rcma.320301 **(Q3)**
5. M.T. Mezher, S.M. Khazaal, **Rusul Ahmed Shakir,** N.S.M. Namer. (2021). A comparative analysis study of hole flanging by incremental sheet forming process of AA1060 and DC01 sheet metals. Journal of Engineering Science and Technology, 16(6), pp. 4383–4403. **(Q2)**