

# Pumice/aluminium syntactic foam

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## ABSTRACT

A novel filler material is introduced to produce high strength metal-matrix syntactic foam. Packed beds of pumice particles, a low-cost natural porous volcanic glass, with the size range of 2.8–4 mm were infiltrated with molten aluminium alloy. The resulting syntactic foams were subjected to microstructural observations and chemical analysis. Furthermore, quasi-static compression testing was applied on heat treated samples. The material strength and the deformation mechanism under compressive loading of the pumice particles and foams were investigated. The results indicate that there is a limited chemical reaction between the particles and matrix. The pumice particles considerably enhance the strength of the foam and result in an average plateau stress of 68.25 MPa and specific energy absorption of 24.8 MJ/m<sup>3</sup>. Pumice particles show higher strength in the direction of tubular pores. The mechanical anisotropy of pumice particles is likely to cause a slight variation in the directional properties of the foams.

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## 1. Introduction

Metallic syntactic foams (MSFs), which are combinations of metal and hollow or porous particles, have attracted great attention in recent years. This is primarily due to their lower price and superior mechanical properties when compared to conventional metallic foams [1]. However, the minimum achievable density and cost of MSFs is limited by the filler material. Man-made filler particles e.g. ceramic [2–9], carbon [10], and glass [11–15] hollow spheres have a relatively high price [16]. Fly ash cenospheres, which are by-product of coal firing, are of highly cost-efficient filler materials. However, like some other ceramic and glass hollow spheres, cenospheres have small size (typically less than 500 $\mu$ m), which may vary over a narrow range (see Table 1). This imposes the requirement of a complex manufacturing technology, i.e. squeeze casting [17], and high pressure infiltration [9,12,18] if a high volume fraction of filler particles is desired. This adds to the production cost. Some of the cost barriers to widespread application of syntactic foams can be overcome by using low cost filler particles [1,19] with a wide size range. In a previous paper [16], we introduced expanded perlite (EP), a natural super-light porous volcanic glass, to produce a low cost and low density MSF (see Table 1). Although the mechanical properties of EP/aluminium syntactic foam can be improved by heat treatment [20], and utilising smaller EP particles [21], it still has a lower quasi-static [16] and dynamic [21] compressive strength when compared with conventional syntactic foams (see Table 1). This is a result of the low crushing strengths of EP particles due to their 95% internal porosity [16].

In this paper, a novel porous filler particle is introduced to produce a MSF with higher compressive strength whilst achieving a low final cost and a density comparable with conventional syntactic foams. Pumice is a silica-base porous aggregate which forms naturally during volcanic eruption. The pressure drop due to the rapid expulsion of magma into the atmosphere causes the release of dissolved gases which forms magma froth. The falling magma froth turns to a porous ceramic after solidification [22]. Pumice is mainly surface-mined in large quantities and has been used in structural applications such as light-weight concretes [23], cements [24], and filters [25].

In the present investigation, a packed bed of pumice particles was infiltrated with molten A356 aluminium alloy and the microstructural and mechanical properties of the created syntactic foam were investigated.

## 2. Experimental procedures

### 2.1. Fabrication process

Pumice is extracted in surface mining and hence comes with some impurities. The as-received material, provided by Australian Perlite Company, was soaked in water and the floating low density pumice particles were separated from high density impurities like sand. Particles were then dried in an oven at the temperature of 120 °C for 24 h. A packed bed of pumice particles having the size of 2.8–4 mm were infiltrated by molten A356 Al alloy through a backward infiltration process which is explained in [16] in detail. In brief, a graphite mould was filled with pumice particles in five layers followed by vibration for 1 min. A stainless steel mesh was attached to the mould on top of

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**Table 1**  
Data of some studied MMSFs.

Matrix	Filler material	Filler size	Filler particle density (g/cm <sup>3</sup> )	MMSF density (g/cm <sup>3</sup> )	Plateau stress (MPa)	Refs.
Pure Al	Cenosphere	90–150 μm	1.00–0.74	1.52–1.43	63–42	[17]
A356	Cenosphere	45–250 μm	0.7	1.25–2.1	45–180	[18]
Al14047	Ceramic HS: 33Al <sub>2</sub> O <sub>3</sub> –48SiO <sub>2</sub> –19 Mullite	150 μm	0.6	1.35		[12]
Pure Al	Ceramic HS: 45 SiO <sub>2</sub> –35 Al <sub>2</sub> O <sub>3</sub> –20 Mullite	100–1450 μm	0.57–0.81	1.43–1.49	77	[26]
Pure Al	Ceramic HS: 60SiO <sub>2</sub> –40Al <sub>2</sub> O <sub>3</sub>	250–500 μm	0.75	1.38	62	[9]
Al 6082	Ceramic HS: 60SiO <sub>2</sub> –40Al <sub>2</sub> O <sub>3</sub>	75–125 μm	0.6	1.45	92	[27]
Al	Ceramic HS: 60SiO <sub>2</sub> –40Al <sub>2</sub> O <sub>3</sub>	12–350 μm		1.56		[4]
A356	Ceramic HS: SiC	1 mm	1.160	1.819	110	[2]
Al2024	Ceramic HS: Alumina	3–4.25 mm		1.25		[8]
A356	Ceramic HS: Alumina	3 mm		1.6–2.11	62.8	[3]
Pure Al	Glass HS: 60SiO <sub>2</sub> –15Al <sub>2</sub> O <sub>3</sub> –15CaO–10Na <sub>2</sub> O	0.5–4 mm	0.95–0.65	1.58–1.88	42	[9]
A356	Expanded perlite	3–4 mm	0.18	1.05	45	[21]

