

Prediction of Mechanical Properties of Glass Fiber Reinforced Concrete Using Micromechanical Techniques

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DOI: <https://doi.org/10.30880/ijscet.2025.16.01.012>

Article Info

Received: 12 November 2024
Accepted: 8 June 2025
Available online: 30 June 2025

Keywords

Glass fiber reinforced concrete,
micromechanical techniques,
representative volume element

Abstract

Glass fibers have been used in concrete at low volume fractions to effectively control cracks in various types of structural elements. Due to its complex nature, determining the mechanical properties of the glass fiber reinforced concrete is a challenging task. This paper aims to evaluate the Young's modulus, shear modulus and Poisson ratio of glass fiber reinforced concrete with homogenization theory and finite element simulation. In order to predict the above properties of glass fiber reinforced concrete, a theoretical model was established by homogenization theory. The elastic tensor matrix of unidirectionally distributed fiber reinforced concrete composites was solved by stimulating the composite representative volume element model using Abaqus software to obtain the Young's modulus, shear modulus and Poisson ratio of glass fiber reinforced concrete. By comparison, it was found that the theoretically predicted values by homogenization and the finite element simulation values were in good agreement, which verifies the accuracy of both the models.

1. Introduction

A composite material is a heterogeneous medium, made up of two or more distinct constituents that are considered to be insoluble in one another. The composite material generally exhibits the best qualities of their constituents and some additional merits that their constituents do not possess. The typical composite consists of one material supported or embedded in a binder or matrix material and in the particular case of reinforced composite, such a component is included to increase stiffness and strength.

The development of new composites and their production methods is a new trend in the field of construction. The use of suitable fibers in the construction industry is an important consideration to improve the performance of concrete with regard to its structural aspects. As the concrete is intrinsically a brittle material with highly weak post-peak behavior, fibers can act as secondary reinforcement in the concrete structures to control crack propagation. Fiber Reinforced Concrete (FRC) is a composite that includes concrete and fibrous materials, which increases structural strength and consistency. FRC contains small, distinct fibers that are oriented randomly and dispersed homogeneously. To enhance the mechanical properties of concrete, may use steel fibers, glass fibers, synthetic fibers, basalt fibers and natural fibers. The most convenient parameter to describe fiber is its aspect ratio, which is the ratio of its length to diameter.

Glass fibers consist of numerous extremely small fibers of glass. It makes the composite significantly less brittle when used in it. Therefore, it is used as a reinforcing agent for concrete and polymer products. Some important types of glass fibers are C-glass, which has excellent chemical resistance properties and S-glass, which has excellent tensile strength. Elastic modulus and Poisson's ratio are two important mechanical parameters of concrete. From a macroscopic perspective, the elastic modulus is a measure of the resistance to elastic deformation of an object. From a microscopic perspective, it is a reflection of the bonding strength between atoms, ions or molecules. The research on the elastic modulus and Poisson's ratio of FRC is mainly based on experimental measurements, which are costly and time consuming. Hence, many comprehensive studies have been conducted in recent years to resolve the problem using micromechanical techniques. Micromechanics deals with the study of the behavior of heterogeneous materials in terms of the interaction of their constituents. The major benefit of micromechanics is its virtual testing, which reduces the cost of an experiment.

Since all heterogeneous materials exhibit a statistical rather than a deterministic arrangement of components, the methods of micromechanics are normally based on the model of the representative volume element (RVE). The RVE is the smallest volume that can be measured to produce a value that represents the entire system. For heterogeneous materials, RVE can be considered as a volume that represents a composite statistically and that must effectively include a sampling of all microstructural heterogeneities that occur in the composite. The RVE must have the same elastic constants and fiber volume fraction as the composite.

