

## Development of new perlite/sodium silicate composites

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### ABSTRACT

A novel mechanical behaviour of perlite/sodium silicate composites is studied. The objective was to develop new perlite composites. The flotation method was adopted for expanded perlite consolidation. For the composites development, sodium silicate dehydration behaviour was characterised with phases formed during dehydration i.e. liquid, gel, and solid phases. The water loss-time curve for dehydration was found to have three distinctive parts - linear part at an early stage for liquid phase, followed by non-linear part during a period between commencements of gel and hydrated solid phase formations, and then another linear part for hydrated solid phase. Foams as composites were manufactured with diluted sodium silicate binder for a density range of 0.2 - 0.5 g/cm<sup>3</sup>. Compressive strengths and foam densities were obtained for optimum performance as functions of two independent variables i.e. compaction ratio and binder content. One of practical milestones observed was a density of 0.3 g/cm<sup>3</sup> at a compressive strength of 1MPa without reinforcement.

Keywords: Expanded Perlite, Sodium Silicate, Foam, Density, Compressive Strength.

### 1. Introduction

Perlite is a glassy volcanic rock of rhyolitic composition [1], which can be processed into an expanded form for cellular structure formation [2,3]. The expansion takes place due to the presence of water in perlite when heated to about 649-816°C [4]. The expanded perlite particles are light, environmentally friendly [5], and possess good acoustic [6] and insulation properties [7]. They have been used as additives or main components for composites, e.g. Portland cement/perlite composites for blocks [8-10], perlite/sodium silicate boards [11], roof insulation panels made of perlite/fibers/bituminous material [12], fibre reinforced perlite/cement composites [13], building boards made of fiber/asphalt coated perlite [14] or urea-formaldehyde resin/mineral fibers/gypsum/glass fibers [15], fibre reinforced sodium silicate/perlite composite [16], moisture resistant gypsum boards modified with perlite/starch/boric acid/vinyl acetate [5], gypsum/perlite composites [17], and light weight concrete [18]. However, their applications as the main constituent of composites have been limited due to relatively poor mechanical properties. One of the reasons is that the expanded perlite particles are fragile and hence easily damaged during the process of mixing with binder, resulting in a high ratio of density to strength. At the same time, the study on mechanical performance of perlite composites compatible with gypsum boards [19,20] has not much been available in the literature. It is only recently that Shastri and Kim [21,22] studied some selected properties for mechanical behavior of expanded perlite consolidated with starch for demonstration of a new manufacturing process based on the principle of flotation [23-28]. The new process appears to be capable of extending the limitation of perlite applications, allowing us to manufacture samples

for exploring novel mechanical behavior of consolidated expanded perlite particles.

In the development of perlite composites, selection of binder is another consideration along with manufacturing process. Sodium silicate may be one of candidate binders, which is an inorganic colloidal system. It has been used as foundry sand binder, fire-retardants, adhesives, and deflocculants among other applications [29]. Also, it is non-combustible, water-resistant and sufficiently inexpensive for developing building materials. This paper focuses on the novel mechanical behavior of expanded perlite/sodium silicate composites developed using the new manufacturing process developed by Shastri and Kim [22].

### 2. Constituent materials and characteristics

#### 2.1 Expanded perlite

Commercial grades of expanded perlite particles were obtained from Australian Perlite Pty Limited. Expanded perlite particles were sieved using a vibratory sieve shaker (Analysette 3 SPARTAN) into three different particle size ranges i.e. sizes between 1 and 2 mm, 2 and 2.8 mm, and 2.8 and 4 mm, which will be referred to as Size 1-2, Size 2-3, and Size 3-4 respectively.

Four different types of perlite densities were measured and listed in Table 1. For bulk density, an initial volume of 100 cm<sup>3</sup> of expanded perlite particles was poured into a glass measuring cylinder with a 28 mm diameter fitted to a manual tapper with a tapping stroke height of 5 mm, and then tapping was conducted for 300 times.

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For envelope density (terminology from ASTM D 3766-08), a volume of about 4 cm<sup>3</sup> of expanded perlite particles was poured into molten paraffin wax in an aluminium container (37 mm in diameter and 13 mm height), ensuring it was fully submerged and each particle was fully wetted before wax solidification. The enveloped volume of perlite was determined by the difference in wax volume before and after submersion of perlite. The calculated envelope density is given in Table 1.

