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A REVIEW ON SYNTACTIC FOAMS PROCESSING, PREPARATION AND APPLICATIONS

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Abstract*-Lightweight materials with high strengths have great impact on engineering applications ranging from deep sea to aerospace. Foam is the most frequently used as structural core material for composite laminates and syntactic foams are general ternary materials made of pre-formed hollow microspheres, binder, and voids added strength, stiffness, and insulation, without adding weight. A significant number of research papers were published previously related to the term syntactic foams. But, every research paper specifically discussed in one type of syntactic foams. This study reviews the syntactic foams microspheres with properties, matrices, various processing and fabrication techniques. Furthermore, various parameters modeling for syntactic foams were collected and a comparison has been made among mechanical properties. At last, the vast applications and difficulties in preparation of syntactic foams were shown. This study will help the researchers in the field of sandwich composites with various syntactic foams core preparation for lightweight and low-density applications.*

Keywords: Syntactic foams, Microspheres, Matrices, Mechanical properties, Composite materials

1. INTRODUCTION

Materials having a combination of high tensile and compressive properties, low density, good damage tolerance has been applied extensively in engineering applications from sea to space involved such as marine and aerospace structural applications [1]. The development of syntactic foam was originally directed toward the formation of low-density materials suitable for use as building materials for deep submergence vehicles, particularly research submarines. Until the introduction of these foams liquid paraffin lighter than water, like gasoline, were used to provide the needed positive buoyancy. Flammability hazard, compressibility, and thermal contraction are the main disadvantages of using gasoline. Syntactic foams, lighter than water, characterized by low compressibility under deep water pressures and low absorption of water are very attractive for such applications. Expanded foams, in contrast with syntactic foams, do not withstand high pressures and tend to absorb water through their interconnected cells. Syntactic foams can be used as various structural components including sandwich composites and also in areas where low density, low moisture absorption, high damage tolerant, low thermal conductivity and low dielectric constant e.g. undersea/marine equipment for deep ocean current-metering, anti-submarine warfare, and others use include products in aerospace, automotive and building industries. In the past, the densities of syntactic foams were relatively high in comparison with the traditional foams provides a barrier in their applications. A wide variety of materials can be used for syntactic foams. Thus, a wide range of different types of syntactic foams can be made by selecting various types of microspheres, matrices and consolidating techniques. Sandwich composites are becoming more and more popular because of their decrease in weight while maintaining mechanical performance using syntactic foams. Figure 1 shows a typical syntactic foam.

Fig. 1: Syntactic foam

2. MICROSPHERES AND MATRICES IN SYNTACTIC FOAMS

Microspheres are the main constituents for syntactic foams and it provides low density, high specific strength, and low moisture absorption. There are various types of microspheres are available today and it may comprise of glass, polymer, carbon, ceramic or even metal. Table 1 shows the researchers used various combinations of microspheres and matrices previously.

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Table 1: Microspheres and matrices in syntactic foams

Microspheres	Matrices	Microspheres Diameter	Microspheres Density	Ref.
Spherical carbamide granules (SPC)	Magnesium alloy AZ61 powder	0.50–0.90 mm	-	[2]
Hollow fly ash (HFA)		100–250 µm	0.70 g/cc	
Hollow glass microballoons (HGMs) K20	Nanomer I.28E	25-105 µm	0.2 g/cc	[3]
Expanded perlite (EP)	Aluminium A356	3-4 mm	0.18 g/cc	[4]
Glass microspheres (GM)	Epoxy resin (E-44)	60 µm	0.11 g/cc	[5]
Glass microballoons (GMs)	VER	5-150µm	0.11 g/cc	[6]
Scotchlite glass bubbles XLD-3000	Epoxy resin	0-40µm	0.23 g/cc	[7]
Ceramic hollow microspheres SL75	Potato starch	31–83 µm	0.68 g/cc	[8]
Ceramic hollow microspheres SL300		101- 332 µm	0.80 g/cc	
Expanded perlite (EP)	Potato starch	3-4 mm	0.83 g/cc	[9]
Scotchlite glass microballoon (SGMs) K1	AIRSTONE 760E	30-120 µm	0.125 g/cc	[10]
Scotchlite glass microballoon (SGMs) K20		30-120 µm	0.200 g/cc	
Hollow glass microspheres (HGM) H20	Epoxy resin	2–150 µm	0.18-0.22 g/cc	[11]
Hollow glass microspheres (HGM) H40		2–100 µm	0.38-0.42 g/cc	
Hollow glass microspheres (HGM) H60		2–95 µm	0.60-0.58 g/cc	

