Prediction of Micromechanical Behavior of Fiber (Glass/Basalt) Reinforced Polymer Composites

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Abstract - *Fiber reinforced polymer (FRP) composite is an important material for the structural application. Improvements in mechanical properties of this class of materials are still under research for diversified applications. The present research work is focused on the evolution of the mechanical properties of the FRP Composites where continuous fibers are reinforced in a Polymer matrix. The effectiveness of the fiber contributions regarding Longitudinal and Transverse properties of Fiber Reinforced Composite at various fiber volume fractions is examined by Finite Element Analysis. The experimental approach is the best way to determine the properties of the composite but it is expensive and time-consuming. Therefore, FEM and analytical methods are the viable methods for the determination of the composite properties. The Finite element results were obtained by adopting Micromechanics approach with the support of Finite Element Method. Assuming a uniform distribution of reinforcement and considering one unit-cell of the whole array, the properties of the composite materials are determined. The predicted Elastic properties from FEA is compared with analytical results. Results suggested that Basalt fiber is a good replacement and better than Glass fiber.*

Key Words: Fiber Reinforced Composite, Polypropylene, Micromechanics, Basalt Fiber, Glass Fiber, Elastic Properties, Finite Element Method, Representative Volume Element.

1. INTRODUCTION

A composite material consists of two or more constituent materials with significantly different properties combined with a recognizable interface between them, to produce a material with characteristics different from its constituents. Composite materials exhibit high mechanical and thermal properties in comparison with the conventional materials such as polymers, metal alloys etc. Two important phases present in the composite materials are the reinforcement and matrix material. The different phases serve different purposes to achieve the characteristics that are possible to composite materials. The reinforcement is characterized as a high stiff and strong phase which is intended for the load carrying purpose. Matrix phase is uninterrupted bonding among fibers to distribute loads through the reinforcement uniformly and protect it from external situations in the environment such as temperature, moisture, chemical reactions etc. Composites are usually described by the variety of matrices, such as a polymer, metal or ceramic and by the nature of reinforcement, such as fibers, particulate, flake or whiskers. Each of the composites is designed and fabricated as per the requirement for specific applications. Most of the composites are fabricated from the matrix materials like Epoxy, Polyester, Polypropylene etc., and reinforcement material fibers like Glass, Boron, Carbon and Kevlar.

The fiber reinforced composite have high strength in the fiber direction. Due to this, the load carrying capacity in that direction (Longitudinal) is very high when compared with other (Transverse) directions. Glass FRP composites are widely used because of the diversified applications. Due to this, Glass fiber production became very high. An alternative to this material is Basalt fiber, which available in large quantity and have similar components which are present in the Glass Fiber.

Polypropylene (PP) is a thermoplastic polymer which is being used in various industries including textile, stationery, automotive, laboratory equipment, plastic parts and reusable containers of various types. The PP is commercially available in the form of granules, sheets etc.

Basalt Fiber is synthesized from the Basalt Rock which is found at volcanic places and available on one-third of the earth's crust. Basalt fiber also has superior properties than the commercially available fibers like glass etc.

C.T. Sun et al., [1] established a Representative Volume Element (RVE) to predict the mechanical properties of unidirectional fiber composites. Analytical estimation of Elastic properties of FRP composites was executed by Bhaskar Pal et al., [2]. Alfredo Balaco de Morais [3] investigated a closed form of the micromechanical equation for predicting the transverse modulus of continuous fiber reinforced polymers. Pericles S. Theocaris et al., [4] calculated the effective transverse elastic moduli for fiber reinforced composites by a numerical homogenization approach. The effective elastic moduli of the composite are determined by using finite element analysis. Validation of FE models in the micromechanical analysis of a unidirectional continuous fiber reinforced composites with theoretical formulae was done by Srihari P. Anne et al., [5]. The Elastic properties of composites from FE models were validated with analytical expressions successfully by P. Prasanthi et al., [6]. General literature about composites and analytical expressions for properties were also studied [7-11]. The Finite Element Analysis of FRP Composites was studied [12].