**Table 1** Densities of expanded perlite particles.

Perlite particle size	Bulk density (g/cm <sup>3</sup> )	Particle envelope density (g/cm <sup>3</sup> )	Particle skeletal density (g/cm <sup>3</sup> )	Material density (g/cm <sup>3</sup> )
Size 1-2	0.089	0.140	1.466	2.46
Size 2-3	0.091	0.160	1.309	2.46
Size 3-4	0.100	0.152	1.207	2.46

Particle skeletal and material/true densities were measured using a gas pycnometer (AccuPyc 1330). For the material density sample preparation, expanded perlite particles were crushed into fine powder using a ball mill (8000D Mixer/Mill SPEX) for at least 5 minutes to remove the closed pores before volume was measured in pycnometer. It was confirmed using an optical microscope (Olympus SZ-CTV) that the closed pores were removed. Various types of porosities were obtained and listed in Table 2.

**Table 2** Various porosities, fractions of open pores and closed pores of perlite particles.

Perlite particle size	Total porosity in bulk volume ( $v_{total}$ ), %	Fraction of open pores in perlite particles ( $v_{opore}$ )	Fraction of closed pores in perlite particles ( $v_{cpore}$ )	Particle porosity ( $v_{pp}$ ), %	Inter-particle Porosity in bulk volume ( $v_{ipp}$ ), %
Size 1-2	96.37	0.9045	0.0386	94.31	36.43
Size 2-3	96.31	0.8778	0.0572	93.50	43.13
Size 3-4	95.92	0.8741	0.0641	93.82	34.21

**2.2 Sodium silicate solution and dehydration behaviour**  
Sodium silicate solution (ChemSupply) with a density range of 1.37-1.40 gm/cm<sup>3</sup>, a solid content range of 37.10 - 38.00% (by mass), and a weight ratio of silica to sodium oxide (SiO<sub>2</sub>/Na<sub>2</sub>O) range of 3.16-3.22 was used as binder. Sodium silicate solution was dehydrated at 80°C to obtain a solid sample, and then was ball-milled (8000D Mixer/Mill, SPEX) for 30 minutes into powder for density measurement. The density was measured using a gas pycnometer (AccuPyc 1330) and found to be 2.17 g/cm<sup>3</sup>.

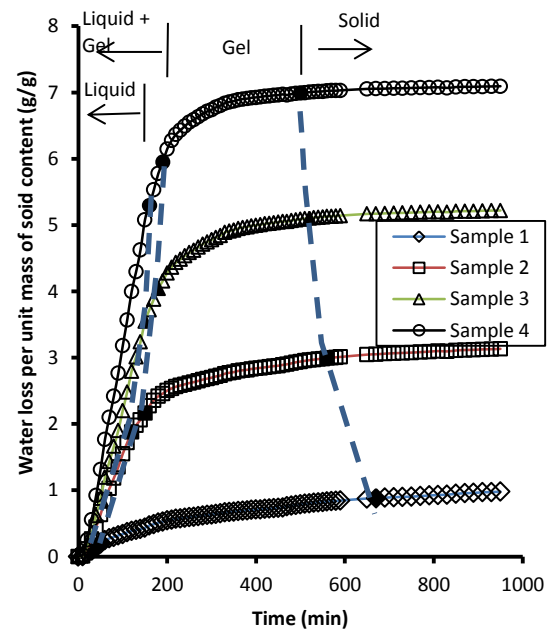
To characterise the dehydration behaviour, sodium silicate solution (SSS) was diluted with water as

specified in Table 3. The diluted samples were kept inside an electric fan forced air oven (Lebec Oven BTC-9090) at 65°C and mass loss was recorded every 10 minutes. Three dehydration phases were identified from diluted sodium silicate solution as dehydration progresses. The first phase was made of liquid, the second made of gel, and the third made of solid. (The gel is a cohesive substance consisting of colloidal particles [29]). The commencement and completion points of the gel formation and other phases are indicated in Fig. 1 and water contents at different stages are listed in Table 4.

