

# Effect of Binder Types and Composition on the Physical and Structural Properties of Alumina Foam

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## Abstract

This research investigates the influence of various binder types and their compositions on the physical and structural properties of alumina foam, a material recognised for its high-temperature resistance, low density, and porosity. The study systematically evaluates binders such as polyethylene glycol (PEG), carboxymethyl cellulose (CMC), and bentonite to optimise manufacturing techniques aimed at enhancing alumina foam's performance in applications including filtration, thermal insulation, and catalysis. Key findings reveal that the choice of binder significantly affects parameters like packing density, pore size distribution, and mechanical strength. Specifically, PEG/CMC demonstrated superior performance in reducing shrinkage at higher binder concentrations, while bentonite contributed to increased density but lower porosity. The results underscore the potential for refining fabrication methods and expanding the applications of alumina foams in diverse industries by balancing binder composition to achieve desired material characteristics.

## 1. Introduction

Alumina foam is one of the important materials in the field of material science, characterised by its excellent high-temperature resistance, lower density, and high porosity. These features enable alumina foam to be used in quite a wide variety of beneficial applications in many industries, such as filtration, thermal insulation, and catalysis. The highly porous nature of alumina foam makes it an ideal filtration medium, allowing for very precise particle separation under very aggressive environmental conditions because of its high thermal resistance [1]. Further, the air-entrainment capability of the foam significantly reduces heat conduction, rendering it suitable in many applications, including fire-proof elements and lightweight building materials. The preparation of this alumina foam material requires a critical mixture of alumina powder with a temporary binder that allows shaping, followed by a high-temperature sintering process that burns out the binder to create a permanent porous network within the alumina structure [2]. This ability to engineer the properties of the foam through variations in binder formulation and processing conditions underscores the flexibility and importance of alumina foam in a wide range of applications.

The selection and composition of binders used in the production of alumina foams have a very important influence on their final properties. Binders are provisional adhesives, keeping the alumina particles in cohesion during shaping before high-temperature sintering. The binder type selected can affect such vital parameters as packing density, pore size distribution, and, subsequently, the mechanical strength of the material. Organic binders, such as polyethylene glycol (PEG) and carboxymethyl cellulose (CMC), burn out during sintering, leaving pores behind that compromise the structural integrity of the foam [3]. For example, lower decomposition temperatures may result in a more open pore structure, but could result in lower strength. In contrast, inorganic binders like silica sol may improve mechanical strength but at the same time also reduce porosity. Thus, an

optimal balance must be found regarding binder content; while high binder concentrations can improve handleability during the shaping step, they can lead to a lower porosity due to the increased packing density of alumina particles.

The main purpose of this study is to systematically investigate the effects of different types of binders and their compositions on the properties of alumina foams. This study will, therefore, establish optimum conditions under which alumina foams with improved mechanical and physical properties are produced for specified applications. Such importance is underlined by its potential in refining fabrication techniques, improving performances, and extending the field of application in several domains of alumina foams. Researchers could thus probe the influence of different binders and their formulations on the characteristics—say, pore size distribution or mechanical strength and, correspondingly, change the fabrication methods to suit the criteria set by specific applications.

This research focuses on some of the key challenges in the selection of binders to produce alumina foam. With a focus on binder types, compositions, and resultant foam properties, the present study hopes to shine light that could result in advancements in both manufacturing process and applications of alumina foams. Its results will not only bring about an enhancement in current uses but also open the route for innovative applications of this versatile material in future technologies.