The objective of the present work is an investigation of the mechanical properties of glass or basalt fiber reinforced composites and the comparison of mechanical properties obtained from FEA with analytical results.

2. PROBLEM MODELING

2.1. Problem Objective

The main objective of the present work is to find the mechanical properties of the fiber reinforced composite which is having continuous fibers of cylindrical shape as reinforcement in the polypropylene matrix. The overall analysis was taken using the ANSYS Software. For the analysis, Micromechanics in association with the finite element method is adopted. The results were compared with the analytical results obtained from the Rule of Mixtures.

2.2. Materials and Properties

The materials for the analysis of the FRP composite are polypropylene shown in Figure 1, Continuous basalt and glass fiber of cylindrical shape of diameter in microns shown in Figure 2 and 3.

Figure 1: Polypropylene (granules)

Figure 2: Continuous Basalt Fiber (Roving)

Figure 3: Continuous Glass Fiber

The materials taken for the analysis are isotropic in nature. The properties of the materials are listed in Table 1.

Table 1: Properties of the Constituents

Material	Young's Modulus (GPa)	Poisson's Ratio	Density (Kg/m³)
PP	1.1-1.3	0.42	910-940
E-Glass#	72.5-75.5	0.22	2510-2570
S-Glass#	83-86	0.23	2480-2520
Basalt#	79.3-93.1	0.26	2600-2700

Fiber properties were taken from Basalt Fiber & Composite Materials Technology Development [13]

2.3. Numerical Homogenization for Fiber Reinforced Composite

The main constituents for the analysis of this Fiber reinforced composites are Polypropylene Matrix and Basalt or Glass Fibers. In this section, the homogenization method is applied to fiber reinforced composite by selecting continuous fibers as reinforcement to perform the analysis. Polypropylene is used as matrix material. The ANSYS Software is used to perform the FE Analysis. Uniform distribution of Fiber in is shown in Figure 4.

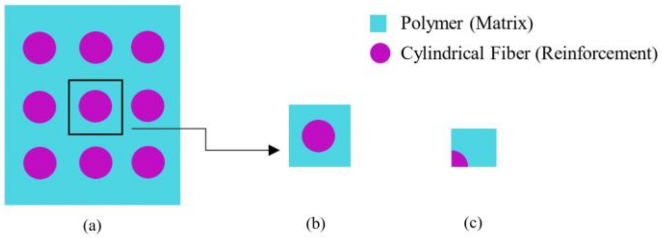

Figure 4: (a) Uniform distribution of fibers in matrix, **(b)** Isolated Unit cell and **(c)** One eighth Model

2.3.1. Geometry and Finite Element Modeling

The shape of RVE taken for the analysis of FRP is a Square Cuboid. Due to symmetry regarding geometry, loading, boundary conditions only one-fourth portion of cross-section of the RVE is modeled and analyzed. As one-fourth portion of the unit cell is taken for finite element modeling, the FE model consists of a cuboid of dimensions X=100units, Y=100units and Z=10units with an embedded one-fourth portion of Continuous Basalt Fiber of radius 'r_f' at one of the corners of square cuboid which is also the center of the cylindrical Basalt fiber where the length of the fiber is taken as 10 units so that analysis become quicker and computational time will become less. The radius of the Fiber is calculated at different volume fractions of Basalt fiber using the equation. The volume percentages of the Fiber, which are taken for the analysis are 20, 40 and 60. The radius of the fiber is calculated by using the following equation

$$r_f = \sqrt{\frac{V_f * 4 * 100^2}{\pi}} \qquad (1)$$

Where V_f = Volume fraction of Fiber

r_f = Radius of the cylindrical fiber

The Finite Element Models were prepared for different volume fractions of the Fiber and Mechanical properties were calculated. Finite Element Model of 60 vol. % of Fiber reinforced composite is shown in Figure 5.

