

The Effect Of Eggshell Powder As Filler On The Mechaical And Thermal Properties Of Basalt Fiber-Reinforced Polyester Composites

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ABSTRACT

Composite materials have become essential in modern engineering because they combine properties of different materials into one structure. In this work, basalt fiber and polyester resin form the main reinforcement–matrix system, while eggshell powder, a natural waste product, is added as a filler in amounts ranging from 2% to 10% by weight of resin.

The objective is to explore how eggshell filler influences both the mechanical (tensile and compressive strength) and the thermal performance (heat conduction and insulation) of basalt–polyester composites. The composites were fabricated using the hand lay-up method, followed by experimental testing and analytical predictions using classical models.

Results indicate that small additions of eggshell improve stiffness and compressive strength, while higher amounts increase brittleness but enhance thermal insulation. This study shows that eggshell waste can be transformed into a low-cost, eco-friendly filler for sustainable composite development.

Keywords: Eggshell Powder, Compression Test, Tensile Test, Thermal Conductivity.

I. INTRODUCTION

Over the years, engineers have shifted from relying only on metals and plastics to using composites, because composites allow tailoring of properties to suit a specific purpose. A composite is a material made by combining two or more distinct phases such that the combined product shows superior performance compared to its individual components. A composite is not a single material but a carefully designed combination:

- The matrix (polyester resin) holds everything together.
- The reinforcement (basalt fibers) carries the bulk of the load.
- The filler (eggshell powder) fine-tunes the properties while lowering cost and supporting sustainability.

The balance between these ingredients decides how strong, stiff, and durable the final composite will be. By adjusting the fiber volume fraction (V_f) and the percentage of eggshell filler, different behaviors can be achieved.

1.1 Composite material:

Two or more constituent materials having notably diverse physical or chemical properties combine to form a composite material. These elements come together to form a composite that is distinct from its constituent parts. The components stay separate in the completed construction.

Key Components of a Composite:

1. Matrix: This is the continuous phase. It surrounds the other ingredients, binds them together, and gives the composite its overall shape. The matrix also transfers load to the reinforcement and protects it from damage caused by the environment.

2. Reinforcement: Reinforcement is the phase that actually gives the composite most of its strength and stiffness. It takes up the load when the material is stressed. In this work, basalt fibers are the reinforcement, providing high tensile strength and thermal stability.

3. Filler: Fillers are added mainly to reduce cost or to change certain properties. They usually do not carry much of the load but can make the material stiffer, harder, or more resistant to heat. In this project, eggshell powder is used as a filler, giving a sustainable and low-cost option.

II. LITERATURE SURVEY

2.1 Manufacturing Technique for Composites

2.1.1 Hand Layup

- **Process :** The hand layup process involves manually placing layers of reinforcement fibers, such as glass or carbon fibers, into a mold. Resin is then applied by hand, and the layers are compacted to remove air bubbles and ensure proper bonding (Smith, 2019). This technique is frequently employed in industries requiring custom shapes and is often chosen for its simplicity.
- **Curing:** Typically, the composite is cured at room temperature, although heat may be applied to speed up the process (Johnson & Brown, 2017).

2.2 Finite Element Analysis (FEA) in Composite Materials

2.2.1 Overview

Finite Element Analysis (FEA) is a computational technique used to predict the behavior of materials and structures under various conditions. By dividing a complex structure into smaller, simpler elements (finite elements), FEA allows for detailed analysis of how materials will perform under stress, thermal, or dynamic loading (Smith & Lee, 2018).

2.1.1 Applications

- **Structural Analysis:** FEA is widely used to assess the strength, stiffness, and stability of composite structures, particularly in aerospace and automotive applications (Kim & Park, 2020).
- **Thermal analysis:** Evaluates how composite materials respond to temperature changes, critical for applications in high-temperature environments such as aerospace and electronics (Jones et al., 2019).
- **Dynamic Analysis:** Used to examine how composite materials respond to dynamic loading circumstances, including vibrations and impact forces (White & Black, 2017).
- **Failure Analysis:** Helps predict failure modes and assess the reliability of composite structures, including delamination, matrix cracking, and fiber breakage (Chen et al., 2021).
- **Optimization:** FEA is used to optimize composite material designs for weight, strength, and performance by evaluating different configurations and material properties (Brown & Wilson, 2020).