3. FABRICATION METHODS OF SYNTACTIC FOAMS

Numerous variations of syntactic foam fabrication methods were developed over the past years. This is due to the increasing variety of available syntactic foams. Emerging technologies like Additive Manufacturing (AM) methods are also being employed to obtain better compositions of syntactic foams that are challenging to fabricate by other methods.

3.1 Pre-Mold Processing

Yu et al. [5] was fabricated epoxy syntactic foam with the reinforcement of short glass fiber and analyzed the tensile and compressive properties. Islam and Kim [8] prepared syntactic foam to investigate manufacturing and mechanical behavior. Shastri and Kim [9] developed expanded perlite foams and investigated its compressive modulus and failure modes under compression with longitudinal splitting and shear planes.

3.2 Resin Infusion Process

This method needs resin injection facilities and defined as resin transfer molding (RTM) which is used for FRP composites. A novel syntactic foam processing method VARTM is an improved modified process of RTM was developed [7]. It has been concluded that resin permeating time, compressive strength and syntactic foam densities increased as the expanded polystyrene (EPS) beads diameter decreased. Yu et al. [10] fabricated syntactic foam with two different types of microspheres and mechanical properties were analyzed. Ding et al. [11] investigated the mechanical properties of co-continuous hollow glass microspheres (HGMs)/epoxy resin syntactic foam prepared by VARTM.

3.3 Stir Casting

Mondal et al. [12] also examined the microstructures, hardness and compressive deformation behavior of cenosphere filled aluminum syntactic foam. Su et al. [13] analyzed the energy absorption capacity, plastic collapse, brittle fracture in compression of aluminum matrix syntactic foams. Wang et al. [14] developed A356 matrix syntactic foam and investigate mechanical properties under compression.

3.4 Compression Molding

Jayavardhan et al. [15] fabricated glass microballoons/high-density polyethylene (GMs/HDPE) syntactic foams. They observed the effect of filler on mechanical properties. Yao and Rodrigue [16] prepared density graded polyethylene foams using a chemical blowing agent. They concluded that blowing agent concentration has substantial effect on foam morphology.

3.5 Semi-Dry Formation

Yazici et al. [17] developed polymer-based syntactic foam for high-temperature applications. Mechanical properties were investigated at room temperature and after heat treatment at 500 °C by quasi-static compression experiments. With the increase of glass bubble percentage as a microsphere enhanced the energy absorption properties in the heat-treated and room temperature specimens. Rugele et al. [18] analyzed the effects of fly-ash cenospheres (FAC) on the clay-ceramic syntactic foams properties. They concluded that compressive properties of the syntactic foam do not show clear tendencies.

3.6 Pressure Infiltration Process

Taherishargh et al. [19] developed perlite-aluminum syntactic foam and investigate mechanical properties at elevated temperatures. At higher temperature, ductility is improved while mechanical strength and energy absorption are decreased. In another study, Fiedler et al. [20] investigated the dynamic compressive loading of expanded perlite/aluminum syntactic foam. Mechanical properties of low-density expanded perlite-aluminum syntactic foam under compression were analyzed by Taherishargh et al. [21]. The notch sensitivity of aluminum matrix syntactic foam was investigated [22]. Fracture energies have found notch sensitive. The fracture toughness values were determined and found insensitive to the notch geometry. It only depends on the matrix material.

