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Prediction and evaluation of density and volume fractions for the novel perlite composite affected by internal structure formation

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

- Mechanism for internal structure formation of perlite composite foam is identified.
- Volume fraction models for structural change of perlite composite are proposed.
- Models are capable of optimising manufacturing and properties.
- Problem with the conventional method for evaluating volume fractions is addressed.

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ABSTRACT

Mechanism of internal structure formation of perlite composite foams due to compaction is identified. Foam and particle envelope densities, and volume fractions are theoretically modelled for prediction and practical evaluation. The volume fractions, as functions of manufacturing variables, include those affected by topological change of internal structure of foam after compaction process, consisting of binder, perlite material, porous zone of original particles, debris zone, and inter-particle voids. Predictions were validated against directly measured values for foam and particle envelope densities. A problem with the conventional method for obtaining volume fraction of binder is analytically addressed in terms of error sensitivity. Values for volume fraction of binder obtained from the conventional method were found to have errors up to about 300% (or about three times validated one). An example is given to show how the predictive models can be used for optimisation of manufacturing and properties. Applicability of formulas based on the new evaluative method is also shown for syntactic foams. Experimental results were obtained from a foam density range of 0.16–0.50 g/cm^3 and a porosity range of 0.79–0.93 for expanded perlite particle sizes between 3 and 4 mm, a compaction ratio range of 1–3.56, and a pure sodium silicate content range of 0.05–0.35 g/ml in dilution of water for binder.

1. Introduction

Volume fractions of composite foam constituents are fundamental elements for foam characteristics, and structural and functional behaviours. They, in general, constantly change at different stages of manufacturing. The change depends on manufacturing method and properties of constituent materials. It also depends on how internal structure forms during manufacturing and on which material is selected for development of light foams. Perlite is one of monolithic materials selected for development of composite foams or light composites. It is a glassy volcanic rock of rhyolitic composition [1], which can be processed into an expanded form for porous structure consisting of micro-cells [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 porous perlite particles are light, environment-friendly [5], and possess good acoustic [6] and insulation properties [7]. Their traditional 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 composite

* Corresponding author.
E-mail addresses: Md.Arifuzzaman@uon.edu.au (M. Arifuzzaman), ho-sung.kim@newcastle.edu.au (H.S. Kim).

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Nomenclature

Symbols

ρ_b	density of hydrated solid binder
ρ_{db}	density of diluted binder
ρ_d	density of diluent
ρ_f	final foam density after drying
ρ_{pB}	bulk density of perlite (from tapping measurements)
ρ_{pE}	particle envelope density before compaction
ρ_{pEc}	particle envelope density after compaction
ρ_{pM}	perlite material density
ρ_{pS}	particle skeletal density before compaction
ρ_{topc}	wet density of top phase mixture after compaction
υ_{cpore}	volume fraction of closed pores within perlite particles in bulk volume
υ_{ipp}	inter-particle porosity in bulk volume
υ_{opore}	volume fraction of open pores within perlite particles in bulk volume
υ_{pp}	total particle porosity
υ_{total}	total porosity in bulk volume
υ_{φ}	total porosity of dry foam

Capital letters

M_b	total mass of hydrated solid binder (pure sodium silicate + bound water) in a container
M_{bc}	total mass of hydrated solid binder in foam after compaction and drying
M_{dbc}	total mass of diluted binder after compaction
M_{dc}	total mass of diluent (water) after compaction (excluding bound water if exists)
M_f	total mass of dry foam
M_{pD}	total mass of debris
M_{pM}	total mass of perlite material used to manufacture perlite foam
M_{pMSoc}	total mass of perlite excluding debris
M_{wf}	total mass of wet mix
R_{bd}	($=M_b/V_{db} = M_{bc}/V_{dbc}$) Mass of hydrated solid binder per unit volume of diluted binder
R_{pbd}	mass of pure binder ($Na_2O + SiO_2$) per unit volume of diluted binder
V_{bc}	total volume of hydrated solid binder in dry foam
V_{db}	total volume of diluted binder in a container
V_{dbc}	total volume of diluted binder in wet foam after compaction
V_{pB}	total bulk volume of dry perlite before compaction
V_{pEc}	total envelope volume of perlite particles including debris after compaction
V_{pM}	total volume of perlite material in dry foam
V_{top}	total volume of top phase (mixture) before compaction
V_{topc}	($\approx V_f$) Total volume of top phase (mixture) after compaction