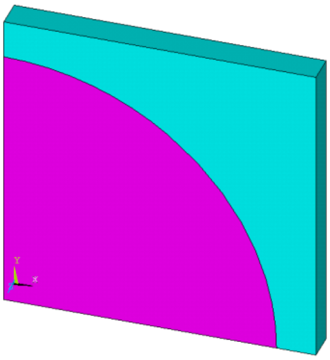

Figure 5: FE Model of FRP Composite at 60 Vol. %

2.3.2. Element Type

For the prediction of the Young's Modulus of the composite accurately, we have to use a suitable element which can calculate the large deflection in all directions.

The element used for the present analysis is SOLID186 of ANSYS, which is a higher-order 3-D 20-node solid element that exhibits the quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom at each node translation in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities [14].

Converged mesh model of the FRP composite with 60 volume percentage of fiber reinforced polymer composite is shown in Figure 6.

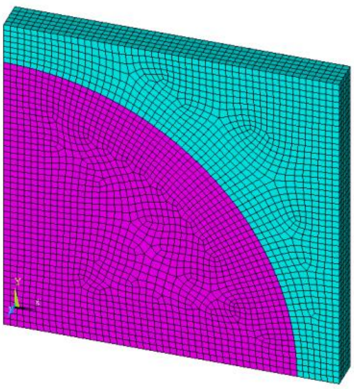

Figure 6: Converged Mesh Model of FRP Composite at 60 Vol. %

2.3.3. Material Properties

The material properties that were used for the calculation of the mechanical properties of the FRP Composite are listed in Table 2. The Matrix properties taken for the analysis are the properties of PP which are taken from the commercially available granules grade of materials. The Properties of continuous fibers are taken from commercially available grade.

Table 2: Material Properties of Constituents taken for FEA

Material	Young's Modulus (GPa)	Poisson's Ratio	Density (Kg/m³)
PP	1.16	0.42	920
E-Glass	75.5	0.22	2550
S-Glass	86	0.23	2520
Basalt	93.1	0.26	2700

2.3.4 Loading and Boundary Conditions

Due to the symmetry of the problem, the following symmetric boundary conditions are used.

At x = 0, $U_x = 0$;

At y = 0, $U_y = 0$;

At z = 0, $U_z = 0$.

In addition, the following multi-point constraints are used.

U_x of all the nodes on the line at x = 100 is same

U_y of all the nodes on the line at y = 100 is same.

U_z of all the nodes on the line at z = 10 is same.

Boundary conditions are imposed on the finite element model in such a way that the model should act as a part of the whole array of composite materials. Due to the symmetry in loading, geometry and boundary conditions, one-fourth of the unit cell is modeled in the analysis.

A uniform tensile load of 1 MPa is applied to the face to obtain a uniaxial state of stress in that direction that facilitates the usage of simple hook's law for predicting Young's modulus and Poisson's Ratio of resulting composite.

- Uniaxial state of stress is applied on the area at z=10 units to predict Longitudinal Young's modulus E_1 and Poisson's Ratios υ_{12}, υ_{13}.
- Uniaxial state of stress is applied on the area at x=100 units to predict transverse Young's modulus E_2 and Poisson's Ratios υ_{21}, υ_{23}.
- Uniaxial state of stress is applied on the area at y=100 units to predict transverse Young's modulus E_3 and Poisson's Ratios υ_{31}, υ_{32}.

Mesh Convergence is carried out for the FE Model. The converged FE model is used for the prediction of the mechanical properties of the FRP composite at various volume fractions. Due cylindrical shape of fibers, symmetrical arrangement of reinforcement and isotropic nature of the fiber, the composite properties are Transverse isotropic in nature. The Elastic properties of the FRP Composites at different volume fractions are calculated.

Because of the isotropic nature and cylindrical shape of the fiber, the following parameters will be equal in magnitude. E_2 and E_3 are equal. Poisson's Ratio's $\upsilon_{12} = \upsilon_{13}$, $\upsilon_{21} = \upsilon_{31}$ and $\upsilon_{23} = \upsilon_{32}$.