**Table 3** Samples of sodium silicate solution (SSS) used for dehydration behaviour.

Samples	Mass of SSS (g)	Mass of diluted SSS, (g)	Water content after dilution with water (%)
Sample 1 (control)	13.85	13.85	62.45 <sup>a</sup>
Sample 2	6.93	11.93	78.21
Sample 3	4.61	11.28	84.66
Sample 4	3.46	10.96	88.14

<sup>a</sup> Provided by the manufacturer (ChemSupply)



**Fig.1** Water loss during dehydration at 65°C.

Some phase transitional points appear to be practically distinguishable on the water loss - time curve (Fig. 1). The first linear portion of the curve corresponds to liquid phase, non-linear portion corresponds to a stage where gel phase started to form from liquid phase until the two phases (liquid and gel) becomes fully gel prior to solidification, and the other linear part corresponds to hydrated solid phase.

It is noted that water contents at the completion of gel formation from (gel+liquid) are approximately constant at high dilution levels (Table 4). Further drying of the gel leads to the hydrated solid phase. However, the water contents in hydrated solid phase are not as much constant as those at the gel completion point. Even some trend is noticeable – the more water content at dilution the less water content at the solid phase.

**Table 4** Water contents at different stages for dehydration at 65°C.

Samples	Water content at commencement of gel (%)	Water content at gel completion (%)	Water content at hydrated solid formation (%)
Sample 1 (control)	61.12	59.44	43.92
Sample 2	63.06	58.71	37.14
Sample 3	66.31	59.58	29.12
Sample 4	68.12	59.73	30.76

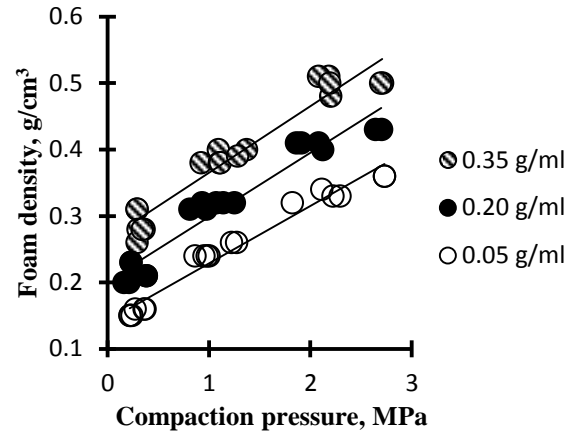
### 3. Manufacturing process of samples and mechanical tests

The process consists of different stages: dilution of sodium silicate binder, mixing of binder and perlite in a container, flotation of wet-mix, moulding and compaction, demoulding and drying as detailed elsewhere [21]. The dilution of sodium silicate was made in drinkable tap water. The perlite was poured into a mixing container containing the prepared binder, followed by stirring/tumbling of the mixture for phase separation consisting of top phase of perlite and binder, and bottom phase of binder. The mixing container was left until perlite particles float to the surface, forming two phases i.e. top phase made of perlite and binder and bottom phase made of just binder. The top phase was formed immediately and transferred into a mould for compaction. The compaction was conducted at a crosshead speed of 10 mm/minute on a universal testing machine (Shimadzu 5000).

Compression tests of manufactured foam specimens were conducted on a universal testing machine (Shimadzu 5000) at a crosshead speed of 5.0 mm/min and at an ambient temperature range 16°-21°C. A Hounsfield compression cage was used, in which the platens were lubricated (engine oil SAE 15-40) to minimize the friction between test samples and platens. Samples of 35mm high and 35mm in diameter were compressed 10-15 % of the initial height of the test sample, which was sufficient to obtain the results for characteristic stages of stress-strain curve. Compressive strength was calculated using the original cross-sectional area and compressive modulus was calculated from the tangent to the inflection point of the stress-strain curve.

### 4. Results and discussion

Data points obtained for dry foam density (of perlite-sodium silicate) versus applied compaction pressure are shown in Fig. 2.



**Fig. 2** Foam dry density versus applied compaction pressure for various binder contents - pure binder mass per unit diluted binder volume (g/ml).