Small letters

c_d	($=\upsilon_{top}/\upsilon_{topc}$) Compaction ratio after drying, where $c_d > 1$
mf_b	mass fraction of hydrated solid binder in foam (after compaction and drying)
mf_{pM}	mass fraction of perlite in foam (after drying)
m_{topc}	mass of top phase mixture after compaction per unit mass of perlite (before drying)
n	($=\upsilon_{top}/\upsilon_{pB}$) Bulk volume ratio for unit mass of perlite
r_{bp}	($=M_{bc}/M_{pM}$)Mass of hydrated solid binder per unit perlite mass after compaction (for either wet or dry compact/foam) (usually < 1)
υ_{ac}	volume of diluted binder trapped in top phase ($c = 1$) per unit mass of perlite
υ_{dbc}	volume of diluted binder trapped in the compact per unit mass of perlite after compaction
υ_{topc}	volume of top phase (mixture) per unit mass of perlite after compaction
vf_b	volume fraction of hydrated solid binder in dry foam
vf_d	($=vf_{vic}$)Volume fraction of diluent after compaction before drying
vf_{dbc}	volume fraction of diluted binder after compaction
vf_{pD}	volume fraction of debris
vf_{pEc}	volume fraction of particle envelope (excluding binder) after compaction
vf_{pM}	volume fraction of perlite material in dry foam
vf_{pMSoc}	volume fraction consisting of perlite material, and closed pores/open pores with respect to foam volume
vf_{vic}	($=vf_{vicD} + vf_{vicE}$)Volume fraction of inter-particle voids (with binder) in dry foam after compaction
vf_{vicD}	volume fraction of inter-particle voids (with binder) within debris zone in dry foam after compaction
vf_{vicE}	volume fraction of inter-particle voids (with binder) surrounded by initially defined particle envelope boundaries, or fragmented particle envelope boundaries, in dry foam after compaction
vf_{vi0c}	($=vf_{vic} + vf_b$) Volume fraction of inter-particle voids without binder in dry foam after compaction
vf_{viwc}	volume fraction of inter-particle voids in wet foam right after compaction
vf_{voc}	volume fraction of open pores within particles in dry foam after compaction

foams have been limited due to their relatively poor mechanical properties. One of the reasons for this is that the porous perlite particles are fragile and hence easily damaged during mixing with binder, resulting in a high density with respect to strength.

It is only recently that Shastri and Kim [19,20] devloped a new manufacturing method for expanded perlite foams involving dilution, mixing, flotation, compaction, and drying/curing. They demonstrated that the method is capable of extending the limitation of traditional perlite uses. Arifuzzaman and Kim [21], subsequently, developed novel perlite/sodium silicate composite foams using the manufacturing method [19,20], and studied the basic mechanical and physical behaviours. Allameh-Haery et al. [22,23] also adopted the same method for manufacturing perlite/epoxy foams for their studies. Perlite has further been extended to other applications e.g. metallic foams [24], structural component reinforcement [25], and others [26].

Now, the volume fraction of binder in perlite composite foam is a critical element for its structural integrity. At the same time, it is required to be reduced for lowering foam density. The low foam density can also be achieved by lowering compaction ratio during manufacturing but at the sacrifice of structural integrity of foam. A range of different properties, hence, can be produced with a single value of foam density. Further, two categories of volume fractions may be considered in perlite composite foams unlike most of other composites – one is for constituent materials and the other is for foam structural elements. The former refers to volume fractions for perlite material and binder, and the latter refers to those for survived porous particles, newly created debris, and