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Mechanical and thermal properties of fly ash/vinyl ester syntactic foams

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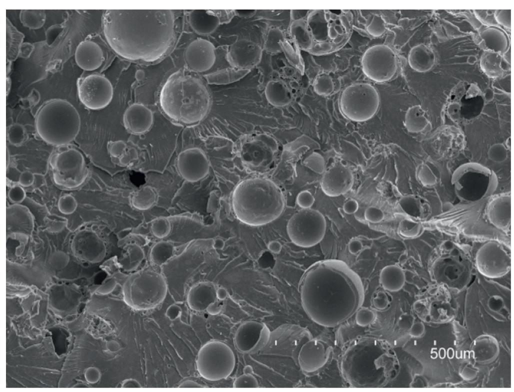
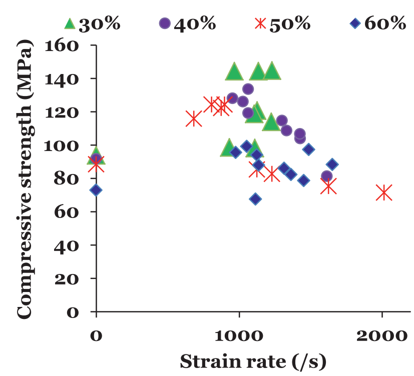
HIGHLIGHTS

- Fly ash/vinyl ester composites are studied for mechanical and thermal properties.
- Modulus of fly ash is evaluated to be 50–70 GPa from the flexural characterization.
- CTE of fly ash filled composite is up to 67% lower than that for neat resin.
- High stiffness and improved dimensional stability of fly ash composites are useful.
- Energy absorption under compression increased with strain rate for fly ash composite.

GRAPHICAL ABSTRACT





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ABSTRACT

Vinyl ester matrix syntactic foams filled with hollow fly ash cenospheres are evaluated for quasi-static and high strain rate compressive, flexural and thermal properties. The results are analyzed to understand the effect of cenosphere parameters such as density and wall thickness on the properties of syntactic foams. The elastic energy absorption under compression, until the peak stress, increased with increasing strain rates for all cenosphere volume fractions. The flexural strength decreased by 73% while the flexural modulus increased by 47% at 60 vol.% cenospheres, in comparison to the neat resin. The coefficient of thermal expansion (CTE) was observed to decrease by 48% corresponding to an increase in cenosphere content from 30 to 60 vol.%. Cenospheres are produced as a by-product of coal combustion and their structure contains numerous defects. Therefore, mechanical properties of cenospheres cannot be directly measured. An existing theoretical model was utilized to predict the cenosphere modulus using the experimental flexural modulus values and the results were confirmed with the CTE values. These results can be used to tailor the mechanical and thermal properties of syntactic foams based on the application parameters.

1. Introduction

Composite materials are widely used in transportation applications. Low density combined with high strength and stiffness helps in reducing the structural weight and increasing the damage tolerance. Composites fabricated by dispersing hollow particles in a matrix are referred to as syntactic foams. Recent literature provides examples of a large number of existing applications of syntactic foams [1,2]. Use of low density composites such as syntactic foams in vehicle structures can provide reduction in the weight, which can improve fuel economy and payload capacity. The higher cost of composite materials can be attributed to the higher raw material cost and the higher processing cost. A low cost

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filler material that can be used in syntactic foams is fly ash cenospheres [3,4], which can help in developing low cost composites. Fly ash is produced as a by-product in coal fired power plants. Approximately 70 million tons of fly ash are generated in the USA each year and about half of them are deposited in landfills. Some of the fly ash particles are hollow, which are called cenospheres. Efforts have been made to utilize cenospheres in the construction industry, where they are used in bricks and concrete [5–8]. Development of beneficial applications of cenospheres can help environment and the composites field alike.

The composition of fly ash depends on the quality of coal and the combustion temperature in the power plant. The main constituents of fly ash are alumina, silica and iron oxides. Several techniques, such as wet separation, dry separation and aggregating the content of cenospheres of a particular size and density range, are available to separate the hollow cenospheres from the coal residue [9–11]. The cenospheres have been used as fillers in polymer [12–17] and metal [18–21] matrix composites. The mechanical properties such as the tensile and compressive strength and modulus [20], impact properties [12], wear properties [22] and thermal properties [23,24] of cenosphere filled composites have been experimentally studied. Theoretical predictions for cenosphere reinforced composites are difficult to obtain, especially because their walls are not fully dense and contain porosity and other defects. Estimation of properties of cenospheres and developing theoretical models that are applicable to cenosphere filled composites can be very useful for such materials.