For any given binder content, foam density tends to increase linearly with increasing compaction pressure for all the particle sizes (not shown). The Pearson correlation coefficients ( $r$ ) for the combined plots in Fig. 2 were found to be 0.968, 0.967, and 0.983 for sodium silicate contents, 0.35 g/ml, 0.2 g/ml, and 0.05 g/ml respectively, indicating foam densities are not sensitive to particle size although there was a weak tendency that the smaller particle size the higher foam density, and a little higher compaction pressure is required for larger particle sizes to achieve a certain density. Also, it is found that a higher compaction pressure is required for a certain foam density as the binder content gets lower as expected. On the other hand, a reason why the initially smaller particles tend to have higher foam densities may be due to a higher binder retention for a higher volume of voids for smaller particles, as will be discussed below (Fig. 3), when there is not much difference in fraction of open pores between different particle sizes as indicated in Table 2.

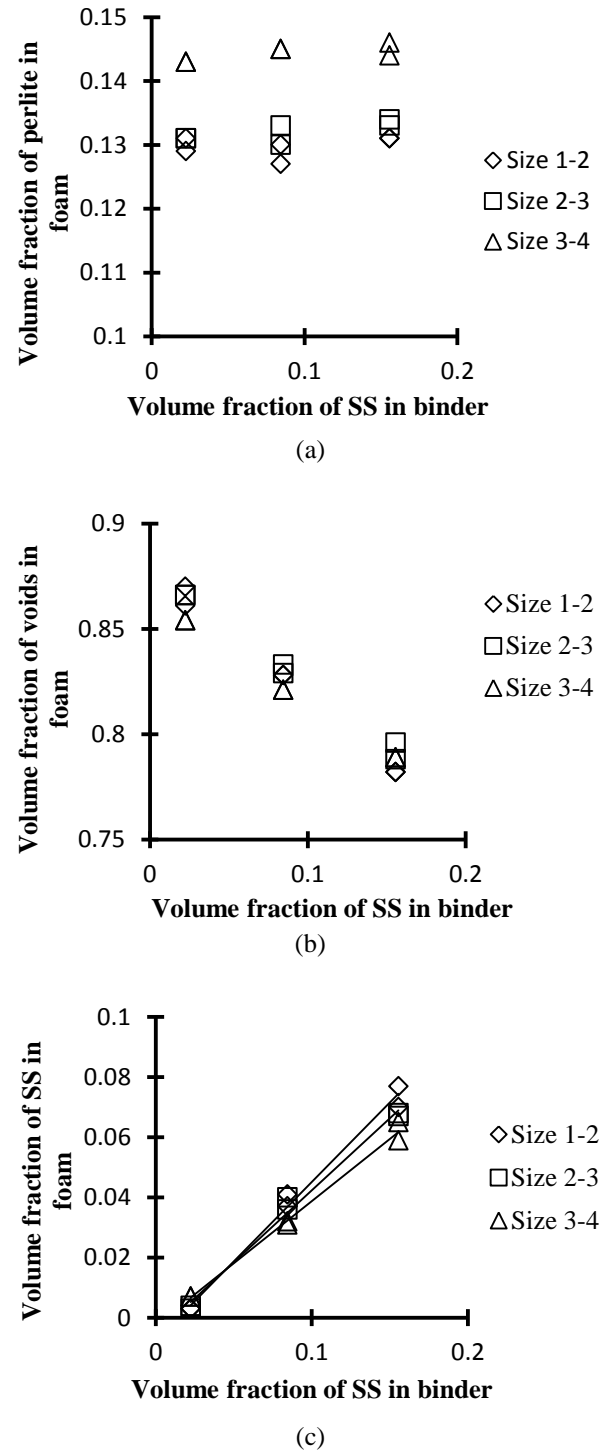
Various volume fractions of perlite foams at a compaction ratio of 3.55-3.66 are plotted in Fig. 3 as a function of volume fraction of sodium silicate in diluted binder (VFSSB). The volume fraction of perlite in foam (VFPPF) [Fig. 3 (a)] appears to be not sensitive to VFSSB but the larger particle size tends to have a higher VFPPF probably because the fragmentation of larger particles during compaction did not leave much space for inter-particle voids.