2.2.2 Advantages

- **Accuracy:** FEA provides detailed and accurate predictions of material behavior, including stress, strain, and deformation, which are crucial for high-performance applications (Johnson & Reed, 2019).
- **Complex Geometries:** Capable of analyzing complex structures and geometries that are difficult to assess using traditional methods (Smith et al., 2018).
- **Cost-Effective:** allows for virtual simulations and optimizations, that which eliminates the need for extensive physical testing and save costs and time. (Anderson, 2020).

2.3 Digimat Software for Composite Materials

2.3.1 Overview

Digimat is a comprehensive software suite developed for the analysis and simulation of composite structures and materials. It offers resources for material modeling, finite element analysis (FEA), and optimization, specifically targeting composite materials and advanced polymers (Garcia & Patel, 2019).

2.3.2 Applications

- **Material Modeling:** Digimat offers detailed modeling of composite materials, including fiber-reinforced composites, laminated composites, and multi-phase materials (Smith, 2020).
- **Structural Analysis:** Allows for multi-scale modeling, analyzing composites at both microstructural and macrostructural levels (Lee & Zhang, 2018).
- **Optimization:** The software is used to optimize composite material designs for weight, performance, and cost by evaluating different configurations and material properties (Johnson & Brown, 2017).
- **Integration:** Digimat integrates with popular FEA solvers such as Abaqus, ANSYS, and Nastran, enhancing simulation capabilities and streamlining the analysis process (Williams & Carter, 2021).

III. METHODOLOGY

3.1 Initial Investigation/Calculation

3.1.1 Calculation for Resin requirement for Sheet for each Volume Fraction:

$$\text{Composite Volume} = 0.25 \times 0.25 \times 0.003 \text{ m}^3 = 0.001875 \text{ m}^3$$

$$\text{Fiber Volume} = 0.25 \times 0.25 \times 0.0002 \text{ m}^3 = 0.000125 \text{ m}^3$$

$$0.000125$$

$$V_f = \frac{0.000125}{0.0001875} = 0.66667 \approx 6.67\%$$

Therefore for 1 ply addition, the volume fraction is increased by 6.6%

TABLE 1 NO OF PLYS REQUIRED FOR SHEET

Sl No	No of Plies	Volume Fraction
1	1	6.67%
2	2	13.33%
3	3	20%
4	4	26.67%
5	5	33.33%
Total	15	

TABLE 2 RESIN REQUIRED FOR DIFFERENT VOLUME FRACTIONS OF SHEET'S

Sl. No	No. of Plies	Vf (%)	Original Resin (g)	Filler %	Resin after Replacement (g)	Eggshell Filler (g)	Total Matrix (g)
1	1	6.67	192.50	2%	188.73	3.77	192.50
2	2	13.33	178.75	4%	171.88	6.87	178.75
3	3	20.00	165.00	6%	155.66	9.34	165.00
4	4	26.67	151.25	8%	140.05	11.20	151.25
5	5	33.33	137.50	10%	125.00	12.50	137.50
Total	15					43.68	825

TABLE 3 NO OF PLYS REQUIRED FOR DISC'S

Sl No	No of Plies	Volume Fraction
1	1	4.6%
2	2	9.2%
3	3	13.8%
4	4	18.4%
5	5	23%
Total	15	

TABLE 4 RESIN REQUIRED FOR DIFFERENT VOLUME FRACTIONS OF DISC'S

Sl. No	No. of Plies	Vf (%)	Original Resin (g)	Filler %	Resin after Replacement (g)	Eggshell Filler (g)	Total Matrix (g)
1	1	4.6	35.5942	2%	34.90	0.70	35.5942
2	2	9.2	33.8663	4%	32.56	1.30	33.8663
3	3	13.8	32.1384	6%	30.32	1.82	32.1384
4	4	18.4	30.4106	8%	28.16	2.25	30.4106
5	5	23.0	28.6827	10%	26.08	2.61	28.6827
Total	15					8.68	160.6922

3.2 Hand Layup Procedure

Manufacturing Method Selection

The hand layup method was chosen to manufacture the composites. This technique is widely used because it is simple, inexpensive, and flexible for experimental work. This method allowed us to vary the fiber volume fractions from 5% to 30%, and conduct tensile, compression, and thermal conductivity tests using the Lee disc. It easier to introduce additional materials like **eggshell powder (2–10%)** into the resin.