## 2. Methodology

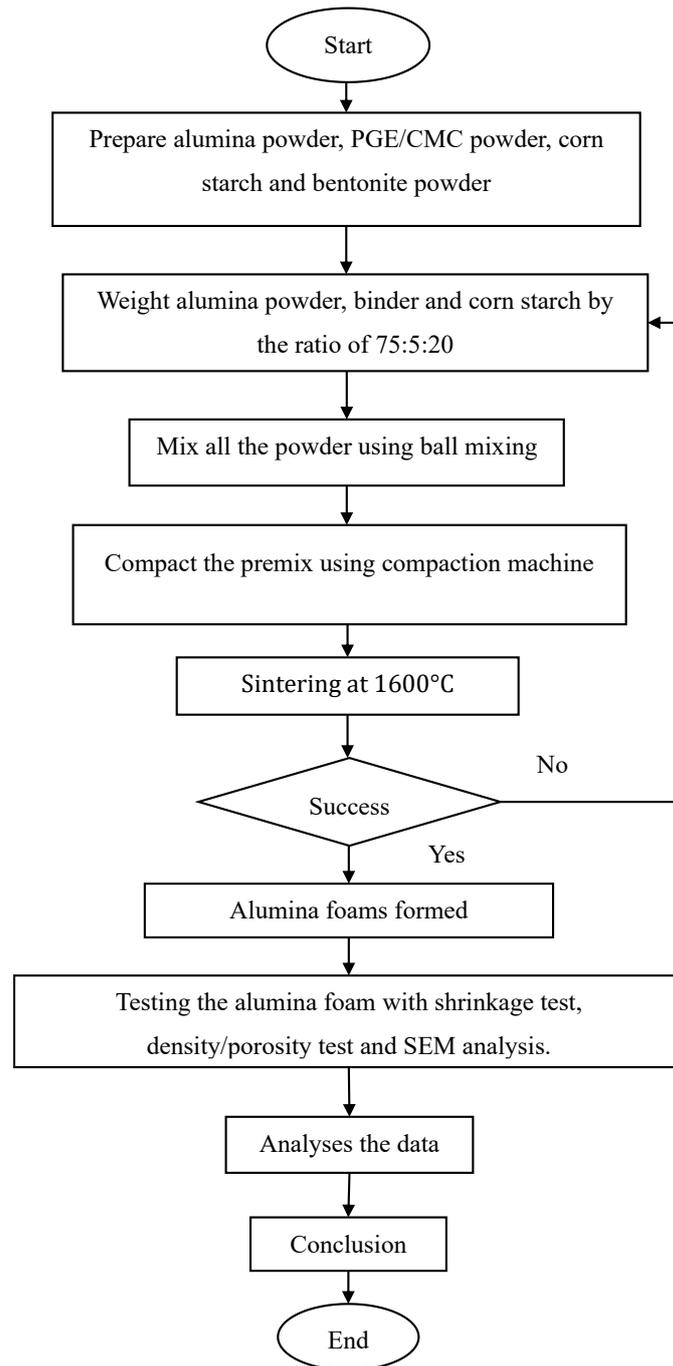
A thorough description of the experimental methodology applied during the study. Material selection, sample preparation, characterisation methods, and analytical tools make up the process. Every piece of equipment and process used in this study is described in this chapter in accordance with the technique flowchart shown in Figure 1.

### 2.1 Material And Sample Preparation

Alumina ( $\text{Al}_2\text{O}_3$ ) powder, was used as the main material, Carboxymethyl Cellulose (CMC), Polyethylene Glycol (PEG) and bentonite powder were used as binders. Corn starch will be used as a space holder material, which will create the microstructure pores in the alumina foam. The amount or ratio of binder in the mixture was different in each sample, as shown in Table 1. The binder with ratios of 0, 3, 5, 7, and 10 wt% were added into the mixture of alumina powder and corn starch, and then it was ball-milled for 1 hour in the ceramic jar at 100 rpm. Cylindrical (diameter 13 mm, height =7 mm) specimens for characterisation were produced using uniaxial compression at a load of 7 tons for 5 minutes using a manual hydraulic press (Carver, maximum load of 11 tons). For each binder composition, 4 samples were prepared, and all the samples were sintered in a box furnace at temperature of 1600 °C with 2 °C/min heating and cooling rate. The soaking time for the sintering process was 60 minutes at 500 °C and 120 minutes at 1600 °C.

