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Pre-mould processing technique for syntactic foams: Generalised modelling, theory and experiment

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ABSTRACT

Pre-mould processing for syntactic foams made of starch and ceramic hollow microspheres was studied. A statistical model to relate various parameters such as volume expansion rate (VER) of initial bulk volume of microspheres (IBVMS), microsphere size, microsphere volume fractions, minimum inter-microsphere distance (MID), and mixing ratio of microspheres was developed for theoretical relations. The statistical model consists of cubic cells which can optionally be simple cubic (SC) or face centered cubic (FCC) or body centered cubic (BCC) cells. The theoretical relations were verified with experimental/numerical data for various mixtures of microspheres and found to be capable of predicting effects of microsphere size and mixture ratio of microsphere size groups on VER under various conditions arising from starch content in binder and IBVMS. Volume shrinkage for mixture of microspheres and binder after moulding but before forming syntactic foam was found to be high for high contents of small microspheres in mixture.

1. Introduction

Syntactic foams, which are made of hollow microspheres and binder, can be used as various structural components. English (1987), Jize et al. (1996) and Kim and Plubrai (2004) highlighted their application in developing sandwich composites. Jackson and Clay (1983), Seamark (1991) and Hinves and Douglas (1993) demonstrated the advantages of using syntactic foams in areas where low densities are required. Their other uses include products in aerospace and automotive industries. However, the densities of syntactic foams in the past have been relatively high compared to the traditional expandable foams, limiting their applications.

A wide range of different types of syntactic foams can be made by selecting different materials and consolidating techniques for binder and hollow microspheres. The consolidating techniques include coating microspheres reported by Narkis et al. (1982a), rotational moulding by Narkis et al. (1982b), extrusion by Lawrence et al. (2001) and Lawrence and Pyrz (2001), pressure infiltration by Rohatgi et al. (2006), and ones that use inorganic binder solution and firing by Verweij et al. (1985), dry resin powder for sintering by Narkis et al. (1980), Puterman et al. (1980) and Kenig et al. (1984), compaction by Kim and Oh (1999, 2000), liquid resin as binder by te Nijenhuis et al. (1989) for in situ reaction injection moulding, and buoyancy by Kim (2003, 2006), Kim and Plubrai (2004) and Islam and Kim (2007a,b, 2008). The last method (buoyancy) has recently been demonstrated by Islam and Kim (2007a) to be capable of control of a wide range of binder contents at low costs, widening applicability of syntactic foams. Also it allows us to use starch as binder for manufacturing syntactic foams. Starch has some advantages over other binders such as epoxies, phenolics, etc. in some potential applications such as building interior sandwich panels. It is readily available, environmentally friendly, and an inexpensive renewable polymeric binder. However, it is dimensionally unstable during manufacturing, limiting its applicability. For example, gelatinised starch binder shrinks significantly when it dries, as claimed by Islam and Kim (2007a,b, 2008). Islam and Kim

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(2007a) have studied relationships between various manufacturing parameters for starch binder and ceramic hollow microspheres. One of the important manufacturing parameters has been identified to be IBVMS (initial bulk volume of microspheres) expansion rate, when mixed with binder, for design of manufacturing facilities and dimensional control of syntactic foam. They demonstrated that their developed relation between IBVMS and MID (minimum inter-microsphere distance) is capable of predicting microsphere size effect. However, applicability of the relation is limited to a single size group of microspheres. Besides, there are few similar relations developed by Carlise et al. (2009) for macro-shell composites, Xu and Li (2010) for self-healing syntactic foams, and by other researchers. However, they are not directly relevant to the relation developed in this study.

In this paper, a generalized relationship between IBVMS and MID for various mixtures consisting of different microsphere size groups is derived as part of continued previous work by Islam and Kim (2007a) for syntactic foam made of starch binder and ceramic hollow microspheres.

2. The buoyancy method for manufacturing syntactic foams

The basic principles for manufacturing of syntactic foams containing starch as binder are based on the buoyancy of hollow microspheres in aqueous starch binder. The starch binder can be diluted for the purpose of controlling binder content in syntactic foam. When microspheres are dispersed in binder in a mixing container as a result of stirring/tumbling, the mixing container is left until microspheres float to the surface and starch settles down, forming three phases, i.e. top phase consisting of microspheres and binder, middle phase of water, and bottom phase of starch and water. The top phase is to be used for moulding. Gelatinisation of starch in the mixture can be conducted in two different ways of timing. One is prior to the addition of hollow microspheres to water–starch mixture and the other after moulding, which will be referred to as pre- and post-mould gelatinisations respectively. In this work, pre-mould gelatinisation was employed. More details are available in references published by Kim (2003, 2006) and Islam and Kim (2007a, 2008).