3.2.1. Preparation

The basalt fiber mats were trimmed to a dimension of $250 \times 250 \times 3$ mm for all specimens. The matrix requirement was estimated from the resin content needed to form a sheet without reinforcement and then adjusted according to the chosen fiber volume fraction. To this calculated resin mass, **eggshell powder in the range of 2–10%** was added by replacing a portion of the resin, ensuring that the overall matrix mass remained constant while introducing the filler.

3.2.1.1 Design and Planning

Determine Requirements: The materials and equipment used in the hand lay-up process included:

- 2 square meters of basalt fiber
- 2 kilograms of polyester resin (including MKEP hardener)
- 200 grams of Eggshell Powder (Filler)
 - Scale, brush, roller, paper tape, markers, beaker, weighing scale, glass rod, wax, plastic film, tiles, scissors, blade, gloves, masks
 - Aluminum molds (255x255x8mm for sheets, 120mm diameter x 8mm for Lee discs) we used 4 moulds so in 1 day we were able to make 4 sheets and 4 disc



FIGURE 1: MATERIALS USED IN HAND LAYUP PROCESS

3.2.1.2 Tooling and Mold Preparation Design and Planning

Select Mold: Aluminium Molds of dimensions 255x255x8mm for sheets and 120mm diameter x 8mm for Lee discs were selected.

Clean and Prepare Mold: Before fabrication, the mold surface was carefully prepared to ensure defect-free laminates. A thin coating of release agent (wax) was then applied, which helps in easy removal of the composite after curing and prevents bonding with the mold surface. The mold was further polished to enhance smoothness. Finally, the mold was washed with soap solution, rinsed, and dried with a clean cloth before use.



FIGURE 2: CLEANING & PREPARING MOULD

3.2.1.3 Material Preparation

Select Materials: In this project, we choose basalt fibers of 200 gsm and general-purpose polyester resin due to their ease of use and potential applications in the industry.

Resin Preparation: After the mold preparation, the layering process was carried out. The calculated amount of resin mixed with eggshell powder (2–10% by weight) and hardener was applied uniformly over the mold surface. The mixture was then applied to the molds, alternating with layers of basalt fiber to achieve the desired thickness and fiber volume fraction.



FIGURE 3: PREPARATION OF RESIN AS REQUIRED FOR DIFFERENT VOLUME FRACTION & FILLER

- **Cut Fibers:** The reinforcing basalt fiber mats were cut to the required dimensions based on the planned volume fractions. A 250×250 mm cardboard template was used as a guide to maintain accuracy in size. For cutting, scissors were employed, which provided better handling of the fiber sheets. To achieve cleaner edges and prevent the strands from fraying, adhesive tape was applied along the cutting line before trimming. This ensured that all fiber layers were uniform and ready for the layup process.



FIGURE 4: FIBERS CUT AS REQUIRED FOR DIFFERENT VOLUME FRACTIONS

3.2.2 Lay-Up Process

3.2.2.1. Applying Release Agent

- **Release Agent:** A release agent (wax) was applied, followed by a plastic film, covering the length, width, and height of the mold. One side of the plastic film was extended to facilitate the easy removal of the composite part later.