Also, as expected, the volume fraction of voids in foam (VFSSF) [Fig. 3 (b)] decreases as VFSSB increases but without much sensitivity of particle size effect. On the

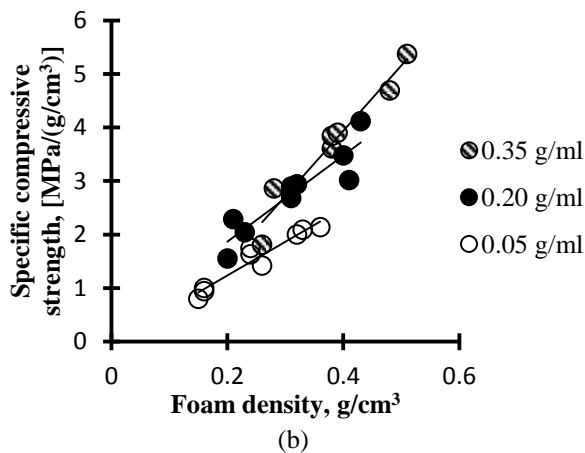
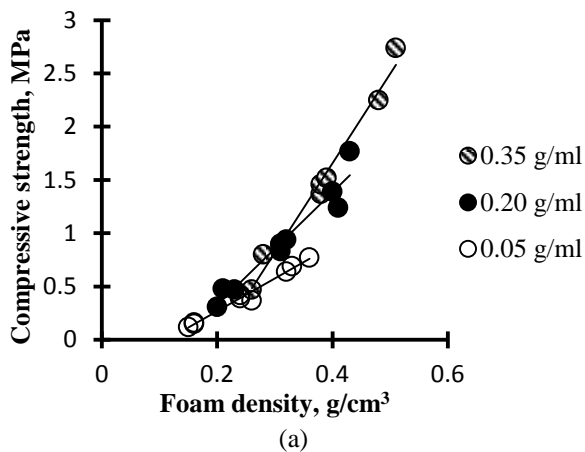
other hand, the volume fraction of SS in foam (VFSSF) [Fig. 3 (c)] is found to be highly proportional to VFSSB. The Pearson correlation coefficients ( $r$ ) with a forced intercept at zero were found to be 0.987, 0.985, and 0.989 for Size 1-2, Size 2-3, and Size 3-4 respectively. The VFSSF displays some dependency on particle sizes as the VFSSB increases - the smaller particles size the higher VFSSF probably because of more void spaces for smaller particles.

Compressive strength and specific compressive strength of perlite-silicate foams are plotted as a function of dry foam density in Fig. 4. It is seen that they increase with increasing foam density as expected for all the different contents of sodium silicate in diluted binder. The least square lines and Pearson correlation coefficients ( $r$ ) for compressive strength were found to be  $y = 8.3871x - 1.6972$  with  $r = 0.982$ ,  $y = 5.3022x - 0.7358$  with  $r = 0.9409$ , and  $y = 3.0676x - 0.3445$  with  $r = 0.9821$  for respective sodium silicate contents of 0.35, 0.20, and 0.05 g/ml. Also, for specific compressive strength,  $y = 12.198x - 0.9403$  with  $r = 0.952$ ,  $y = 8.0803x + 0.2482$  with  $r = 0.8485$ , and  $y = 6.3112x - 0.0268$  with  $r = 0.9821$  for respective sodium silicate contents of 0.35, 0.20, and 0.05 g/ml were found. Each data set for each least square line includes three different particle size ranges (Sizes 1-2, 2-3, and 3-4) appearing in a small cluster for similar foam density values in Fig. 4.