2.4. Analytical Analysis

The results obtained from the FE models prepared for FRP composite are compared with the analytical results which are obtained from the Rule of Mixture and Betties Reciprocal Theorem formulae. The elastic properties are calculated and compared with FE results using the following Equations.

$$E_1 = E_m(1-V_f) + E_fV_f \quad (2)$$

$$\upsilon_{12} = \upsilon_m(1-V_f) + \upsilon_fV_f \quad (3)$$

$$E_1/\upsilon_{12} = E_2/\upsilon_{21} \quad (4)$$

Where E_m - Young's Modulus of Matrix

E_f - Young's Modulus of Fiber

υ_m - Poisson's Ratio of Matrix

υ_f - Poisson's Ratio of Fiber

V_f - Volume fraction of Fiber

3. RESULTS

3.1. Elastic Properties of PP/Basalt Fiber Composites

The Elastic Properties of the Basalt reinforced composite are calculated using the FE Model. In this, the matrix material is resin (PP) and reinforcement is Basalt Fiber. The Elastic properties of the PP/Basalt fiber FRP Composite at different volume fractions are tabulated in Table 3.

Table 3: Elastic Properties of Basalt FRP Composites

S.No.	V_f in %	E_1 (MPa)	E_2 or E_3 (MPa)	υ_{12} or υ_{13}	υ_{21} or υ_{31}	υ_{23} or υ_{32}
1	20	19554.9298	2092.4004	0.3841	0.0411	0.6475
2	40	37944.904	3753.9228	0.3502	0.0346	0.5506
3	60	56336.7586	8138.5506	0.3166	0.0457	0.3731

The analytical results of FRP are calculated using the ROM and Betties Reciprocal Theorem i.e., using the Equation (2) Equation (3) and Equation (4).

3.2. Validation of the FRP FE model

The Finite element model is validated by comparing the longitudinal Young's Modulus and Poisson's Ratio predicted from FEM to an analytical equation ROM and the transverse modulus is compared with Betties Reciprocal Theorem.

The Longitudinal properties were compared with ROM, % of error was calculated and tabulated in Table 4.

Table 4: Comparison (FEA vs. Theoretical) of Elastic Properties of Basalt FRP

V_f in %	E_1 in MPa		% of Error	υ_{12}		% of Error
	FEA	ROM		FEA	ROM	
20	19554.9298	19548.8	0.0313	0.384168	0.388	-0.997
40	37944.904	37936.6	0.0218	0.350262	0.356	-1.638
60	56336.7586	56324.4	0.0219	0.316635	0.324	-2.325

The Transverse Properties of Basalt fiber reinforced composites were compared with Betties Reciprocal theorem and plotted as shown in Chart 1.

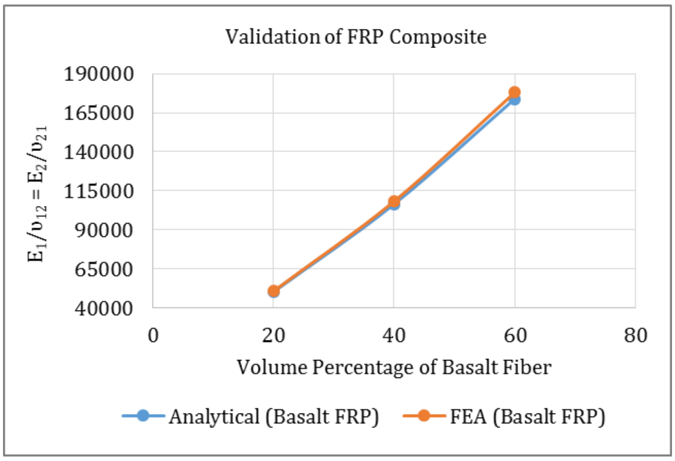

Chart 1: Validation of FRP Composite

3.3. Elastic Properties of PP/E-Glass Fiber Composites

The Elastic Properties of the E-Glass reinforced composite are calculated using the FE Model which validated in the earlier section. In this, the matrix material is resin (PP) and reinforcement is E-Glass Fiber. The Elastic properties of the PP/E-Glass fiber FRP Composite at different volume fractions are tabulated in Table 5.

