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# Mathematical Analysis of Matrix and Filler Formulation in Composite Materials

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***Abstract*****—**Composite material is an important area that has gained global visibility in many research fields in recent years. Composite material is the combination of separate materials with different properties to form a single material having different properties from the parent materials. Material composition and combination is an important aspect of composite material. The focus of this study is to provide insight into an easy way of calculating the compositions and formulations of constituent materials that make up any composite material. The compositions of the matrix and filler used for fabricating composite materials are taken into consideration. From the composite fabricated, data can be collected and analyzed based on the test and characterizations such as tensile, flexural, compression, impact, hardness, etc. Also, the densities of the matrix and the filler with regard to their constituent materials are discussed.

***Keywords*****—**Composite material, density, filler, matrix, percentage weight, volume fraction.

## I. Introduction

COMPOSITES are materials made of two constituents that are at a microscopic scale and have chemically distinct phases, they are different from heterogeneous material but comprises of strong fibers, with continuous or noncontinuous layers, and are surrounded by a weaker matrix material. They are made up of at least two separate elements coming together to form a material that will possess different properties from the properties of the separate parent materials [1], [2]. Practically speaking, most composites consist of a bulk material known as matrix, and a reinforcement of some kind, which is to give an addition to the strength, and stiffness of the matrix which is usually in fiber form.

According to Kamal [3], composite materials were described as a major class of advanced elements and are either used or been considered as an alternative to metals/traditional materials in aerospace, automotive, civil, mechanical, and other industries because of their lightweight, flexibility, impact strength, fatigue strength, and high corrosion resistance. Some of the excellent performance of composite can be seen in their high strength, high specific stiffness, and controlled anisotropy, which make them very attractive materials.

The specific characteristics feature of composites is in their ability to tailor their finished product towards a unique engineering requirement by careful consideration of the matrix and filler. Such characteristics make them useful for different applications [3]. There are natural composites such as wood and there are man-made composites such as structural beam, which is an inhomogeneous mixture of cement (matrix), stone (reinforcing particle), and steel rod (reinforcing fiber) [4]. There are different kinds of matrix material such as ceramics, glass, polymer, metal, organic material in solid (plate or powder) or semisolid form. The filler or reinforcement also comes in different forms like fiber (short and long), glass, particle, etc.

The composite materials (CM) have been described as materials having strong fibers either continuous or noncontinuous and surrounded by a weaker matrix material [5]. Characterization studies for composites are performed for their evaluation in the targeted areas like mechanical, thermal, electrical, magnetic, piezoelectric, tribological, rheological, and biological [3].

Chen et al. [6] studied the mechanical behavior of sandwich composite structure with foam core and fiber-reinforced polymer skin under crushing load. The crushing behavior, failure mode, and energy absorption of the CM are correlated with the number of fiber layers in the face-sheets in both longitudinal and transverse directions, and the density and thickness of the core material. Mohamed et al. [7] studied the thermal degradation temperature (DT), heat stability, degradation kinetics, and water uptake of CM made of epoxy resin and wheat gluten. It was observed that the DT increased at higher heating rates of the CM.

Also, Shunmugasamy et al. [8] studied the viscoelastic properties of syntactic foam composite material made from hollow glass particles and vinyl ester using dynamic mechanical analyzer. It was observed that the increased in volume fraction of the particles improved the storage modulus, loss modulus, and Tan δ, of the composite material. Meanwhile, it has been observed that most work focused more on the mechanical properties [9]-[11], characterizations [7], [12]-[16], density [17]-[19] and applications [20]-[22] of composite material either by using single filler [8], [18] or hybrid fillers [23]-[25].

The mathematical and compositional aspect of concentration in composite material is not commonly discussed. Therefore, the focus of this study is to give an insight to mathematical composition of constituent formulations in composite materials. The densities and volume fractions of constituent materials are also taken into consideration.

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## II. Materials and Processing

### A. Material Selection

For the purpose of this study, the materials for consideration will be matrix, filler, and possible reinforcements. For the matrix, epoxy resin (ER) and hardener (HN) will be considered, and for filler, hollow glass microspheres (HGM), and nanocellulose (NCL) will be considered.

### B. Processing

The mound size is considered as 275 x 100 x 3 mm$^3$ (length x width x thickness). The matrix comprises of the combination of ER and HN in 10:2 as recommended by the supplier. The filler which comprised of the HGM and NCL, the volume fraction of HGM is maintained as 5 vol%, while NCL volume fractions varied as 0.5, 1.0, and 1.5 vol%.