4. PROPERTIES OF SYNTACTIC FOAMS

Researchers investigated various properties of syntactic foams over the years. Various mathematical models and equations were developed not only for parameter evaluation but also for model validation with investigated results. Inter facial adhesion and particle distribution have a significant effect on syntactic foams properties. Figure 2 shows the SEM images of the interfacial adhesion and particle distribution including porosities and voids [6]. Matrix porosity can be calculated using Eq. (1) [6].

$$V_{p,gm} = V_{gm} \times V_{c,gm} \quad (1)$$

where, V_{gm} is volume of glass microballoons in syntactic foam, volume cavity $V_{c,gm} = \eta^3$.

Radius ratio,

$$\eta = (1 - \frac{\rho_{sf}}{\rho_{gm}})^{\frac{1}{3}}$$

ρ_{gm} density of glass microballoon, ρ_{sf} density of syntactic foam.

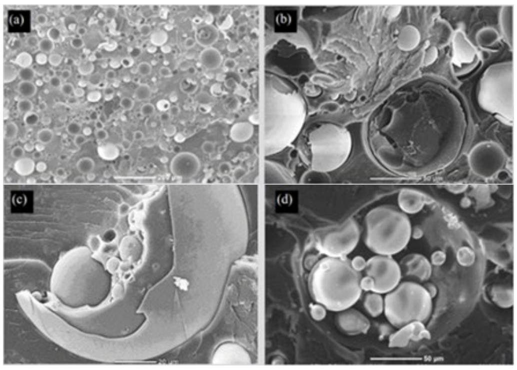

Fig. 2: A SEM showing (a) Two types of porosity cavities and matrix porosities for (8 wt.%) (b) Air entrapped for (4 wt.%) (c) Filled with resin for (2 wt.%) (d) Filled with small glass microballoons for (4 wt.%) [6].

Other than the porosity cavities and matrix porosities, HS shell contained some micropores shown in Fig 3 by an arrow, which reduces the strength. To account for this, compaction pressure is calculated using Eq. (2) [2].

$$P_c = \sigma_m V_{f,m} + \sigma_{HS} V_{f,HS} [C \times (1 - V_{void,HS})^n] \quad (2)$$

P_c is the compaction pressure, σ_m is the yield strength of the matrix, σ_{HS} is the yield strength of fully compacted HS , and $V_{f,m}$ is the volume fraction of matrix, $V_{f,HS}$ is the volume fraction of the fully compacted HS, C and n are the material constants, $V_{void,HS}$ is the void fraction in HS and it is estimated using Eq. (3) [2].

$$V_{void,HS} = \frac{\rho_{c,HS} - \rho_{HS}}{\rho_{c,HS}} \quad (3)$$

where $\rho_{c,HS}$ is the density of fully compacted HS and ρ_{HS} is the density of microspheres.

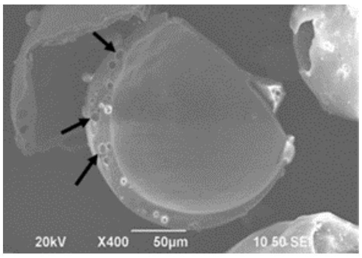

Fig. 3: Micropores (black arrows) in the shell of a fractured fly ash particle [2].

In order to calculate the density of the syntactic foams, where mass is divided by the volume of syntactic foam it is necessary to determine the volume of the syntactic foams. To calculate the volume fraction for each of the constituents in syntactic foams, the rule of mixtures was implemented by Salleh et al. [6] using Eq. (4). They concluded that a decrease in the syntactic foam densities when the glass microballoon contents are increased.

$$V_f = \frac{W_f}{W_f + (1 - W_f)\frac{\rho_f}{\rho_m}} \quad (4)$$

Where, W_f is weight of filler, ρ_f is density of filler/and ρ_m is density of matrix.