Table 5: Elastic Properties of E-Glass FRP Composites

S.No.	V_f in %	E_1 (MPa)	E_2 or E_3 (MPa)	υ_{12} or υ_{13}	υ_{21} or υ_{31}	υ_{23} or υ_{32}
1	20	16039.0068	2081.9453	0.3752	0.0487	0.6428
2	40	30911.9010	3719.5185	0.3329	0.0400	0.5475
3	60	45783.3531	7953.1717	0.2909	0.0505	0.3720

3.4. Elastic Properties of PP/S-Glass Fiber Composites

The Elastic Properties of the S-Glass reinforced composite are calculated using the FE Model which validated in the earlier section. In this, the matrix material is resin (PP) and reinforcement is S-Glass Fiber. The Elastic properties of the PP/S-Glass fiber FRP Composite at different volume fractions are tabulated in Table 6.

Table 6: Elastic Properties of S-Glass FRP Composites

S.No.	V_f in %	E_1 (MPa)	E_2 or E_3 (MPa)	υ_{12} or υ_{13}	υ_{21} or υ_{31}	υ_{23} or υ_{32}
1	20	18137.6283	2089.2528	0.3774	0.0434	0.6461
2	40	35109.8939	3743.4676	0.3372	0.0359	0.5496
3	60	52081.7057	8077.2834	0.2973	0.0461	0.3722

3.5. Comparison of Elastic Properties of Fiber Reinforced Composites

The FE results of E-Glass, S-Glass and Basalt Fiber Reinforced Polymer Composite are compared and plotted.

The comparison of Moduli of FRP Composites is shown in Chart 2 and Chart 3.

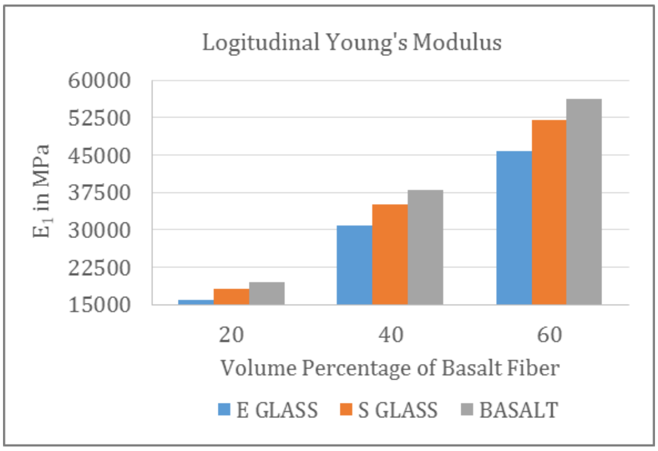

Chart 2: Comparison of E_1

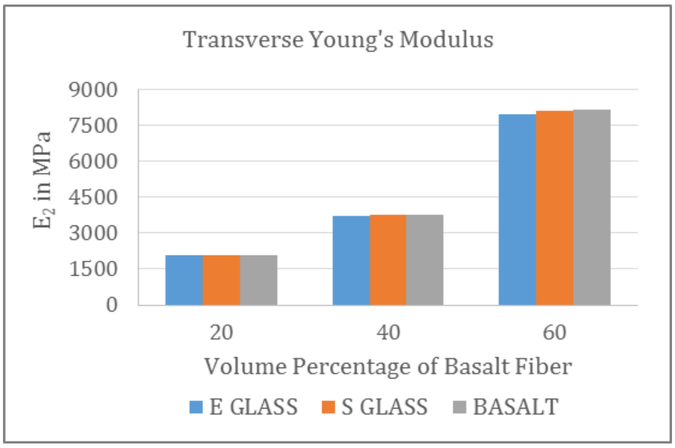

Chart 3: Comparison of E_2

The comparison of Poisson's ratios of FRP composites is shown in Chart 4, Chart 5 and Chart 6.