A strong mechanical foundation was established by C. T. Sun and R. S. Vaidya [7] for the use of RVE to predict the mechanical properties of unidirectional fiber composites. They predicted elastic constants using finite element analysis, which are in good agreement with the available experimental data and the results of existing prediction models. Dinesh Kumar and Ashish Srivastava [3] determined the effective elastic moduli of a hybrid nano-composite, involving CNT and graphene, using square RVE. They observed a substantial increase in normal stiffness in all directions of the hybrid nano-composite with the addition of a small amount of reinforcement. W. I. Goh et al. [2] presented the results of finite element analysis and compressive tests of foamed concrete cubes. They developed a three-dimensional nonlinear finite element model and analyzed it using the aquasi static technique through the ABAQUS explicit module. Through experimental results, the input parameters of the model were obtained. Their results confirmed the accuracy of the proposed finite element model in predicting the damage behavior of the foamed concrete cube. Tipika Martin and Jitka Vašková [8] conducted experiments on different types of concrete and fiber reinforced concrete to determine the modulus of elasticity in tension and compression. George and Mohamad [1] analysed the structural behaviour of precast foamed concrete slab containing hybrid fibers under flexural load by finite element analysis using Abaqus software.

Job Thomas and Ananth Ramaswamy [9] conducted an experimental program to assess the influence of the addition of steel fibers on the mechanical properties of concrete. They considered various strength properties like modulus of rupture, modulus of elasticity, Poisson's ratio, compressive strength, split tensile strength, post cracking performance and strain corresponding to peak compressive stress. Using finite element simulation and homogenization theory, Yue Li et al. [4] assessed the elastic modulus and Poisson ratio of FRC by considering the elastic tensor matrix. Furthermore, they used MATLAB to create a random distribution meso-model of fiber reinforced concrete and simulate its axial compression using ABAQUS. They found a good agreement between the predicted values from homogenization theory, the simulated values from the finite element method and the macroscopic experiment values. P. Paramasivam et al. [6] determined the linear and non-linear elastic properties by considering a three dimensional finite element model of fiber reinforced cement composites. To incorporate the necessary boundary conditions, they adopted micromechanical techniques by forming constraint equations. M. L. Nazargah et al. [5] employed some important micromechanical methods, such as Mori-Tanaka, Bache, Hirsch, etc., to estimate the young's modulus and Poisson's ratio of ordinary and nano-material concretes. To predict the young's modulus of recycled aggregate concrete, S. Yan et al. [10] adopted four important micromechanical methods, namely the Voigt, Reuss, Eshelby and Mori-Tanaka methods. By comparing experimental data and the results from the four models, they identified the Mori-Tanaka method as the optimal model to produce more accurate predictions compared to other models.

2. Theoretical Prediction of Elastic Properties of FRC

2.1 Analytical Approach

The mechanical characteristics of fiber-reinforced concrete are assessed using the following analytical techniques. Rule of Mixture (ROM): This method is used to determine the constitutive properties of fiber reinforced concrete made up of continuous and unidirectional fibers using the following formulas as in Table 1.

Table 1 Formulas on rule of mixture

	Longitudinal direction	Transverse direction
Young's Modulus	$E_{xx} = E_f V_{fF} + E_M V_{fM}$	$E_{yy} = E_{zz} = \frac{E_F E_M}{E_M V_{fF} + E_F V_{fM}}$
Poisson's Ratio	$\nu_{xy} = \nu_{xz} = \nu_f V_{fF} + \nu_M V_{fM}$	$\nu_{yz} = \frac{\nu_F \nu_M}{\nu_M V_{fF} + \nu_F V_{fM}}$
Shear Modulus	$G_{xy} = G_{xz} = \frac{G_F G_M}{G_M V_{fF} + G_F V_{fM}}$	$G_{yz} = \frac{E_{yy}}{2(1 + \nu_{yz})}$

Halpin-Tsai Method (HTM): This method is used to predict various properties of a fiber reinforced concrete made up of unidirectional as well as randomly oriented fibers using the following formulas as in Table 2.

Table 2 Formulas on Halpin-Tsai method

	Longitudinal direction	Transverse direction
Young's Modulus	$E_L = \frac{1 + 2 \left(\frac{l_f}{d} \right) n_l V_f}{1 - n_l V_f} E_m$	$E_\tau = \frac{1 + 2n_\tau V_f}{1 - n_\tau V_f} E_m$
Poisson's Ratio		$G_{LT} = \frac{1 + 2n_G V_f}{1 - n_G V_f} G_m$
Shear Modulus		$V_{LT} = V_f \nu_f + V_m \nu_m$