Previous study shows that prominent peaks are available for Mg matrix, but no peaks were available for carbamide granules in XRD patterns. In case of polyurethane syntactic foam filled with nanoclay, none of XRD peaks appeared in the absence of nanoclay. However, syntactic foam filled with 0.5 wt% nanoclay, also shows no available XRD peaks shown in Fig 4. The interlayer distances of the nanoclay increased from 2.6 nm to 3.8 nm, indicating that the polyurethane molecules intercalated between layers of the nanoclay [3].

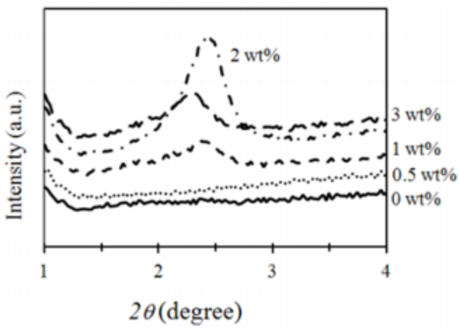

Fig. 4: XRD results of polyurethane syntactic foams filled with nanoclay [3].

A mixed mode of fracture mechanism with dominant quasi-cleavage and dimples which is indicative of limited plasticity is shown in Fig 5a. Figure 5b shows that the heat treatment results in a transition of the fracture mode to ductile transgranular fracture. The debonding and

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breaking of the elongated eutectic silicon flakes in UT cell walls, shown in Fig 5c. The uniform cuplike dimples with spheroidized Si particles at the bottom in the fracture surface of the HT cell wall shown in Fig 5d. Figure 5e and 5f reveal that micro shrinkage defects play an important role as crack initiation areas in both untreated and heat-treated cell walls.

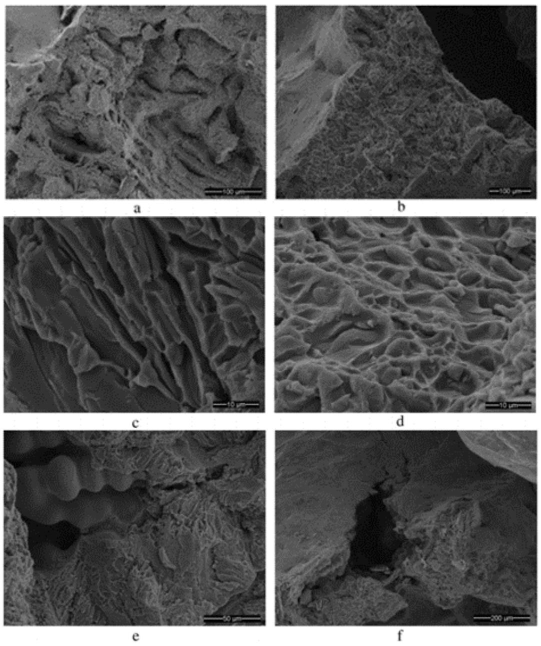

Fig. 5: SEM image of the fractured cell wall (a) UT foam, (b) HT foam, (c) fractured and debonded Si particles in UT foam, (d) uniform dimples around the spheroidized Si in HT conditions, (e) crack initiation in UT foam and (f) crack initiation in HT foam [4].

Moisture absorption measurements of syntactic foam panels subjected to 70% relative humidity at 32°C are shown in Figure 6. It is seen that moisture content increases rapidly in the first several hours and then is saturated afterward. The saturated moisture content appears high for the high starch volume fraction of the syntactic foam panel for a given microsphere [8].