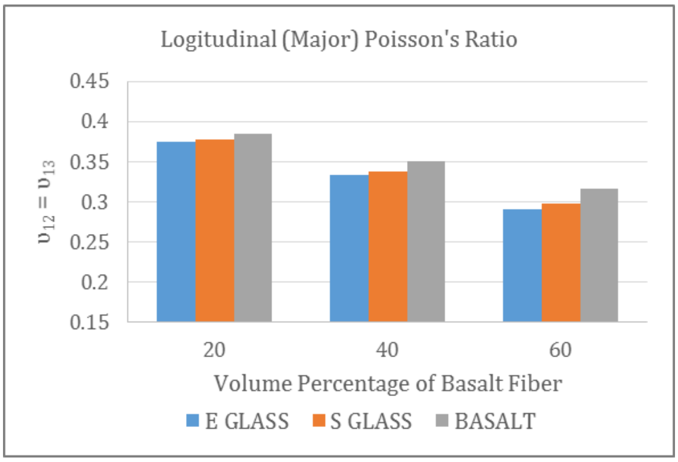

Chart 4: Comparison of υ_{12}

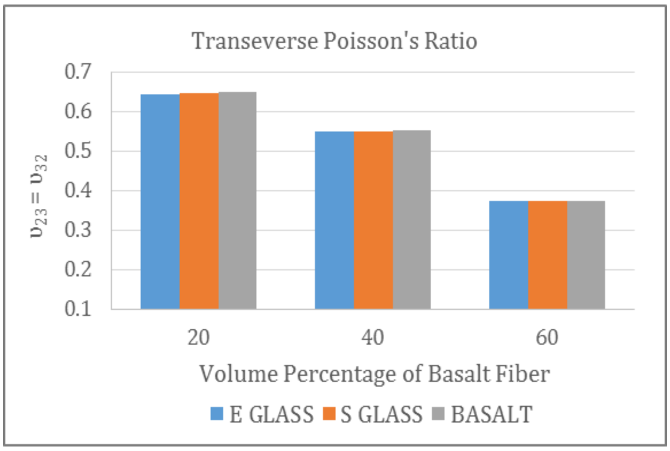

Chart 5: Comparison of υ_{23}

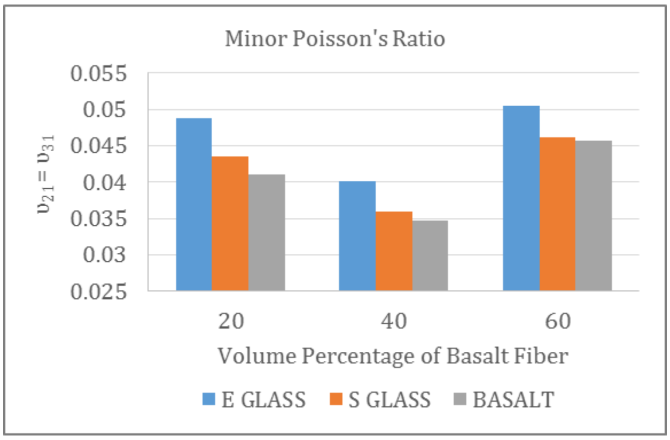

Chart 6: Comparison of υ_{21}

The comparison of Specific Modulus in Longitudinal Direction of FRP composites at 60 volume percentage is shown in Chart 7.