2.2 Numerical Approach

To ascertain the constitutive properties of fiber reinforced concrete, finite element analysis software, specifically ABAQUS, is utilized. Using finite element analysis of the RVE, the effective elastic moduli, Poisson’s ratio and shear modulus of the composite are found. It was assumed that fibers are oriented in one direction with an infinite aspect ratio and uniform diameter. There is a perfect bonding between fibers and matrix. Strains experienced by the fiber and matrix are equal. The structure of the RVE is given in Figure 1, where the width of it can be calculated using the formula.

$$a = \sqrt{\frac{\pi r^2}{V_{fF}} + \pi r^2} \tag{1}$$

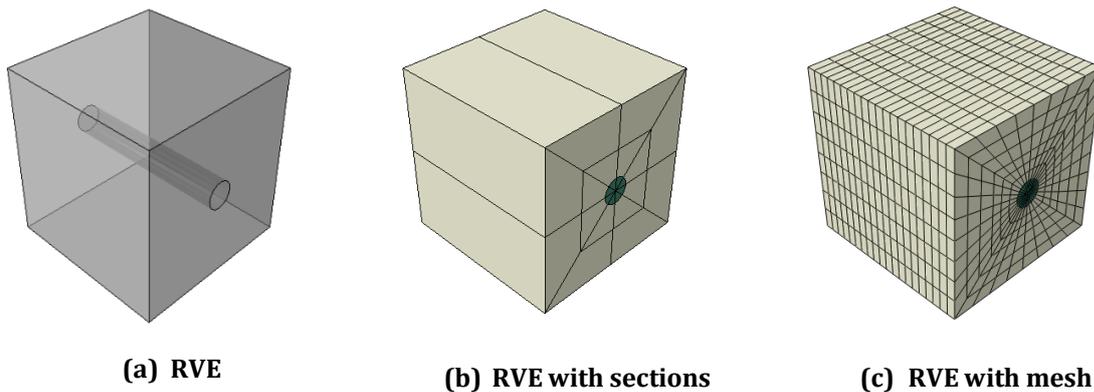


Fig. 1 Representative volume element

In mesh Linear Hexahedral Elements of type C3D8R is used for matrix and Linear Wedge Elements of type C3D6 is used for fiber.

3. Periodic Boundary Conditions for Normal Loading

To calculate E_1, ν_{12} and ν_{13} used

$$u(0, y, z) = v(x, 0, z) = w(x, y, 0) = 0, u(L, y, z) = \delta_1 \quad (2)$$

To calculate E_2 and ν_{23} used

$$u(0, y, z) = v(x, 0, z) = w(x, y, 0) = 0, v(x, a, z) = \delta_2 \quad (3)$$

To calculate E_3 used

$$u(0, y, z) = v(x, 0, z) = w(x, y, 0) = 0, u(x, y, a) = \delta_3 \quad (4)$$

Where u, v and w represent displacement components in x, y and z directions, respectively. δ_1, δ_2 and δ_3 are the constant values of displacement applied in x, y and z direction respectively.

4. Periodic Boundary Conditions for Shear Loading

By To calculate G_{23} used

$$u(x, y, 0) = v(x, y, 0) = w(x, y, 0) = 0, v(x, y, b) = \delta_t \quad (5)$$

To calculate G_{12} used

$$u(x, 0, z) = v(x, 0, z) = w(x, 0, z) = 0, u(x, a, z) = \delta_s \quad (6)$$

To calculate G_{13} used

$$u(x, y, 0) = v(x, y, 0) = w(x, y, 0) = 0, u(x, y, b) = \delta_r \quad (7)$$

where δ_t, δ_s and δ_r are the constant values of displacement in y -direction on $z = b$ face, x -direction on $y = a$ face and x -direction on $z = b$ face of the RVE respectively.

Table 3 Material properties S-glass and C-glass fibers

	S-Glass Fiber	C-Glass Fiber	Concrete
Diameter/ Grade	12 μm	12 μm	M30
Density g/cc	2.53	2.53	2.5
Poisson's ratio	0.20	0.276	0.15
Elastic modulus Gpa	85.5	69	27.386

In order to decide the best finite element model for fiber reinforced concrete, convergence studies have been performed for various mesh sizes starting from coarse mesh to finer mesh as shown in Table 3. The convergence studies have been performed for various weight percentages, such as 1%, 2% and 3% of concrete as shown in the Table 4. In convergence studies, longitudinal elastic modulus value has been considered. Once the best FE model is obtained through convergence studies, the same model is used further in the analysis to compute other constitutive properties such as Poisson's ratio and shear modulus.