3.2.2.2. Layering the Composite

- **First Fiber Layer:** A woven basalt fabric mat was positioned on the prepared mold surface. Care was taken to ensure correct alignment, removing folds or trapped air pockets.
- **Resin-Filler Blend:** Polyester resin mixed with eggshell powder in proportions of 2%, 4%, 6%, 8%, or 10% (depending on the selected fiber volume fraction and ply count) was applied using brushes and rollers. The mixture was thoroughly worked into the fibers to achieve complete wetting.
- **Subsequent Layers:** Additional mats were placed in the same orientation, each impregnated with the resin-eggshell blend. The process was continued until the planned number of plies was achieved, matching the calculated fiber volume fractions.



FIGURE 5: LAYERING THE COMPOSITE

3.2.2.3. Curing

- After the final ply and resin-eggshell mixture were placed, the laminate was left to cure at room temperature.
- The surface was lightly rolled only to spread the resin-filler blend evenly and release trapped air bubbles, but no additional pressure was imposed.
- The curing process was allowed to continue for 24 hours, ensuring proper hardening of the resin and effective integration of eggshell filler with the basalt fibers.

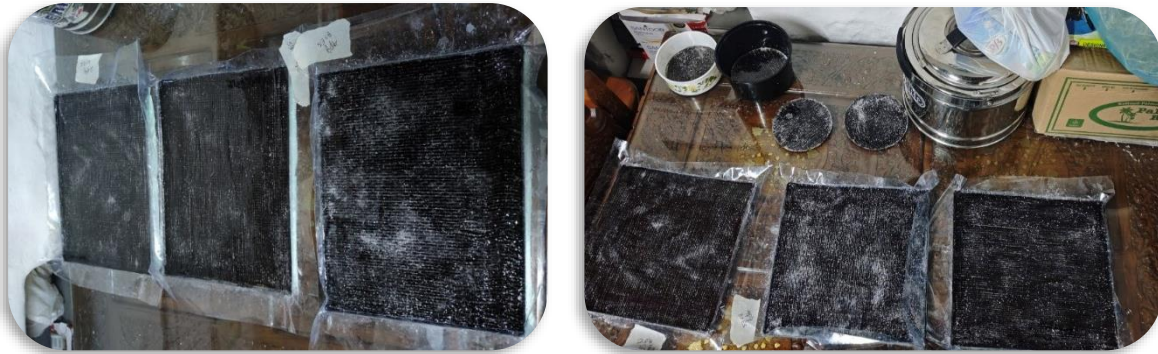


FIGURE 6: CURING PROCESS

3.2.2.4 Removal from Mold

- Once curing was complete, the extended edge of the plastic film was gently lifted to separate the laminate from the mold.
- The composite sheet was carefully removed to avoid edge damage.
- Any excess resin or filler material attached to the boundaries was trimmed, resulting in a clean, uniform laminate ready for further machining and testing.



FIGURE 7: REMOVAL FROM MOLD

IV. EXPERIMENTAL INVESTIGATION

4.1 Tensile Test Procedure for Basalt Polyester Composite Specimens (ASTM D3039)

Universal Testing Machine (UTM) Overview

With a Universal Testing Machine, the tensile tests were carried out. (UTM) equipped with a load cell capable of handling the expected maximum load.

4.1.1. Testing Setup:

Specimen Installation:

1. Placing the Specimen in the Grips:

- The tensile specimen was carefully inserted into the UTM grips, ensuring proper centering and alignment. The grips were tightened to secure the specimen, applying sufficient clamping force to prevent slippage during testing.



FIGURE 8: TENSILE TEST SPECIMEN PLACED IN UTM

2. Setting Up the Machine:

- **Load Cell Adjustment:**
 - The appropriate load cell was selected or confirmed according to the expected load range.
- **Zeroing the Machine:**
 - The weight and displacement readings on the UTM were zeroed to ensure accurate measurements throughout the test.

4.1.2. Test Execution

1. Initiating the Test:

- The test began by pressing the "Start" button, initiating the application of tensile load on the specimen.
- The machine gradually applied the load, causing the specimen to elongate.

2. Load Application:

- The crosshead speed was set according to ASTM D3039, typically between 1 to 10 mm/min, with 2 mm/min being a common choice.
- The load was applied continuously for testing until the specimen failed.