**Table 1** Parameters for types of binder and their composition ratios

Types of Binder	Composition	Weight Ratio (alumina: binder: corn starch)
Bentonite	0 wt%	80: 0: 20
	3 wt%	77: 3: 20
	5 wt%	75: 5: 20
	7 wt%.	73: 7: 20
	10 wt%	70: 10: 20
	PEG/CMC	0 wt%
3 wt%		77: 1.5+1.5: 20
5 wt%		75: 2.5+2.5: 20
7 wt%.		73: 3.5+3.5: 20
10 wt%		70: 5+5: 20



**Fig. 1** Methodology flow chart

## 2.2 Data Analysis

Shrinkage, density and porosity tests as well as microstructure analysis will be conducted to analyse the physical and structural properties of the alumina foams. The diameter and height of the sample will be measured before and after the sintering process, and the volume of the cylinder sample will be calculated. The volume of the before and after sintering process will then be calculated using the formula below to get the shrinkage result.

$$Volume = \pi \left(\frac{d}{2}\right)^2 h \quad (1)$$

$$Shrinkage (\%) = \frac{V_{initial} - V_{final}}{V_{initial}} \times 100 \quad (2)$$

Alumina foam's porosity was measured using the standard ASTM C 271-94, while the Archimedes principle was employed in porosity analysis utilizing the Mettler Toledo X64 and the formula below were used.  $W_d$  is dry weight of the alumina foam,  $W_w$  is the weight of the wet sample after immersed in the water and  $W_s$  is weight of the sample while immersed in water.

$$Density = \frac{W_d}{W_w - W_s} \tag{3}$$

$$Porosity = \frac{W_d}{W_w - W_s} \times 100\% \tag{4}$$

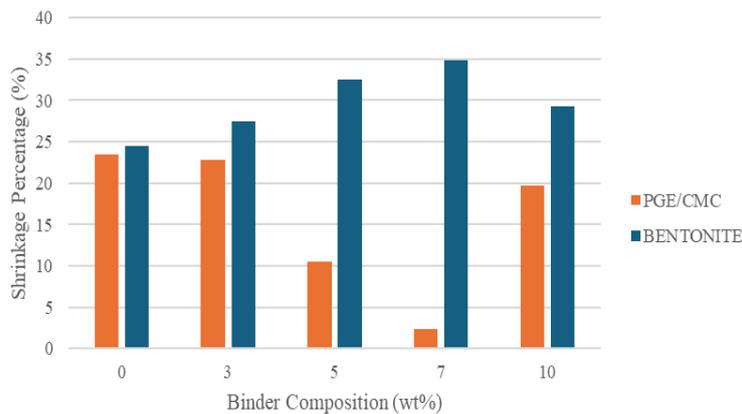
Pore distribution and size of Al2O3 foam was examined using Hitachi U10510 scanning electron microscope (SEM). The sample will be cut into half so that the microstructure pores easier to analyse.

### 3. Results and Discussion

Alumina foam made from various binder compositions was tested using characterisation testing utilising SEM, density and porosity kit, and Universal Testing Machine SEM to examine the foam's pore size and distribution. In the meantime, the compressive strength, densities, porosities, and shrinkage percentage of alumina foam were examined using the UTM and the density and porosity kit, respectively.

#### 3.1 Shrinkage Test

The graph shows the average shrinkage percentage of alumina foam as a function of binder composition in weight percentage for two different binders: PGE/CMC and bentonite.



**Fig. 2** Graph of average shrinkage of alumina foam using PGE/CMC and Bentonite as the binder

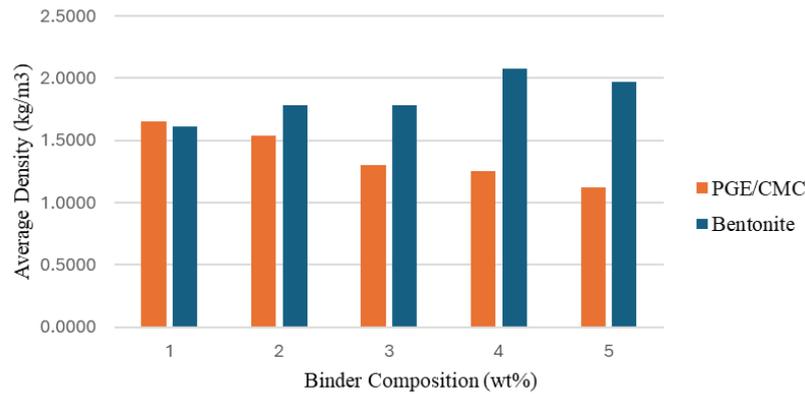
The shrinkage behaviour follows systematically different trends for each type of binder. In the case of PGE/CMC, the percentage of shrinkage remains quite stable at about 25% up to a 3 wt% binder composition. Then, a strong reduction of the shrinkage occurs, reaching a minimum value close to 0% at 7 wt%. For higher binder compositions up to 10 wt%, the shrinkage rises slightly again up to about 10%.

