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Novel mechanical behaviour of perlite/sodium silicate composites

Md Arifuzzaman *, Ho Sung Kim

Mechanical Engineering, School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia

HIGHLIGHTS

- A novel mechanical behaviour of perlite/sodium silicate composites is studied.
- Dehydration behaviour of sodium silicate as binder is characterised.
- Mechanical properties are discussed in relation with manufacturing parameters.
- Manufacturing parameters and volume fractions of constituents are correlated.
- A rule of mixtures is proposed for a constant compaction ratio.

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ABSTRACT

A novel mechanical behaviour of perlite/sodium silicate composites is studied with the benefits of a new manufacturing method based on the perlite particle buoyancy. The objective was to develop perlite composites and to understand their quantitative relations between manufacturing parameters, volume fractions of constituents, and properties. 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^3. One of practical milestones achieved for composite properties without reinforcement was a density of 0.3 g/cm^3 at a compressive strength of 1 MPa. Manufactured perlite/sodium silicate composites are analysed/discussed for understanding from three different perspectives i.e. manufacturing parameters (i.e. binder content, compaction pressure, and compaction ratio), properties (i.e. particle size, density, compressive strength, and modulus), and volume fractions of constituents. A rule of mixtures applicable for perlite composites for a constant compaction ratio was developed in comparison with that for particulate composites with non-compaction. It may be a basis for further development for variable compaction ratio in the future.

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 it is heated to about 649–816 °C [4]. The expanded perlite particles are light, environment-friendly [5], and possess good acoustic [6] and insulation properties [7]. Their uses are broadly covered in the literature by Kendall [8]. They have been used as additives or main components for composites, e.g. Portland cement/perlite composites for blocks [9,10], perlite/sodium silicate boards [11], roof insulation panels made of perlite/fibres/bituminous material [12], fibre reinforced perlite/cement composites [13], building boards made of fibre/asphalt coated perlite [14] or urea–formaldehyde resin/mineral fibres/gypsum/glass fibres [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 their relatively poor mechanical properties. One of the reasons for this 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.

* Corresponding author.
E-mail address: md.arifuzzaman@uon.edu.au (M. Arifuzzaman).

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Nomenclature

F_p	load carrying capacity of perlite particles
F_b	load carrying capacity of binder
ρ_{pB}	perlite bulk density
ρ_{pE}	perlite envelop density
ρ_{pM}	perlite material density
ρ_{pS}	perlite skeletal density
ρ_f	density of dry foam
ρ_b	density of binder (sodium silicate)
$m_p = m_{pm}$	mass fraction of perlite in foam
m_b	mass fraction of binder (sodium silicate) in foam
M_p	mass of perlite in foam
M_f	mass of foam
M_b	mass of binder (sodium silicate) in diluted binder
M_{bc}	mass of binder (sodium silicate) in foam after compaction
$R_{bd}\left(=\frac{M_b}{V_i}=\frac{M_{bc}}{V_{ic}}\right)$	mass of pure binder per unit volume of diluted binder
σ_{bond}	bonding strength between binder and particles
σ_b	binder strength
σ_f^c	compressive strength of perlite/sodium silicate foam
σ_f^s	shear strength of perlite/sodium silicate foam
σ_b^s	shear strength of binder
$\sigma_b^{s'}$	shear stress of binder
σ_P^s	shear strength of perlite particles
υ_{cpore}	volume fraction of closed pores in perlite particles
υ_{opore}	volume fraction of open pores in perlite particles
υ_{ipp}	inter-particle porosity in bulk volume
υ_{pp}	particle porosity
υ_{total}	total porosity in bulk volume
v_b	volume fraction of binder in foam
v_{bi}	volume fraction of binder in foam between perlite particles
v_{bs}	volume fraction of binder in skeletal volume of perlite particles
v_{pe}	volume fraction of perlite envelope in foam
v_{pm}	volume fraction of perlite material in foam
v_{tv}	volume fraction of voids in foam including both inter- and intra-particle voids
v_{vi}	volume fraction of inter-particle voids in foam
v_{vi0}	volume fraction of inter-particle voids in foam without binder
V_i	total volume of diluted binder
V_{ic}	total volume of diluted binder in foam after compaction

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 behaviour of expanded perlite consolidated with starch for demonstration of a new manufacturing process based on the principle of buoyancy [23–28]. The new process appears to be capable of extending the limitation of perlite application, allowing us to manufacture novel perlite/sodium silicate composites.

In the development of perlite composites, selection of binder is another consideration along with manufacturing process. Sodium silicate, which is an inorganic colloidal system, may be one of candidate binders. It has been used as foundry sand binder, fire-retardants, adhesives, and deflocculants among other applications [29] even though the behaviour of sodium silicate is not fully understood [30]. Also, it is non-combustible, water-resistant and sufficiently inexpensive for developing building materials. This paper focuses on the novel mechanical behaviour of expanded perlite/sodium silicate composites developed using the new manufacturing process [21,22].

2. Constituent materials and characterisation

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 perlite densities measured and listed in Table 1. The density terminology is based on ASTM D 3766-08 and illustrated in Fig. 1. For bulk density measurement, an initial volume of 100 cm^3 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. For envelope density measurement, a volume of about 4 cm^3 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. 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 min to remove the closed pores before volume was measured in pycnometer. It was visually confirmed using an optical microscope (Olympus SZ-CTV) that the closed pores were removed.

Various porosities defined below were obtained and listed in Table 2. The total porosity (υ_{total}) in bulk volume is defined as

$$\upsilon_{total} = \left(1 - \frac{\rho_{pB}}{\rho_{pM}}\right) \tag{1}$$

where ρ_{pB} is the perlite bulk density and ρ_{pM} is the perlite material density; the volume fraction of open pores in perlite particles (υ_{opore}) as

$$\upsilon_{opore} = \left(1 - \frac{\rho_{pE}}{\rho_{pS}}\right) \tag{2}$$

where ρ_{pE} is the perlite envelop density and ρ_{pS} is the perlite skeletal density; the volume fraction of closed pores in perlite particles (υ_{cpore}) as

Table 1
Densities of expanded perlite particles.

Perlite particle size	Bulk density (ρ_{pB}), g/cm^3	Particle envelope density (ρ_{pE}), g/cm^3	Particle skeletal density (ρ_{pS}), g/cm^3	Material density (ρ_{pM}), g/cm^3
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