3. Statistical models and theory

When microspheres are mixed with starch binder, the bulk volume of the mixture expands significantly. Therefore, volume expansion rate (VER) should be known for the design of manufacturing facility.

Various microsphere sizes in a group (or statistically population) of microspheres can be represented by a mean size which is expected value for random sizes. Cubic unit cells such as SC (simple cube), FCC (face centered cube), and BCC (body centered cube) can be used as building blocks for the statistical model shown in Fig. 1 in which each sphere represents a mean size of random sized

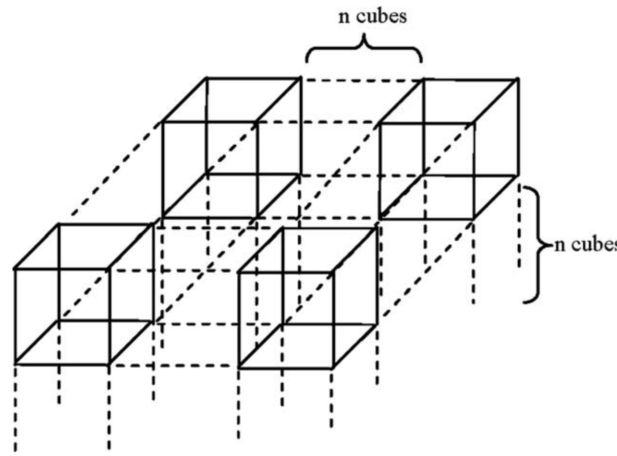

Fig. 1. General model consisting of cubic cells.

spheres. There can be various ways of combining cubic unit cells for modelling mixture of two different groups of microspheres. The number of unit cells of two size groups of microspheres depends on the mixture ratio. The model is of three-dimensional arrangement of cubic cells rather than one or two dimensional arrangement because a mixture is a 3D entity, and spheres (large ones in one of groups of microspheres in this work) in a minority group in number are located approximately at the middle of the model representing of mean values of random positions. Three types of unit cells as shown in Fig. 2 can be employed for relation derivations. The VER is defined as top phase volume divided by IBVMS and can be derived independently of unit cell type as

$$\mathrm{VER} = \left(1 + \frac{d_e}{r_1 + r_2 + fd_0}\right)^3 \quad \text{or} \quad \left(\frac{r_1 + r_2 + \mathrm{MID}}{r_1 + r_2 + fd_0}\right)^3 \qquad (1)$$

where r_1 is the mean radius of microspheres for a group of small microspheres, r_2 is the mean radius of microspheres for a group of large microspheres, d_0 is the minimum inter-microsphere distance (MID) of IBVMS as defined in Fig. 2, d_e is an increment of d_0, so that $d_e = 0$ for IBVMS but $d_e \neq 0$ for MID = $fd_0 + d_e$ when expanded, f is a factor for packing correction because the model does not represent the way of packing of microspheres for IBVMS.

The d_0 in Eq. (1) may now be found from the model consisting SC unit cells as

$$d_0 = \sqrt[3]{\frac{\pi(n_{1/8}r_1^3 + N_{1/8}r_2^3)}{6pn_c}} - r_1 - r_2 \qquad (2)$$

where p is a packing factor of IBVMS, n_c is the total number of cubic cells, n and N are the total number of small and large microspheres respectively, subscripts in n and N denote volume fractions of microspheres in one unit cube (e.g. $n_{1/8}$ is the total number of 1/8th small microspheres located on corners, $N_{1/8}$ is the total number of 1/8th large spheres located on corners). The total number of

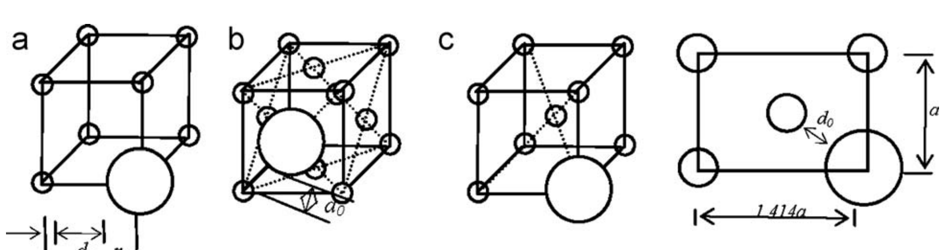

Fig. 2. Three types of unit cells as building blocks for the general model shown in Fig. 1: (a) simple cubic (SC); (b) face centered cubic (FCC); and (c) body centered cubic (BCC) unit cells with diagonal cross sectional view. Each unit cell contains one large sphere representing a group of large microspheres.