By contrast, bentonite always indicates a higher shrinkage percentage for all compositions compared to PGE/CMC. The shrinkage for bentonite at 0 wt% is about 30%, and the trend increases with an increase in binder composition; it reaches the maximum of over 35% at 7 wt% and then decreases slightly to around 30% at 10 wt%.

This investigation highlights that PGE/CMC exhibits higher efficiency in reducing shrinkage at high binder content, especially above 5 wt% to 7 wt%. On the other hand, bentonite shows the trend of augmenting shrinkage regardless of its formulation. This indicates that PGE/CMC might be a more suitable binder for use in alumina foam with a requirement of low shrinkage.

#### 3.2 Density and Porosity Test

The graph displays the average density of alumina foam as a function of binder composition (wt%) for two types of binders:

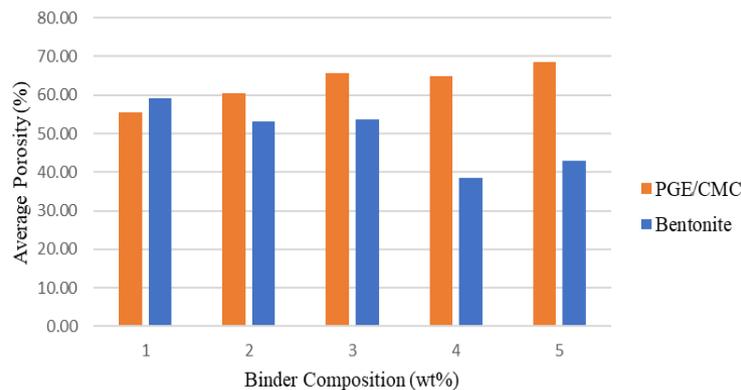


**Figure 3** Graph of average density of alumina foam using PGE/CMC and Bentonite as the binder

PGE/CMC and bentonite. For PGE/CMC, the average density remains relatively constant between 1.5 and 1.6 kg/m<sup>3</sup> for binder compositions of 1 wt% and 2 wt%. However, as the binder composition increases beyond 2 wt%, the density decreases consistently, reaching a minimum of approximately 1.0 kg/m<sup>3</sup> at 5 wt%. This trend suggests that increasing the PGE/CMC binder composition reduces the density of the alumina foam, likely due to changes in the foam structure or porosity.

In contrast, bentonite exhibits consistently higher densities across all compositions compared to PGE/CMC. The density starts at around 1.8 kg/m<sup>3</sup> at 1 wt% and increases steadily with higher binder compositions, reaching a peak of approximately 2.0 kg/m<sup>3</sup> at 4 wt% and 5 wt%. This indicates that bentonite contributes to a denser alumina foam, possibly due to its ability to create a more compact structure.

The comparison highlights a distinct difference in the behaviour of the two binders. PGE/CMC produces less dense foams at higher binder compositions, which could be advantageous for applications requiring lightweight materials. Conversely, bentonite results in higher densities, making it more suitable for applications where structural integrity and weight are critical factors.