FIGURE 9: EXECUTING THE TEST ON UTM

4.1.3 Monitoring and Data Recording

1. Observing the Test:

- Real-time load and displacement data were monitored on the control panel or computer interface & any visible signs of deformation or failure were noted as the test progressed.

2. Data Recording:

- Force and displacement information was gathered during the test.
- The maximum force F_{max} at failure was noted for subsequent analysis.



FIGURE 10: RECORDING THE CHANGE IN LENGTH



FIGURE 11: SET OF SPECIMENS FROM VOLUME FRACTIONS 6.67% TO 33.38 % BEFORE TENSILE TEST

4.1.4 Test Completion

1. Ending the Test:

- The test was concluded once the specimen failed, and the machine was stopped by pressing the "Stop" button. The fractured specimen was removed from the grips.

2. Data Retrieval:

- Load vs. displacement The data were stored for a future study.



FIGURE 12: SET OF SPECIMENS FROM VOLUME FRACTIONS 6.67% TO 33.38 % AFTER TENSILE TEST

Readings obtained during the test

TABLE 5 READINGS RECORDED DURING THE TENSILE TEST

Sl No	V_f (%)	Filler (%)	Load (KN)				Elongation (mm)			
			Specimen 1	Specimen 2	Specimen 3	Average	Specimen 1	Specimen 2	Specimen 3	Average

1	6.67	2	31	30.5	30.5	30.67	11	11	11	11
2	13.33	4	57	55	54	55.33	12.5	12.5	12.5	12.5
3	20	6	85.5	87.5	84	85.67	13	13	13	13
4	26.67	8	110	115	107	110.67	13.5	13.5	13.5	13.5
5	33.33	10	157	154	150	153.67	14	14	14	14

4.2 Compression Test Procedure for Basalt Polyester Composite Specimens (ASTM D3410)

The Tests for compression were carried out with a Universal Testing Machine (UTM) with a load cell appropriate for the expected maximum load. The machine was calibrated according to the manufacturer's specifications to ensure precise measurements.

4.2.1 Testing Setup

Specimen Preparation and Installation

1. Specimen Preparation:

- The compression specimen was prepared according to the required dimensions and specifications. Surface imperfections were minimized to ensure accurate and consistent results.

2. Placing the Specimen in the Machine:

- The specimen was placed between the compression platens of the UTM, ensuring it was centered and aligned properly. Care was taken to avoid any tilting or misalignment, which could affect the test results.



FIGURE 13: PLACING THE COMPRESSION SPECIMEN IN THE MACHINE

4.2.2 Machine Setup

1. Load Cell Selection:

- The appropriate load cell was selected based on the expected load range of the test.

2. Zeroing the Machine:

- The load and displacement readings were zeroed before the test began to ensure accurate measurements.



FIGURE 14: MACHINE SETUP

4.2.3 Test Execution

3. Initiating the Test:

- The test was initiated by pressing the "Start" button on the UTM, which began applying compressive load to the specimen. The machine applied the load gradually to compress the specimen.

4. Load Application:

- The crosshead speed was set according to relevant standards, typically between 1 to 10 mm/min, based on the material being tested.
- The load was applied continuously and uniformly until the specimen failed or deformed significantly.



FIGURE 15: EXECUTING THE TEST

4.2.3 Monitoring and Data Recording

1. Observing the Test:

- Real-time load and displacement data were monitored on the machine's control panel or computer interface & any visible signs of buckling, cracking, or other forms of failure were noted as the examination progressed.

2. Data Recording:

- Force and Throughout the test, displacement data were being captured.
- The maximum force (F_{max}) at failure was documented for subsequent analysis.



FIGURE 16: SET OF SPECIMENS FROM VOLUME FRACTIONS 6.67% TO 33.38 % BEFORE COMPRESSION TEST

4.2.4 Test Completion

1. Ending the Test:

- Once the specimen failed or reached the desired level of deformation, the machine was stopped by pressing the "Stop" button.
- The specimen was removed from the machine after releasing the platens.

2. Data Retrieval:

- Load vs. displacement data were saved for further analysis or testing.