particles to fix them in place. A block of A356 alloy was placed in a graphite crucible and the filled mould was inserted in this crucible upside-down leaving only a tight gap between the crucible and the mould. All filling and assembly steps were performed in a glove box with a controlled Argon atmosphere. This was to minimise any oxygen between and inside particles and to achieve a better particle wetting. The whole setup was placed in a resistance furnace and the temperature was increased to 720 °C at the rate of 40 °C/min. After 20 min at 720 °C, the assembly was removed from the furnace and the mould was pushed down using a 1.5 kg weight. As a result, the pumice particles were infiltrated with molten aluminium and excess melt and argon gas exited the mould through a 1 mm hole. The mould was cooled in air before pumice/aluminium syntactic foam (PASf) samples were removed and machined. The volumes of 5 cylindrical PASf samples with a diameter of 27 ± 0.1 mm and heights of 41 ± 1 mm were obtained by measuring the dimensions using a digital calliper. Sample densities were measured by dividing the sample mass by its calculated volume (see Table 2). Samples were then subjected to a T6 heat treatment comprising solution at 540 °C for 16 h, quenching in water, and aging at 160 °C for 10 h [28].

## 2.2. Characterisation of samples

Samples for metallography were cut from the untreated PASf foam and were subjected to a standard polishing procedure which comprised grinding using 180-, 240-, 320-, 600-, and 1200-grit silicon carbide papers and subsequent polishing with 0.5 μm and 0.05 μm diamond powder suspended in distilled water. Samples were then placed in an ultrasonic ethanol bath to remove debris and contaminations. Microstructural observations were performed using scanning electron microscopy (FEI XL30 SEM). Chemical composition analysis was done by Energy-dispersive X-ray spectroscopy (EDS) using a Zeiss SEM.

Compression tests were performed on PASf cylindrical samples according to the ISO 13314 standard [29]. A uni-axial computer-controlled 50 kN Shimadzu testing machine was used at a crosshead speed of 3 mm/min. The two sample contact surfaces were lubricated with a silicone lubricant to minimise friction effects. The load and cross-head displacement data were recorded by a built-in data acquisition software (Trapezium2) and subsequently converted to engineering stress–strain curves based on the initial sample cross sectional area and height. A digital camera captured images of samples while deforming in compression test.

## 3. Results and discussion

### 3.1. Microstructural observations

Fig. 1a and b shows SEM images of the highly porous surface of pumice particles. The pores are formed when the magma brakes

**Table 2**  
Samples information.

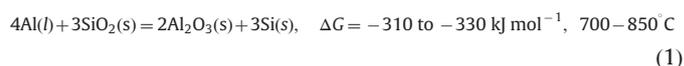
No.	Foam density (g/cm <sup>3</sup> )	Pumice volume fraction (%)	Pumice particle density (g/cm <sup>3</sup> )	Total porosity (%)
SF1	1.48	62.10	0.76	45.30
SF2	1.48	63.06	0.79	44.99
SF3	1.49	61.89	0.79	45.04
SF4	1.50	61.77	0.78	44.61
SF5	1.50	63.50	0.80	44.96

through the earth surface and dissolved gas is released due to the sudden pressure drop. This creates a molten froth which solidifies rapidly in the air and falls back to earth as pieces of pumice. Depending on the final cooling state, two forms of pores can be formed, tubular (see Fig. 1a) or spherical (see Fig. 1b). The predominant structure is tubular which forms when pumice is cooled during extrusion or any form of flow. A spherical structure with large pores is less common and formed when pumice cools in a hydrostatic environment and bubble coalescence occurs [22].

Fig. 1c shows the cross section of a pumice particle. It comprises a heterogeneous near circular pore structure. The larger pores with thinner walls are formed by partial coalescence of bubbles during cooling and solidification of magma [30]. Fig. 1c also shows the location of the EDS spectrum shown in Fig. 1d. The spectrum indicates the elemental composition of pumice particle: 75 wt% SiO<sub>2</sub>, 13.5 wt% Al<sub>2</sub>O<sub>3</sub>, 2.5 wt% Na<sub>2</sub>O, 2.8 wt% K<sub>2</sub>O, 1.8 wt% CaO, 1.7 wt% Fe<sub>2</sub>O<sub>3</sub>, 0.45 wt% MgO, 0.18 wt% TiO<sub>2</sub>, and traces of heavy metals.

Fig. 2a shows a cross section of PASf. Depending on the cutting direction, the tubular pores of the pumice can be seen as long grooves or equiaxed near circular shapes. The internal cellular topology of pumice particles can be seen in Fig. 2a as a vesicular structure which forms because of elongation of air bubbles during the directional solidification of magma. Molten metal does not penetrate into the surface pores of particles. The pumice structure is mainly closed cell and only the surface pores are open to the surroundings [31]. However, the high surface tension of molten aluminium prevents the infiltration of these small surface pores.

Like most reported filler particles, pumice is mostly made up of SiO<sub>2</sub> which can react with molten Al through the following reaction [12,16,32]:



The occurrence of this reaction was investigated by X-ray mapping of oxygen and aluminium at the interface area recorded with OK<sub>α</sub> (see Fig. 2b and c). In case of reaction, amorphous SiO<sub>2</sub> transforms to crystalline α-Al<sub>2</sub>O<sub>3</sub> in the matrix and Si inclusions precipitate along the interface. Accordingly, high concentration of

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