**Fig. 4** Graph of average porosity of alumina foam using PGE/CMC and Bentonite as the binder

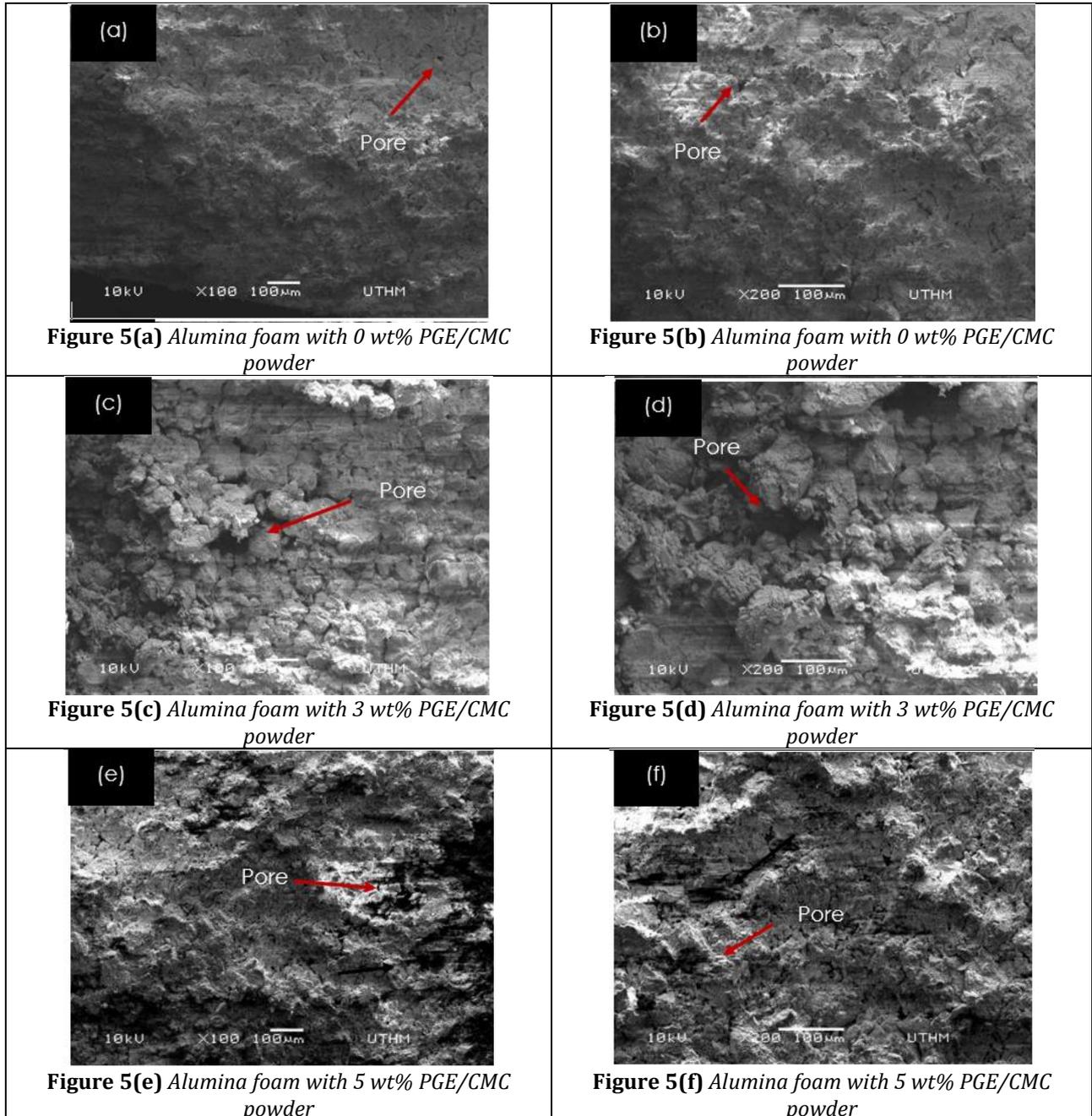
The graph shows the average porosity of alumina foam as a function of binder composition (wt%) for two binders: PGE/CMC and bentonite. For PGE/CMC, the porosity consistently increases with higher binder composition. At 1 wt%, the porosity is approximately 60%, and this value remains steady up to 3 wt%. Beyond this point, porosity begins to increase significantly, peaking at nearly 70% at 5 wt%. This trend suggests that PGE/CMC promotes higher porosity at greater binder concentrations, likely due to its ability to enhance foam formation and maintain structural voids.

In contrast, bentonite exhibits a significantly lower porosity across all compositions compared to PGE/CMC. The porosity starts at around 50% at 1 wt% and decreases gradually as the binder composition increases, reaching a minimum of approximately 30% at 5 wt%. This indicates that bentonite creates a denser and less porous structure, possibly due to its tendency to fill voids and reduce pore sizes.