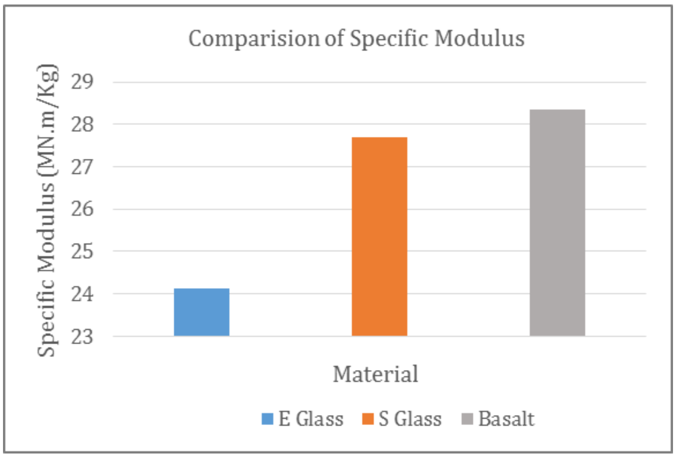

Chart 7: Comparison of Specific Modulus at 60 Vol. %

4. DISCUSSION OF RESULTS

4.1. Elastic Properties of Fiber Reinforced Composite

The Longitudinal Young's modulus (E_1) of the FRP composite increases in high amount with an increase in the volume fraction of Basalt fiber since Fibers can bear the higher load in fiber direction which results in more increase in the magnitude of E_1. The transverse Young's Modulus (E_2) of FRP increases along with the volume fraction of fiber, but the increment is very less when compared with the magnitude of E_1. The Longitudinal and Transverse Poisson's ratio decreases with the increase in the volume fraction of fiber since the strain in the longitudinal direction decreases with an increase in the volume fraction of fiber. The Minor Poisson's Ratio primarily decreases with the increase volume fraction of fiber up to 40 % and then increases along with the volume fraction of fiber.

4.2. Validation of FE Models with Theoretical Models

The FE models are validated by comparing the FE results with analytical results obtained from theoretical formulae. Moreover, it was observed that FE Models of FRP predicts a higher value of Moduli than ROM value and less value of Poisson's Ratio than ROM value. A good correlation was observed between FE results and analytical results. Almost zero percent error was observed in Moduli and a negligible error was observed in Poisson's Ratio.

4.3. Specific Modulus of Composite

The density of Basalt Fiber is 2700 Kg/m^3, there is not much variation between densities of Glass and Basalt Fibers. The Density of the composite will also have less effect regarding the densities of fibers. The Specific Modulus (Elastic Modulus per Density) of the Basalt fiber reinforced composite is very high since the Moduli of Basalt FRP Composites higher than Glass FRP Composites.

5. CONCLUSIONS

In the present work, three-dimensional finite element analysis is carried out for finding the elastic properties of FRP Composites at different volume fractions and then results were compared with the theoretical formulations. The influence of volume fraction of reinforcement on Young's Moduli and Poisson's ratios is studied and Glass FRP Composites are compared with Basalt FRP Composites. From the results and discussions, the following conclusions have been made from this present research work.

- The present work shows the successful prediction of elastic properties of FRP composites by Finite Element Analysis.
- The FE model is validated by comparing the elastic properties obtained from the theoretical formulae.
- The mechanical properties of the FRP composites were compared and it was observed an increase in the magnitude of the elastic properties of Basalt FRP composites.
- The enhancement in longitudinal properties (E_1 and υ_{12}) is very significant, i.e. the change in the properties is high.
- The enhancement in transverse properties (E_2 and υ_{23}) is not significant, i.e. the change in the properties is very less.
- The Minor Poisson's ratio (υ_{21}) is highly decreased.
- Specific Modulus of the Basalt FRP composites also very high.
- Basalt Fiber reinforced composite exhibit better properties over the Glass FRP Composites. So Basalt is a good replacement for Glass.

FUTURE SCOPE

For the improvement of mechanical properties of Fiber reinforced composites researches are being done. The inclusion of micro/nano particles will improve the properties in the Transverse direction of FRP Composites. So by adopting this FEA approach we can do an analysis of Composites, which are having both particles and fibers as reinforcement.

We can do analysis with different fibers and particles and can find the best combination which will have the Good Mechanical Properties in all directions. Thus, we can fabricate that Composite, without trying each combination with an experiment which will be a costly and time taking process.

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