Novel flexural behaviour of sandwich structures made of perlite foam/sodium silicate core and paper skin

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A B S T R A C T

A sandwich structure consisting of perlite composite foam as core and Brown paper as skin is developed and its flexural behaviour is studied in relation with properties of constituents and manufacturing variables of perlite composite foam core consolidated with sodium silicate binder by compaction. Tensile properties of Brown paper coated with binder were affected by sodium silicate content in diluted binder. The best performance of the Brown paper was found for strength and energy absorption when coated with undiluted binder. The sandwich structure was fabricated with the best performed Brown paper and perlite composite foam cores with various binder contents and compaction ratios. The performance of the sandwich structure for core shear strength, skin normal strength, and stiffness was similarly affected by manufacturing variables to those of perlite foam core. Load carrying capacity of perlite foam core reinforced with Brown paper for the sandwich structure was increased about 3–7 times the unreinforced one depending on how binder and compaction ratio are combined for manufacturing perlite foam core. The flexural failure of perlite composite foam core was initiated from the tension side of the flexural specimen. However, when the foam core was sandwiched with the Brown paper, the failure initiation site was shifted to the mid-plane of flexural specimen.

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1. Introduction

Sandwich structures consisting of skin and core are widely used for components, for which high stiffness to weight ratios are critical, in various industries associated with aerospace, marine, and building materials applications. The skin of sandwich structure is typically made of thin but strong and stiff materials while a core is made of relatively light materials. One of the major roles of the core is for keeping the distance between top and bottom sandwich skins to increase the second moment of cross sectional area whereas the skin is for protection of core in the first instance. The performance of sandwich structures depends on materials selection and design. Materials selection for skin and core depends on various factors including material availability, cost, properties of materials, etc.

For building materials applications, the cost may be a driving force along with other properties due to a large quantity of materials to be dealt with. Expanded perlite particles may be one of candidates for core materials of the sandwich structures. The uses of

perlite are broadly covered in the literature by Kendall [1] and more recently by Rashad for building materials [2]. The expanded perlite particles are light, environment-friendly [3], non-spherical but inexpensive compared to spherical hollow microspheres [4,5] and possess good acoustic [6] and insulation properties [7]. The study, however, on the mechanical performance of light perlite composites had not much been available until a new manufacturing method [8–12] was introduced for perlite by Shastri and Kim [13]. The binders for consolidating expanded perlite particles studied for the mechanical performance include starch [13], sodium silicate [14,15] and epoxy [16,17]. However, sandwich composites made of any one of these binders for perlite foam core have not been investigated for building materials.

In the development of perlite composites for sandwich core, selection of binder material is another consideration. Sodium silicate, which is an inorganic colloidal system, may be one of candidate binders as Arifuzzman and Kim [14] studied for the behaviour of diluted sodium silicate for manufacturing perlite foams. It has traditionally been used as foundry sand binder, fire-retardants, adhesives, and deflocculants among other applications [18]. Also, it is non-combustible, water-resistant, and sufficiently inexpensive for developing building materials. Another candidate material to develop sandwich structures for building materials may be the cel-

lulosic paper as sandwich skin for the similar reasons to those of perlite and sodium silicate i.e. environment-friendly, inexpensive, and the most abundant renewable polymeric material [19].

In this paper, sandwich composites made of cellulosic paper skin and perlite foam/sodium silicate core are developed and investigated. The ultimate aim was to study the flexural behaviour of the novel sandwich structure and to investigate the various effects of manufacturing variables of perlite foam core and properties of constituent materials on the mechanical behaviour for development of building materials.