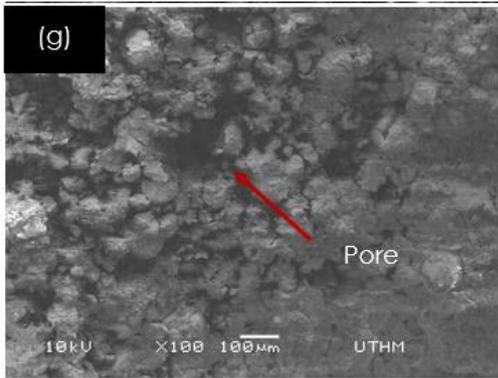
The comparison highlights the distinct effects of the two binders on foam porosity. PGE/CMC is more effective in producing highly porous alumina foams, making it suitable for applications requiring lightweight and high-porosity materials. On the other hand, bentonite results in lower porosity, which may be advantageous for applications requiring denser materials with reduced permeability.

### 3.3 Microstructure Analysis

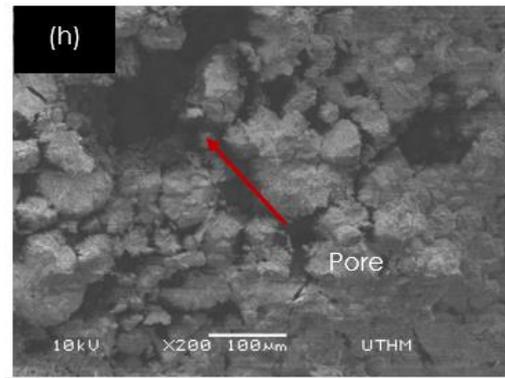
In this part, the microstructure of alumina foam was observed to observe the pore distribution and pore size because of the different compositions of binder powder used as space holder materials. The magnification of the Scanning Electron Microscope (SEM) is varied in order to measure and capture the best image of the microstructure. The pore size was measured using the software ImageJ. Since the alumina foam samples were brittle, microstructural observations were conducted only on the top surface of these samples, as shown in Figure 5.



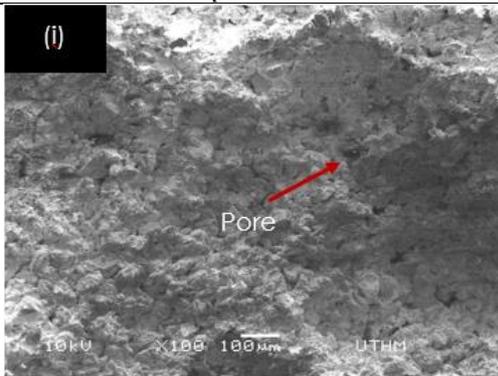
**Fig. 5** Microstructure of alumina foam under SEM



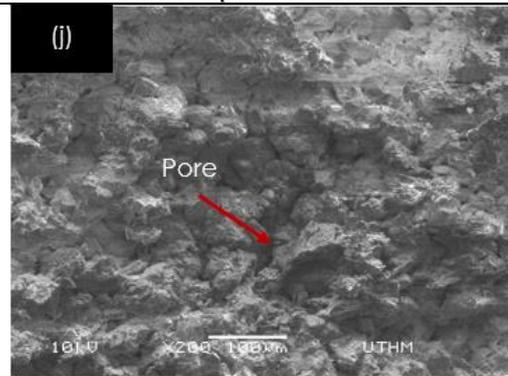
**Figure 5(g)** Alumina foam with 7 wt% PGE/CMC powder



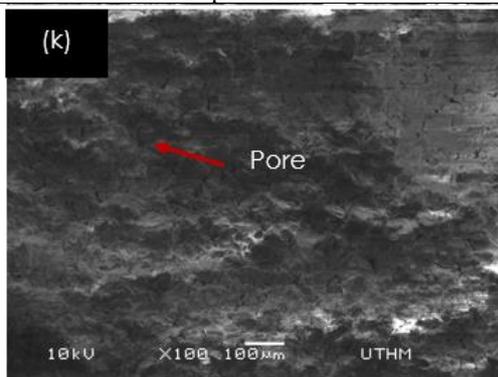
**Figure 5(h)** Alumina foam with 7 wt% PGE/CMC powder