5. Results and Discussion

5.1 Constitutive Properties of C-Glass Fiber Reinforced Concrete

The inclusion of fibers generally enhances various mechanical properties of concrete. The average increases in longitudinal and transverse Young's modulus, in plane and out of plane Poisson's ratio, longitudinal and transverse shear modulus of fiber reinforced concrete due to the addition of C-glass fibers up to 3% are 4.51%, 2.311%, 3.47%, 2.22%, 1.965% and 2.29% respectively, which are found to be minimal as shown in the Figure 2.

Table 4 Mechanical properties of C-glass using numerical and analytical results

Weight % of Fiber	ROM	HTM	FEM	ROM	HTM	FEM
	Longitudinal Young's Modulus			Transverse Young's Modulus		
0%	27.386	27.386	27.386	27.386	27.386	27.386
1%	27.788	27.788	27.797	27.547	27.654	27.594
2%	28.183	28.183	28.208	27.706	27.919	27.806
3%	28.570	28.570	28.620	27.864	28.180	28.019
	In Plane Poisson's Ratio			Out of Plane Poisson's Ratio		
0%	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
1%	0.1512	0.1512	0.1517	0.1507	0.1512	0.1512
2%	0.1524	0.1524	0.1534	0.1513	0.1524	0.1523
3%	0.1536	0.1536	0.1552	0.152	0.1536	0.1535
	Longitudinal Shear Modulus			Transverse Shear Modulus		
0%	11.907	11.907	11.907	11.907	11.907	11.907
1%	12.053	11.997	11.997	11.972	11.997	11.984
2%	12.197	12.086	12.088	12.036	12.086	12.062
3%	12.338	12.173	12.180	12.100	12.173	12.141