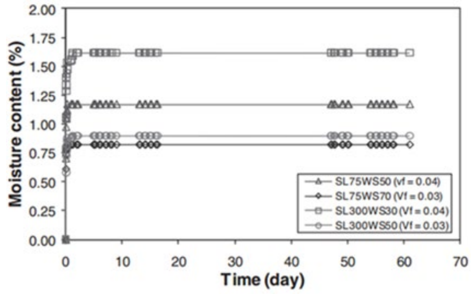

Fig. 6: Moisture absorption in syntactic foam panels at 32°C with starch volume fraction in each syntactic foam panel (v_f) [8].

Water absorptions are the most important criteria for syntactic foams due to their vast marine applications. The water absorptions of the syntactic foams under 110-140MPa hydrostatic pressure are shown in Fig 7. The water absorptions increase slowly as the hydrostatic pressure increases when hydrostatic pressure destruction tests implementing. Percentage of water absorption can be calculated using Eq. (5) [9]. A comparison has been shown in Table 2 among previously investigated syntactic foams results.

$$\rho = \frac{(m_2 - m_1)}{m_1} \times 100 \quad (5)$$

where m_1 represents initial weight, and m_2 represents final weight.

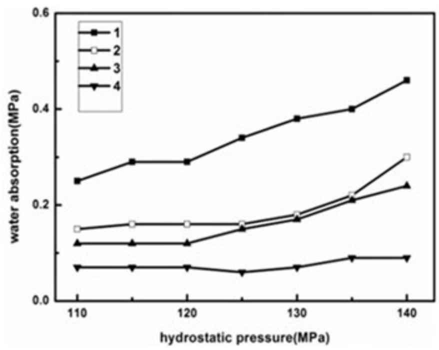

Fig. 7: The water absorption of the syntactic foams under 110-140MPa hydrostatic pressure [9].

Table 2: Various syntactic foams investigated results

Syntactic foams	Results	Ref.
SPC+magnesium alloy HFA+magnesium alloy	For both Group 1 and 2- compressive strength and energy absorption capacity increased as the volume fraction of HS and CB was increased respectively..	[2]
HGMs K20+ Nanomer I.28E	The compressive strength decreased with the incorporation of the nanoclay, however specific hardness of the syntactic foam was enhanced.	[3]
EP+ aluminium A356	Under compression, the heat-treated foam show more uniform deformation, heat treatment reduces the deleterious impact of the columnar dendritic structure of the cell wall and limits the crack propagation.	[4]
GM+Epoxy resin (E-44)	10% fiber weight ratio is found more efficient for higher compressive and tensile strength, beyond that ratio both strengths are decreased.	[5]
GMs+VER	Tensile modulus is found to be 70–80% higher than the compressive modulus.	[6]
EP+potato starch	Damage occurred during compaction, failure modes under compression in longitudinal splitting and shear planes.	[9]
SGMs+ AIRSTONE 760E epoxy resin	Density distribution is not uniform, higher compressive property ranging from 35MPa to 49MPa.	[10]

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HGM+ Epoxy resin (TTA-21P)	Matrix pores were the main factors reducing the mechanical performance of the composites, compressive strength and compressive modulus increased while water absorption decrease.	[11]
Cenosphere+aluminum alloy	The plateau stress of syntactic foam decreases with cenosphere volume fraction vis-à-vis porosity following a power-law relationship. But, the densification strain increases linearly with cenosphere volume fraction.	[12]
GM+HDPE	Flexural modulus and particle fracture increase with increasing glass microballon while tensile strength decreases with the increase of glass microballon.	[15]
FAC+clay matrix	Development of foam greatly influenced by the processing conditions, compressive strengths do not show clear tendencies.	[18]
EP+A356 aluminium	The elastic stiffness, strength and energy absorption of foam and solid samples decrease with increasing temperature.	[19]
EP+ A356 aluminium	Consistent plateau stress, large densification strain, and high energy absorption efficiency.	[21]