The high correlation coefficients indicate that the particle size effect on the compressive strength is insignificant. The slope of the least square line increases with increasing sodium silicate content. The foam density increases for each sodium silicate content is due to the increase of compaction ratio from 1.5 up to 3.5. Thus, the compressive strength is a function of two independent variables. Accordingly, an optimum combination of two independent variables may be necessary for practical manufacturing purposes. If we choose a value of 1 MPa for compressive strength with a density of 0.3 g/cm<sup>3</sup>, there may be two different choices i.e. sodium silicate contents, 0.35 g/ml with a compaction ratio of about 1.5 (not shown on graph), and 0.20 g/ml with a compaction ratio of 2.5(not shown on graph). A gypsum compressive strength of 1MPa with a density of 0.87 g/cm<sup>3</sup> by Colak [19] may be a reference for comparison. Also, a specific compressive strength range of 0.8-5.37 MPa/(g/cm<sup>3</sup>) in Fig. 4(b) may be compared with a range of 0.62 – 2.03 MPa/(g/cm<sup>3</sup>) for gypsum by Colak [19], a range of 1.1- 3.1 MPa/(g/cm<sup>3</sup>) for foam gypsum by Skujans et al [20] or 1-3.86 MPa/(g/cm<sup>3</sup>) for gypsum/perlite composites by Vimmrova et al[17].



**Fig. 3** Volume fractions of perlite-sodium silicate foam as a function of volume fraction of sodium silicate in diluted binder for compaction ratio  $c = 3.55-3.66$ : (a) volume fraction of perlite material excluding pores in foam; (b) volume fraction of voids in foam; and (c) volume fraction of sodium silicate in foam (Person correlation coefficients  $r$  with forced intercept at zero for 1-2 mm = 0.987, 2-2.8mm = 0.985, and 2.8 – 4 mm = 0.989).

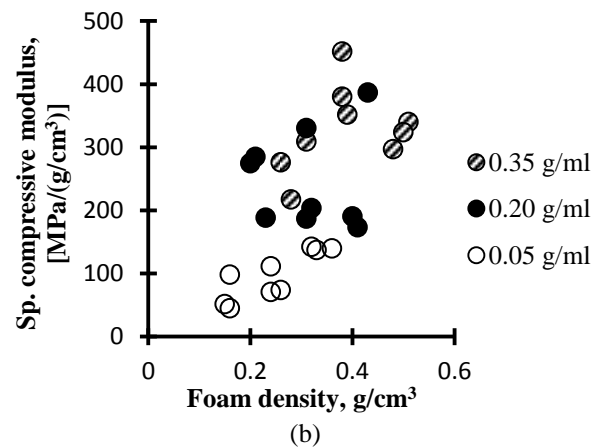
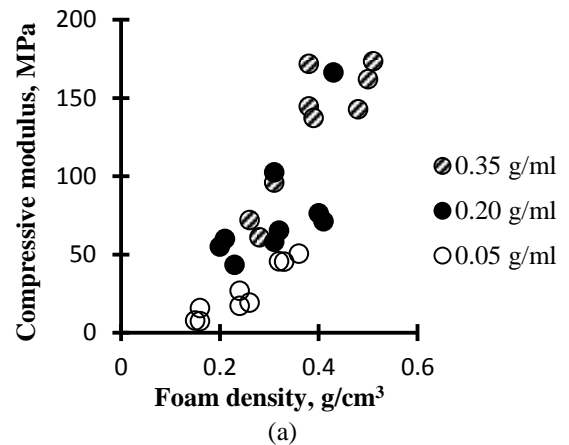


**Fig. 4** (a) Compressive strength as a function of foam density for various sodium silicate contents. (b) Specific compressive strength as a function of foam density for various sodium silicate contents. [Compaction ratio was varied within a range of 1.5 -3.5 for all the sodium silicate contents.]

Compressive modulus and specific compressive modulus for various binder contents (but without distinguishing particle sizes) are given in Fig. 5. As expected, they increase with increasing foam density, and more rapidly increase with increasing binder content despite relatively high scatters compared with compressive strengths.

## 5. Conclusion

Sodium silicate as binder has been characterised for developing perlite foams. Perlite foams have been manufactured with sodium silicate as new composites for a foam density range of 0.2 - 0.5 g/cm³. Compressive strengths and foam densities can be optimized with two independent variables i.e. compaction ratio and binder content. One of practical milestones achieved appears to be a density of 0.3 g/cm³ at a compressive strength of 1MPa without reinforcement.



**Fig. 5** (a) Compressive modulus and (b) specific compressive modulus as function of foam density.

## Acknowledgments

The authors gratefully acknowledge the Newcastle University International Postgraduate Research Scholarship (NUIPRS) and The University of Newcastle Research Scholarship (UNRSC 50:50) provided for one of authors (MA).

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