2. Constituent materials

2.1. Expanded perlite

A commercial grade of expanded perlite particles obtained from Australian Perlite Pty Ltd was used for experiment. Elemental analysis for typical perlite particles provides: Si 33.8%, Al 7.2%, K 3.5%, Na 3.4%, Fe 0.6%, Ca 0.6%, Mg 0.2%, and O 47.5%. A range of expanded perlite particle sizes between 2.0 and 2.8 mm was selected unless otherwise stated for this work using a vibratory sieve shaker (Analysette 3 SPARTAN). Four different initial perlite densities [i.e. for bulk (ρ_{pB}), envelope (ρ_{pE}), skeletal (ρ_{pS}), and material (ρ_{pM})] before compaction are given in Table 1. (The terminology is based on ASTM D 3766-08 [20].) 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 at least 300 times. For particle envelope density measurement (ASTM C914-09), a volume of about 4 cm^3 of expanded perlite particles was poured into molten paraffin wax in an aluminum container (37 mm in diameter and 13 mm high), ensuring it was fully submerged and each particle was fully coated before wax solidification. The envelope volume of perlite was determined by a difference in wax volume before and after submersion of perlite. Particle skeletal (ρ_{pS}) and material (ρ_{pM}) densities were measured using a gas pycnometer (AccuPyc 1330). For the perlite 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 before compaction for expanded perlite particles defined below were obtained and listed in Table 1. The total porosity in bulk volume (v_{total}) is defined as

$$v_{total} = 1 - \frac{\rho_{pB}}{\rho_{pM}}; \tag{1}$$

the volume fraction of open pores in perlite particles (v_{opore}) as

$$v_{opore} = 1 - \frac{\rho_{pE}}{\rho_{pS}}; \tag{2}$$

the volume fraction of closed pores in perlite particles (v_{cpore}) as

$$v_{cpore} = \frac{\rho_{pE}}{\rho_{pM}\rho_{pS}}(\rho_{pM} - \rho_{pS}); \tag{3}$$

the total particle porosity (v_{pp}) as

$$v_{pp} = 1 - \frac{\rho_{pE}}{\rho_{pM}}; \tag{4}$$

and inter-particle porosity in bulk volume (v_{ipp}) as

$$v_{ipp} = 1 - \frac{\rho_{pB}}{\rho_{pE}}. \tag{5}$$

2.2. Sodium silicate

Sodium silicate solution (ChemSupply) with a density of 1.385 ± 0.015 g/cm^3, a solid content of 37.55 ± 0.45% (by mass), and a weight ratio of 3.19 ± 0.03 for silica to sodium oxide (SiO$_2$/Na$_2$O) was used as binder. The dilution of sodium silicate solution (SSS) was made by adding drinkable tap water. Mass of pure binder (Na$_2$O + SiO$_2$) per unit volume of diluted binder (R_{pbd}) was calculated using a mass of Na$_2$O and SiO$_2$ in a volume consisting of Na$_2$O, SiO$_2$, and water (Table 2). The density of dehydrated sodium silicate solution was measured using a gas pycnometer (AccuPyc 1330) and found to be 2.17 g/cm^3. The dehydration behaviour of

Table 2
Mechanical properties of Brown paper with and without coating.

R_{pbd} (g/ml)	Tensile Strength, MPa	Tensile modulus, GPa
0.00[a]	41.16 (0.38)	2.28 (0.11)
0.05	40.01 (2.40)	2.66 (0.11)
0.10	40.04 (4.57)	2.77 (0.17)
0.15	36.79 (3.67)	3.04 (0.17)
0.20	37.37 (1.29)	2.96 (0.25)
0.25	30.19 (1.88)	3.06 (0.06)
0.30	38.68 (0.33)	3.14 (0.10)
0.38[b]	42.50 (1.10)	2.64 (0.06)

Standard deviations of four specimens are given in parenthesis.
[a] Without coating.
[b] Without dilution.

Table 1
Various densities and porosities of expanded perlite particles.

Properties	Values
Bulk density (ρ_{pB}), g/cm^3	0.091
Particle envelope density (ρ_{pE}), g/cm^3	0.160
Particle skeletal density (ρ_{pS}), g/cm^3	1.309
Material density (ρ_{pM}), g/cm^3	2.460
Total porosity in bulk volume (v_{total}), %	96.31
Volume fraction of open pores in perlite particles (v_{opore}), %	87.78
Volume fraction of closed pores in perlite particles (v_{cpore}), %	05.72
Total particle porosity (v_{pp}), %	93.50
Inter-particle porosity in bulk volume (v_{ipp}), %	43.13

Fig. 1. Brown paper surface made of lignocellulosic fibres.