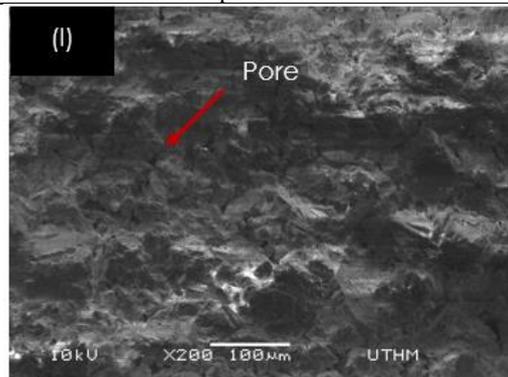
**Figure 5(i)** Alumina foam with 10 wt% PGE/CMC powder



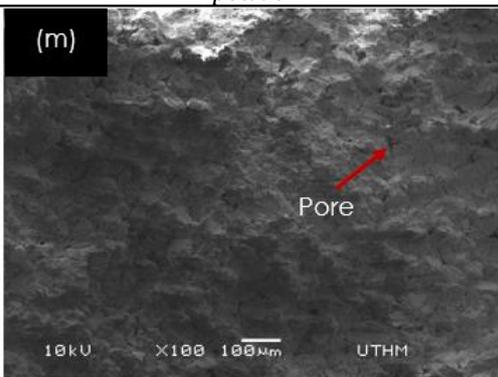
**Figure 5(j)** Alumina foam with 10 wt% PGE/CMC powder



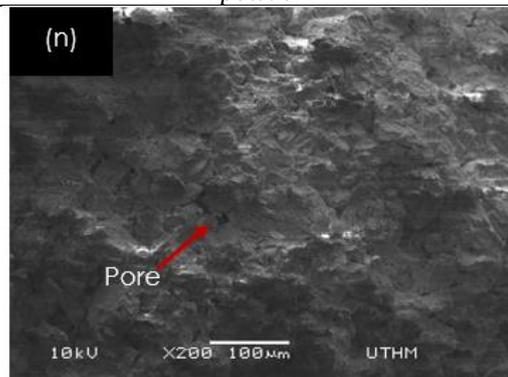
**Figure 5(k)** Alumina foam with 0 wt% bentonite powder