5. APPLICATIONS OF SYNTACTIC FOAMS

Syntactic foams have been used extensively in previous and also finding the applications in the replacement of existing materials[23][24].The first applications were introduced in marine structures due to its buoyant behavior with low absorption of water and high hydrostatic compressive strength. Still now, marine is considered as the primary application field of syntactic foam. Remotely operated vehicles (ROVs) and human-operated vehicles (HOVs) used in deep-sea exploration have been constructed using syntactic foam. Additionally, syntactic foams have been used in flaps and rudders of submarines, structural components for construction and maintenance of underwater pipelines, autonomous underwater vehicles (AUVs), deep water moorings, torpedo targets, and sonar arrays, thermal insulation for undersea pipelines and high depth applications. In the field of aerospace, syntactic foam is used in filling the hollow areas within the aircraft. Excluding these applications syntactic foam used in jet aircraft radomes, rubstrips, cowls, antenna units and potting materials used to fill the ends of honeycomb structures and sandwich material cores. In consumer applications like sports industry, furniture, food containers have been used extensively. In 2006 soccer world cup, the Adidas Fever-nova soccer balls used have been developed Bayer and Adidas on a polyurethane syntactic foam. Nowadays synthetic wood has been made by syntactic foam. Eccolite product line, which is approved by the U.S. Food and Drug Administration for usage in food and beverage containers. Syntactic foam with the thermoplastic matrices enables repeatedly thermoforming, allowing the containers to be recycled repeatedly. The radio transmission properties of syntactic foams are highly tailorable. The British Aerospace Dynamics Group, U.K., has developed syntactic foam using quartz microspheres and epoxy or polyimide matrix for use in radomes for broadband microwave transmission. Other than these, significant application of syntactic foam is such as Syntactic Foams for Temperature With-standability, Syntactic Foams for Microwave Transparency, Syntactic Foams for Electromagnetic Interference (EMI) Shielding/ Electromagnetic Compatibility (EMC), Syntactic foam as Blast Protection, Syntactic foam Fire Protection, Syntactic Foam as Thermal Insulation Material etc.

6. DIFFICULTIES IN SYNTACTIC FOAMS PREPARATION

Though syntactic foams showed exceptional properties over the conventional materials, researchers face difficulties in syntactic foams preparation. Crushing of microspheres during foam preparation leads to density and distribution of microspheres is not uniform [10]. Many researchers faced difficulties in determination of optimum volume fraction of microspheres. Compression molding is not applicable for fabricating thermoplastic syntactic foams because particles may fracture under compressive load during fabrication [15]. Heat treatment has a great effect on elastic stiffness, strength, and energy absorption of syntactic foam [19]. In stir casting method, impeller design is an important consideration for mixing objectives. The wettability between the particle and melt is a major concern due to its effects on the particle engulfment and dispersion in the melt in pressure infiltration process.

7. DISCUSSION

This review on syntactic foams covers the combination of microspheres with matrices, fabrication techniques, parameter determination with various properties comparison and vast applications. The review has concluded the following outcomes by a sharp understanding of the cited literature. They are:

(a) Metal matrix syntactic foams have more emphasis rather than polymer, epoxy, ceramics, etc. syntactic foams previously. Nowadays researchers put concentrations on polymer, epoxy, ceramics, etc. syntactic foams due to enhanced properties.

(b) Microspheres and matrices characteristics have a direct effect on the thermal, electrical, and mechanical properties of syntactic foams.

(c) The maximum weight/volumetric percentage of microspheres is limited to 65% for metal matrix, 65% for epoxy, 60% for polymer syntactic foams. However, microspheres weight/volumetric percentage is common recorded 30-50% for metal matrix, 30-40% for polymer, 10% for epoxy and vinyl ester syntactic foam.

(d) Fibers are used as a reinforcement in syntactic foams.

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9. NOMENCLATURE

Symbol	Meaning
VER	Vinyl Ester Resin
FRP	Fiber Reinforced Plastic
VARTM	Vacuum Assisted Resin Transfer Molding
HS	Hollowspheres
XRD	X-ray Diffraction
UT	Untreated
HT	Heat Treated

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