## III. Calculations of Constituent Parameters

### A. Density of Materials

Table I shows the densities of raw materials.

TABLE I
THE DENSITIES OF ER, HN, HGM, AND NCL

| Materials | Density (g/cm$^3$) |
|---|---|
| ER | ($D_{ER}$) = 1.13 |
| Hardener (HN) | ($D_{HN}$) = 0.94 |
| HGM | ($D_{HGM}$) = 0.7083 |
| NCL | ($D_{NCL}$) = 1.35 |

### B. Density of Matrix and Filler

1. Matrix

The matrix comprises of the ER and the HN in the ratio 10:2. To get the volume fraction of each constituent element, the ratio is added together, i.e.,

$$10 + 2 = 12. \quad (1)$$

Then, the volume fraction of ER in matrix ($V_{ER}$)

$$= \left({}^{10}\!/_{12}\right) \times 100 = 83.3\% \; or \; 0.833 \quad (2)$$

and the volume fraction of HN in matrix ($V_{HN}$)

$$= \left({}^{2}\!/_{12}\right) \times 100 = 16.7\% \; or \; 0.167 \quad (3)$$

Density of matrix ($D_m$) = density of ER ($D_{ER}$) × $V_{ER}$ + density of HN ($D_{HN}$) × $V_{HN}$ (4)

$$D_m = (1.13) \times (0.833) + (0.94) \times (0.167) \quad (5)$$

$$D_m = 1.0983 \text{ g/cm}^3 \quad (6)$$

2. Filler

Fillers in this study are maintained as HGM and NCL. The fillers are considered in the ratio 5: 0.5-1.5, i.e., 5vol% of HGM and 0.5-1.5 vol% of NCL.

At 0.5vol% nanocellulose (NC), the ratio is added to get each volume percent in the filler, i.e.,

$$5 + 0.5 = 5.5 \quad (7)$$

Then, the volume fraction of HGM ($V_{HGM}$) in filler

$$= \left({}^{5}\!/_{5.5}\right) \times 100 = 90.91\,\% \; or \; 0.9091 \quad (8)$$

and the volume fraction of NC ($V_{NC}$) in filler

$$= \left({}^{0.5}\!/_{5.5}\right) \times 100 = 9.09\,\% \; or \; 0.0909 \quad (9)$$

Density of filler ($D_f$)=density of HGM ($D_{HGM}$) × $V_{HGM}$ + density of NC ($D_{NCL}$) × $V_{NCL}$ (10)

$$D_f = (0.7083) \times (0.9091) + (1.13) \times (0.0909) \quad (11)$$

$$D_f = 0.7666 \; g/cm^3 \quad (12)$$

### C. Composition of Matrix and Filler in the Composites

In calculating the composition of the matrix and filler formation in any composite, the mold size in terms of the length, width, and thickness must be known. The size of the mold can sometimes be a function of the type of experiment to be carried out and the thickness of sample in view. For this study, the mold size has been stated to be:

$$275 \times 100 \times 3 \text{ mm}^3 = 82500 \text{ mm}^3 \quad (13)$$

Matrix Composition

The volume of mold ($v_{mold}$) = 82500 mm$^3$

Taking the percentage of matrix in the composite to be 'a', from the formula: density = mass/volume:

$$density\ of\ matrix\ (D_m) = {mass\ of\ matrix\ (M_m)}\Big/{'a' \times volumeof\ mold\ (v_{mold})} \quad (14)$$

$$1.0983 \times 10^{-3} = {M_m}\big/{a \times 82500} \quad (15)$$

$$M_m = (1.0983 \times 10^{-3}) \times (a \times 82500) \quad (16)$$

$$M_m = 90.61a\ g \quad (17)$$

Filler Composition

Taking the percentage of filler in the composite as 'b':

$$density\ of\ filler\ (D_f) = {mass\ of\ filler\ (M_f)}\Big/{'b' \times volumeof\ mold\ (v_{mold})} \quad (18)$$

$$0.7666 \times 10^{-3} = {M_f}\big/{b \times 82500} \quad (19)$$

$$M_f = (0.7666 \times 10^{-3}) \times (b \times 82500) \quad (20)$$

$$M_f = 63.24b\ g \quad (21)$$

### *D. Mass Concentration of Constituent Materials in Composite*

Mass of ER and Hardener in the Composite

*Case 1: At 100vol% of Matrix*

When the composite is made of 0 vol% of filler, i.e., matrix is 100 vol%. Therefore, the composition of matrix in the composite