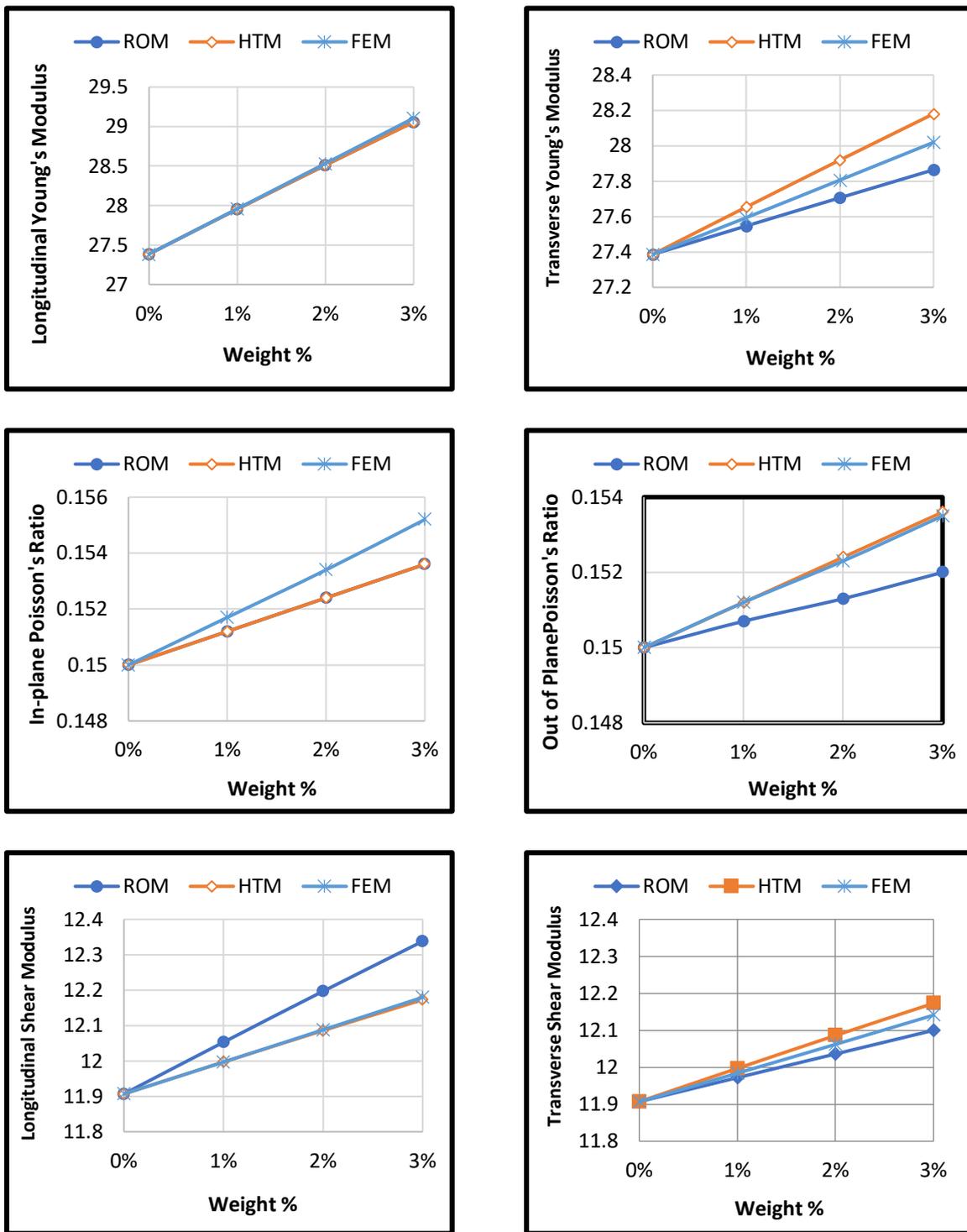


Fig. 2 Constitutive properties of C-glass fiber reinforced concrete with respect to the weight percent of fiber

5.2 Constitutive Properties of S-Glass Fiber Reinforced Concrete

The average increases in longitudinal and transverse Young's modulus, in plane and out of plane Poisson's ratio, longitudinal and transverse shear modulus of fiber reinforced concrete due to the addition of S-glass fibers up to 3% are 6.28%, 2.75%, 1.4%, 1.73%, 2.46% and 3% respectively, which are found to be quite small as shown in the Figure 3.

Table 5 Mechanical properties of S-glass using numerical and analytical results

Weight % of Fiber	ROM	HTM	FEM	ROM	HTM	FEM
	Longitudinal Young's Modulus			Transverse Young's Modulus		
0%	27.386	27.386	27.386	27.386	27.386	27.386
1%	27.955	27.954	27.959	27.569	27.72	27.634
2%	28.512	28.511	28.533	27.752	28.051	27.884
3%	29.059	29.057	29.107	27.933	28.378	28.139
	In Plane Poisson's Ratio			Out of Plane Poisson's Ratio		
0%	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
1%	0.1505	0.1505	0.1507	0.1504	0.1505	0.1509
2%	0.1510	0.1510	0.1513	0.1507	0.1510	0.1517
3%	0.1514	0.1514	0.1521	0.1511	0.1514	0.1526
	Longitudinal Shear Modulus			Transverse Shear Modulus		
0%	11.907	11.907	11.907	11.907	11.907	11.907
1%	12.139	12.024	12.025	11.985	12.024	12.004
2%	12.367	12.139	12.143	12.063	12.139	12.102
3%	12.590	12.254	12.264	12.140	12.254	12.200