**Figure 5(l)** Alumina foam with 0 wt% bentonite powder

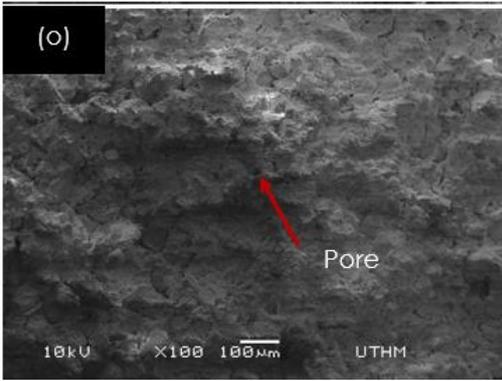


**Figure 5(m)** Alumina foam with 3 wt% bentonite powder

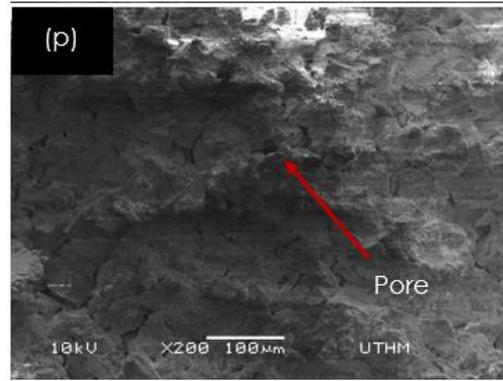


**Figure 5(n)** Alumina foam with 3 wt% bentonite powder

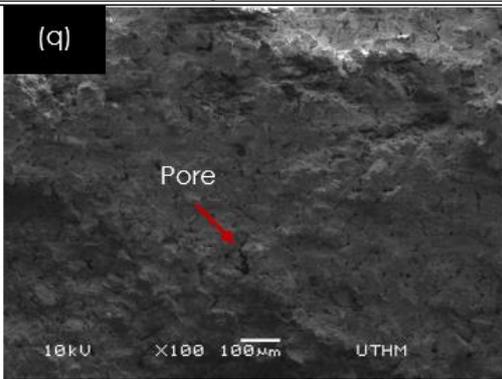
**Fig. 5** Continue



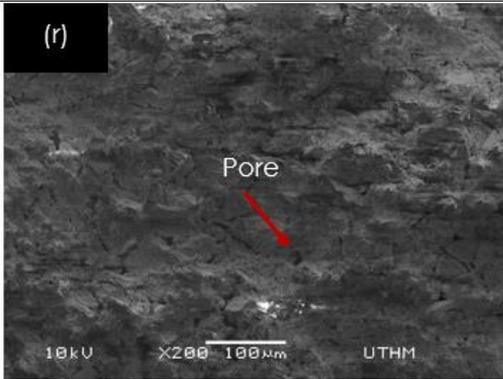
**Figure 5(o)** Alumina foam with 5 wt% bentonite powder



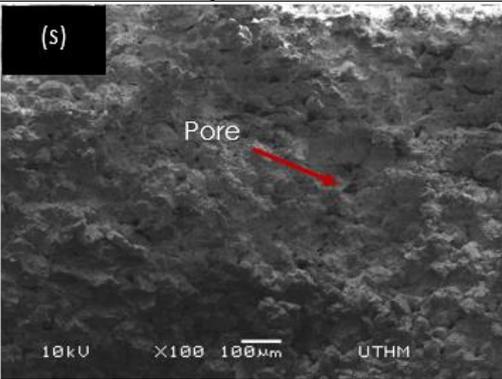
**Figure 5(p)** Alumina foam with 5 wt% bentonite powder



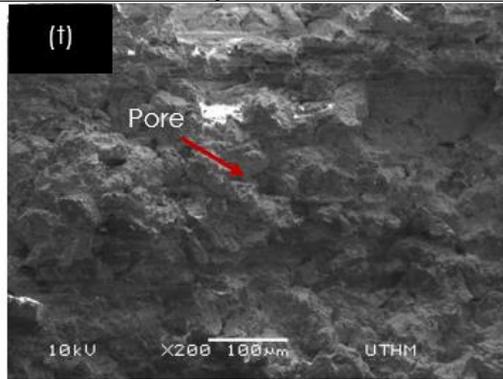
**Figure 5(q)** Alumina foam with 7 wt% bentonite powder



**Figure 5(r)** Alumina foam with 7 wt% bentonite powder



**Figure 5(s)** Alumina foam with 10 wt% bentonite powder



**Figure 5(t)** Alumina foam with 10 wt% bentonite powder

**Fig. 5 Continue**

According to the data collected, the samples did not all have an equal number of pores and failed to generate the expected pattern of intersecting pores and closed holes. This is because it is impossible to regulate the amount of binder and space holder that is removed during the sintering process in order to achieve a uniform distribution. As a result, PGE/CMC and bentonite as the binder have nearly identical pore formations when corn starch is used as a spacer holder. Pore development is also influenced by the type of space holder and the physical characteristics of the binder components. According to earlier studies, this is because of the nature of the foaming process [1].

#### 4. Conclusion

The study found that several binders, including bentonite, carboxymethyl cellulose (CMC), and polyethylene glycol (PEG), have a major impact on the mechanical and physical characteristics of alumina foams. In particular, changes in binder composition have a significant impact on the final product's density, porosity, and strength in addition to handling and shaping procedures. The findings show that there is an ideal binder content that achieves a balance between desirable material qualities and processing accessibility. Higher binder concentrations, for example, enhanced sample handling during fabrication, but because of the increased packing density, it also

resulted in decreased porosity and mechanical strength. On the other hand, reduced binder levels improved porosity at the expense of structural integrity.

Additionally, the effects of binder interactions with alumina particles on pore formation and distribution were shown by microstructural analysis using scanning electron microscopy (SEM). The results highlight how important it is to choose binders that are suitable for a certain application because doing so can improve performance in areas like thermal insulation and filtration. The study indicates that optimizing the alumina foam fabrication process requires an understanding of the link between binder types, their composition, and the resulting material qualities. In order to improve the qualities of alumina foams and maybe expand their range of applications in modern technological areas, future research should concentrate on investigating different binder materials and creative processing methods. Overall, this research contributes valuable knowledge to the field of material science, particularly in optimizing alumina foam fabrication for various industrial applications.

## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

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