$$\text{'a'} = 1 \tag{22}$$

Then, from (17) the mass of matrix is calculated as:

$$M_m = 90.61 \times 1\ g = 90.61g \tag{23}$$

Also, from (2) and (3), mass of ER and HN in the matrix is calculated as:

$$M_{ER} = (90.61 \times 0.833)\ g = 75.48g \tag{24}$$

$$M_{HN} = (90.61 \times 0.167)\ g = 15.13g \tag{25}$$

*Case 2: At 95vol% of Matrix*

When the matrix is 95vol%,

$$\text{'a'} = 0.95 \tag{26}$$

Then, (23) becomes:

$$M_m = (90.61 \times 0.95)\ g = 86.08g \tag{27}$$

and (24) and (25) become:

$$M_{ER} = (86.08 \times 0.833)g = 71.73g \tag{28}$$

$$M_m = (86.08 \times 0.167\ )g = 14.35g \tag{29}$$

Mass of HGM and NCL in the Filler

*At 5vol% of Filler*

When the composite consists of 5vol% of filler, i.e., at 95vol % matrix; therefore, the composition of filler in the composite

$$\text{'b'} = 0.05 \tag{30}$$

Then, from (21) the mass of matrix is calculated as:

$$M_f = (63.24 \times 0.05)g = 3.16g \tag{31}$$

When a single filler is used, i.e., HGM alone,

$$M_f = M_{HGM} = 3.16g \tag{32}$$

Also, from (8) and (9), the mass of HGM and NC in the filler is calculated as:

$$M_{HGM} = (3.162 \times 0.9091)\ g = 2.88g \tag{33}$$

$$M_{NC} = (3.162 \times 0.0909)\ g = 0.29g \tag{34}$$

## IV. Discussion

Fabrication of composite materials require series of calculations to arrive at the desired formulation. All the equations above, (1)-(34) have just demonstrated insight to procedures to consider while calculating the grams each material in the composite will be required. This varies from composite to composite, based on the materials to be used and the volume percent of the filler in the composition.

The densities of both the matrix and the respective fillers are used at various stages of the calculation. From (1)-(6), the density of the matrix is calculated from the densities of ER and hardener by considering their mixing ratio. Equations (7)-(12) also highlighted the steps to getting the filler density by considering the densities of the HGM and NCL. In the case of a single filler, the density of the filler remains the same.

The mold size constitutes an important factor for consideration in determining the overall composite formulation, (13). The mass of the matrix in the composite formulation is calculated using (14)-(17), while the mass of the filler is calculated using (18)-(21). The percentage composition of the matrix and filler in the composite is determined by the desired volume percent of each required in the composite material. This is determined by an individual based of the type of material in view. For the base sample (i.e., neat sample, or 0 vol% of filler), the matrix percentage is 100% or 1 and the ER and HN percentage for it is calculated using (22)-(25). Variation in volume percent of the matrix to filler in the composition of the composite material can be calculated using (26)-(34). The input for each equation differs based on an individual, the type of materials used, and the volume fraction for consideration.

## V. Conclusion

Material composition in composite formulation is an important aspect for consideration in fabricating composite material. This study has highlighted the importance of mold size, matrix density, filler density and volume fraction as it affects the overall composite material fabrication. The different stages involved and step by step ways of calculating the constituent material compositions were discussed. In general, the percentage composition of matrix and filler in a composite material is a function of their respective densities.

## References

[1] D. Gay, S.V, Hoa, and S. Tsai, "Composite Materials Design and Application," Boca Raton London Ney York Washington, D.C:CRC Press. 2003
[2] A. Gurit., Guide to Composites.
[3] K.K. Kamal, "Composite Materials Processing Applications, Characterizations" Heidelberger Platz 3, 14197 Berlin, Germany:Mater Springer.com. 2017
[4] K.K. Kar, Composite Materials Processing, Applications, and Characterizations, Kanpur, Uttar Pradesh, India: Springer. 694, 2017.
[5] Y. Hong, Processing of Expandable Thermoplastic/Thermoset Syntactic Foam. Georgia Institute of Technology, PhD, 2015.
[6] Z. Chen, et al., Experimental and modeling investigations of the behaviors of syntactic foam sandwich panels with lattice webs under crushing loads. Adv. Mater. Sci. 2021, 60: p. 450–465.
[7] A.A. Mohamed, et al., Thermal Degradation and Water Uptake of Biodegradable Resin Prepared from Millet Flour and Wheat Gluten

Crosslinked with Epoxydized Vegetable Oils. J. Chem, 2019, p. 1-12.