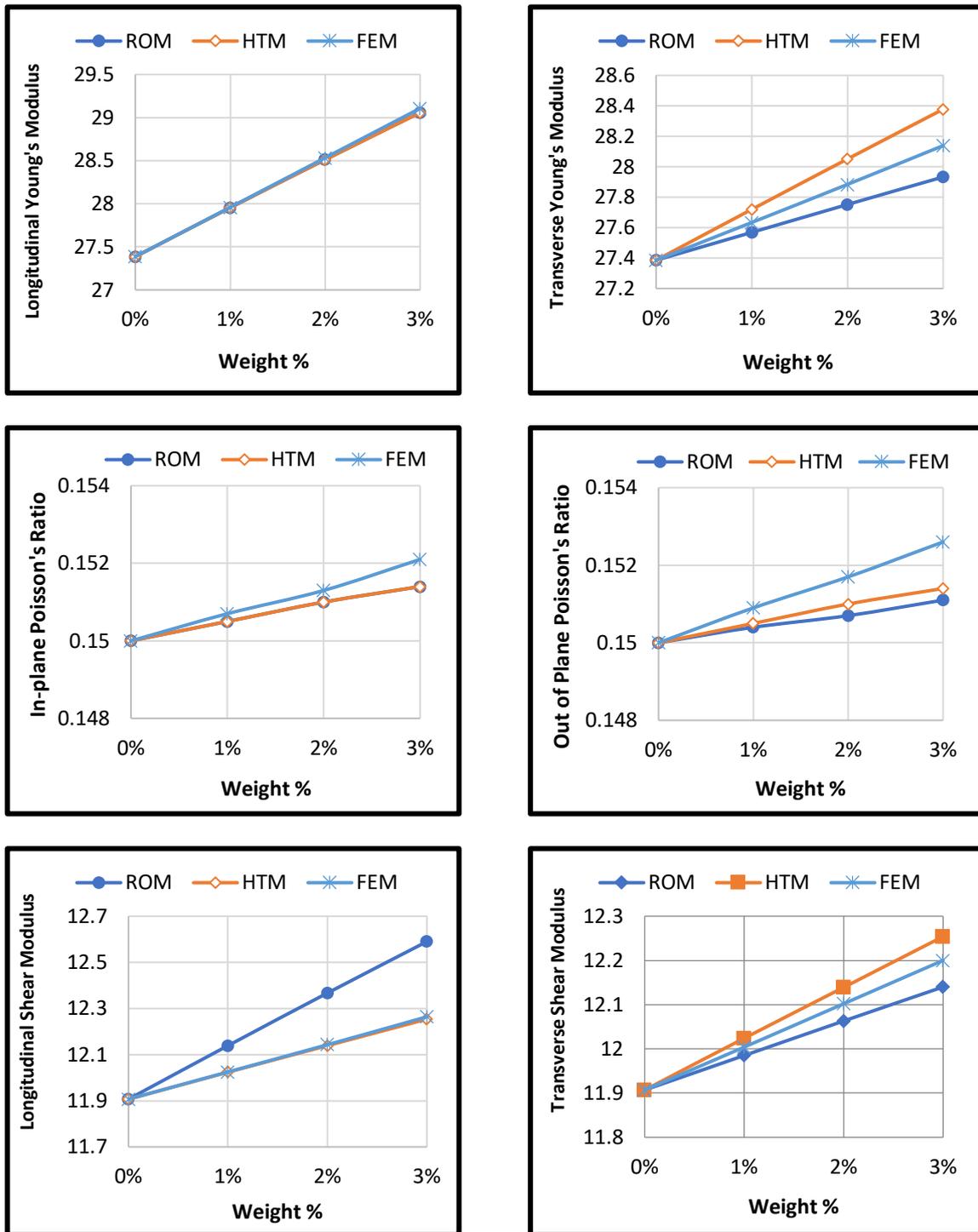


Fig. 3 Constitutive properties of C-glass fiber reinforced concrete with respect to the weight percent of fiber

6. Conclusion

In this paper, the Young's modulus, shear modulus and Poisson ratio of glass fiber reinforced concrete were first calculated by the homogenization method and then predicted by stimulating the composite representative volume element model of unidirectionally distributed fiber reinforced concrete using Abaqus software. Finally, the theoretically calculated results from homogenization and finite element simulated results were compared, and the following conclusions were obtained.

- The theoretically predicted values by homogenization and the finite element simulation values were in good agreement, which verified the accuracy of both the models.

- By adding various weight percentages of glass fibers to concrete, find a significant and almost uniform improvement in longitudinal and shear modulus.
- The increase in longitudinal and shear modulus of concrete reinforced with C-glass and S-glass fibers is almost the same.
- In the case of Poisson's ratio, find no considerable improvement by adding various weight percentages of glass fibers.

Acknowledgement

The authors would like thank all the reviewers for their invaluable suggestions and comments towards improving our manuscript.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Kavya B R, H S Sureshchandra; **data collection:** Kavya B R; **analysis and interpretation of results:** Kavya B R, H S Sureshchandra, Shrikanth A S; **draft manuscript preparation:** Kavya B R, Shrikanth A S. All authors reviewed the results and approved the final version of the manuscript.

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