The modeling efforts for cenosphere filled syntactic foams are relatively scarce. Kerner's and Halpin-Tsai models have been used to predict the tensile modulus of fly ash/polyethylene syntactic foams [25]. The ratio of the filler to matrix modulus was used as 5.4 to fit the experimental results in the Halpin-Tsai model. The Guth–Smallwood, Kerner and Halpin-Tsai equations were utilized to obtain estimates of the tensile modulus of fly ash/polypropylene syntactic foams in another study [16]. Models developed for fly ash filled metal matrix composites can also be useful for polymer matrix composites [24]. The available studies on cenosphere filled composites show that the theoretical predictions for the composites are mostly based on curve fitting on the experimental values by varying the parameters for the fly ash. It is noted that experimentally validated models for syntactic foams are used to back calculate the properties of cenospheres. It is also observed that there is a great variety in the composition and properties of fly ash cenospheres used in various studies. Therefore developing correlations in properties of syntactic foams across different studies is very difficult. In the present work, fly ash cenosphere filled vinyl ester matrix syntactic foams are characterized for quasi-static and high strain rate compressive, flexural and thermal properties. Theoretical models are used to estimate the properties of cenospheres from the experimental results on flexural modulus and the values are confirmed with those obtained from the CTE results.

2. Materials and methods

2.1. Composite fabrication

Vinyl ester resin catalyzed with methyl ethyl ketone peroxide (MEKP) hardener procured from U.S. Composites, FL, is used as the matrix material. Fillite 300 fly ash cenospheres (Trelleborg, GA, USA) are used as the filler material. Syntactic foams are synthesized by taking cenospheres and vinyl ester resin in the desired proportions and stirring gently to obtain a uniform slurry. The hardener was added (1.25 vol.% of the resin) and stirred. The slurry is poured into aluminum molds, and cured at room temperature for 24 h followed by post-curing in a convection oven at 70 °C for 2 h.

The cenosphere true particle density is taken as 700 kg/m^3 from the range given in the manufacturer's datasheet [26]. In the present study, the cenosphere content is varied from 30 to 60 vol.% in syntactic foams. These volume fractions are chosen because the fly ash cenospheres are dispersed randomly in the matrix resin using a mechanical mixing process. Cenospheres tend to float and segregate at lower than 30 vol.%, which defines the lower bound for the syntactic foam composition. At higher than 60 vol.%, the viscosity of the mixture becomes very high and cenospheres break during the mixing process, resulting in poor quality composites. The experimental densities of the syntactic foams containing 30, 40, 50 and 60 vol.% cenospheres were measured to be 979, 954, 900 and 835 kg/m^3, respectively. The experimental density of syntactic foams is compared to the theoretical estimates obtained from rule of mixtures and the difference was found to be between 2.3% and 5.5%, which reaffirms the selection of the cenospheres density value. The syntactic foams are represented by notations such as FVE-30, in which "FVE" represents fly ash reinforced vinyl ester matrix syntactic foams containing 30 vol.% of the filler.

2.2. Quasi-static compression

Cylindrical specimens of 10 mm diameter are core drilled from the fabricated slab for quasi-static and high strain rate (HSR) compression testing and cut to 5 mm thickness using a diamond blade precision saw (IsoMet®, Buehler Ltd., Lake Placid, NY). Quasi-static compression testing is performed using an Instron 4469 universal mechanical test system equipped with a 50 kN load cell. The crosshead velocity is set at 1 mm/min and the specimens are compressed to 40% strain. Compression platens are coated with a lubricant to avoid specimen barreling. Load and extension data used in the calculation of stress and strain are recorded using Bluehill 2.0 software. The testing is conducted in accordance with the ASTM D695 standard. The peak strength, defined as peak stress at the end of the elastic region, and the absorbed energy, defined as the area under the stress-strain curve up to peak stress, are evaluated from the results. Five specimens are tested for each type of syntactic foam and average and standard deviations are reported for each property.

2.3. High strain rate compression

High strain rate (HSR) compression testing was conducted using an in-house developed split-Hopkinson pressure bar (SHPB) test system. An in-depth description of the SHPB can be found in previously published studies [27,28]. Inconel 718 alloy incident and transmitter bars are used for the present experiment. Strain gages bonded on the incident and the transmitter bars are used to record the strain pulses propagating in the bar during the test. The time dependent strain rate $\dot{\varepsilon}(t)$, stress $\sigma(t)$ and strain $\varepsilon(t)$ are calculated by

$$\dot{\varepsilon}(t) = \frac{2c_b\varepsilon_r(t)}{l_0} \tag{1}$$

$$\sigma(t) = \frac{AE\varepsilon_t(t)}{A_0} \tag{2}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(\tau)\,d\tau \tag{3}$$

where c_b is the sound wave velocity in the bars, $\varepsilon_r(t)$ is the reflected strain recorded from the incident bar, $\varepsilon_t(t)$ is the transmitted strain