[8] V.C. Shunmugasamy, D. Pinisetty, and N. Gupta, Viscoelastic properties of hollow glass particle filled vinyl ester matrix syntactic foams: effect of temperature and loading frequency. J. Mater Sci., 2013, 48: p. 1685–1701.

[9] F. Galvagnini, et al., Mechanical Behaviour of Multifunctional Epoxy/Hollow Glass Microspheres/Paraffin Microcapsules Syntactic Foams for Thermal Management. Polym (Basel), 2021. 13(17).

[10] S. Bhatia, S. Angra, and S. Khan, Mechanical and wear properties of epoxy matrix composite reinforced with varying ratios of solid glass microspheres, in J. Phy. 2019. p. 012080

[11] N. Nawafleh, and F.M. Al-Oqla, Evaluation of mechanical properties of fiber-reinforced syntactic foam thermoset composites: A robust artificial intelligence modeling approach for improved accuracy with little datasets. J Mechan Behav Mater, 2023. 32(1).

[12] O.A. Afolabi, K. Kanny, and T.P. Mohan Processing of Hollow Glass Microspheres (HGM) filled Epoxy Syntactic Foam Composites with improved Structural Characteristics. Sci. Eng. Compos. Mater., 2021. 28, 116-127 DOI: 10.1515/secm-2021-0011.

[13] L. Peroni, L., et al., Dynamic mechanical behavior of syntactic iron foams with glass microspheres. Mater Sci Eng: A, 2012. 552: p. 364-375.

[14] C. Huang, et al., Mechanical and dynamic mechanical properties of epoxy syntactic foams reinforced by short carbon fiber. Polym. Compos, 2016, 37(7): p. 1960-1970.

[15] T.P. Mohan, and K. Kanny, Thermal, mechanical and physical properties of nanoegg shell particle-filled epoxy nanocomposites. J. Compos Mater, 2018, 52(29): p. 3989-4000.

[16] O.J. Gbadeyan, T.P. Mohan, and K. Kanny, Processing and characterization of 3D-printed nanoclay/acrylonitrile butadiene styrene (abs) nanocomposite gear. The Inter. J. of Adv. Manuf. Technol., 2020, 109(3-4): p. 619-627.

[17] H.S. Ashritha, M. Doddamania, and V. Gaitondeb, Effect of wall thickness and cutting parameters on drilling of glass microballoon/epoxy syntactic foam composites. Compos. Struct. 2019, 211: p. 318–336.

[18] M. Ozkutlu, C. Dilek, and G. Bayram, Effects of hollow glass microsphere density and surface modification on the mechanical and thermal properties of poly(methyl methacrylate) syntactic foams. Compos. Struct, 2018, 202: p. 545-550.

[19] F.Y. Addou, et al., Influences of porosity on dynamic response of FG plates resting on Winkler/Pasternak/Kerr foundation using quasi 3D HSDT. Comput. and Concr., 2019, 24: p. 347-367.

[20] A. Mohammed, et al., Sustainable Machining of Mg-9Al-1.4Zn Foam Used for Temporary Biomedical Implant Using Cryogenic Cooling. Mater (Basel), 2022, 15(19).

[21] V. Manakari, et al., In-Vitro Degradation of Hollow Silica Reinforced Magnesium Syntactic Foams in Different Simulated Body Fluids for Biomedical Applications. Metals, 2020, 10(12).

[22] A. Mohanan, et al., Tribocorrosion Mechanisms of Pure Mg–SiO2 Nano Syntactic Biodegradable Foams Against Bovine Bone in Artificial Saliva Solution. J. Bio- Tribo-Corrosion, 2021, 7(4).

[23] A.A. Ajayi, T.P. Mohan, and K. Kanny, Influence of hybridizing fillers on mechanical properties of foam composite panel. Polym. Eng. Sci., 2023.

[24] A.V. Ullas, D. Kumar, and P.K. Roy, Epoxy-Glass Microballoon Syntactic Foams: Rheological Optimization of the Processing Window. Adv. Polym. Technol., 2019, p. 1-12.

[25] C. Kádár, P. Kubelka, and A. Szlancsik, On the compressive properties of aluminum and magnesium syntactic foams: experiment and simulation. Mater. Today Commun., 2023.