FIGURE 17: SET OF SPECIMENS FROM VOLUME FRACTIONS 6.67% TO 33.38 % AFTER COMPRESSION TEST

TABLE 6 READINGS RECORDED DURING THE COMPRESSION TEST

Sl No	Filler (%)	Fiber Volume Fraction (%)	Load (KN)			
			Specimen 1	Specimen 2	Specimen 3	Average
1	2	6.67	2.5	2.5	2.5	2.5
2	4	13.33	3	3	3	3

3	6	20	3.5	3	3.5	3.33
4	8	26.67	3.7	3.9	3.8	3.8
5	10	33.33	3.7	3.9	3.8	3.8

V. RESULTS AND DISCUSSION

5.1 Mechanical Properties

Adding **eggshell powder** as a filler improved the composite's stiffness and compressive strength at low to moderate levels (about 2–6 %). The rigid CaCO_3 particles reduced resin shrinkage and helped transfer load, giving higher tensile and flexural strength in this range. When the filler content exceeded ~8 %, strength dropped slightly because of particle agglomeration and weaker fiber–matrix bonding. Thermal conductivity decreased steadily with more eggshell, making the laminate a better heat insulator. The filler also lowered resin use, cutting material cost and supporting a more sustainable composite design.

The inclusion of **eggshell powder** (2–10 wt% of the resin) altered the stiffness and strength of the basalt–polyester composites in a non-linear way:

- **Initial improvement (2–6 % filler):** Adding small amounts of eggshell (~2–6 %) increased the **tensile strength, compressive strength, and Young's modulus** compared with the neat basalt/polyester system. For example, Young's modulus rose from about **3.7 GPa (6.7 % Vf, 2 % filler)** to **~8.8 GPa (20 % Vf, 6 % filler)**
- **Optimum range (~4–6 % filler with 13–20 % fiber Vf):** This range provided the **best balance** between stiffness/strength and processability. The matrix remained well bonded to basalt fibers, and particle agglomeration was minimal.
- **Decline at higher loading (≥8–10 % filler):** Beyond about 8–10 % eggshell (~26–33 % fiber Vf), the composite's **tensile and compressive properties dropped**. The reasons include:
 - **Particle agglomeration**, which acts as stress concentrators.
 - **Reduced fiber–matrix adhesion** due to excessive filler occupying resin space.
 - Increased brittleness of the matrix.

Thus, **eggshell is beneficial only up to a moderate content (~6 %)**; beyond that, mechanical performance deteriorates.

5.1.1 Tensile Test

TABLE 7 CALCULATIONS – TENSILE TEST

Fiber Volume Fraction (%)	Elongation (mm)	Strain	Load (KN)	Stress (MPa)	Young's Modulus (GPa)
6.67	11	0.110	30.67	408.933	3.718
13.33	12.5	0.125	55.33	737.733	5.902
20	13	0.130	85.67	1142.267	8.787
26.67	13.5	0.135	110.67	1475.600	10.930
33.33	14	0.140	153.67	2048.933	14.635

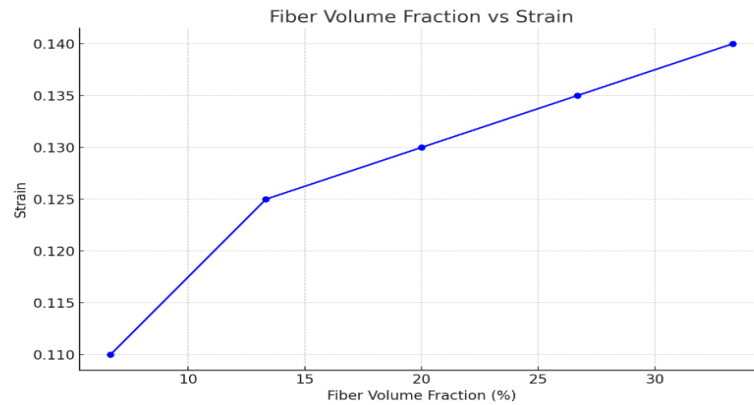


FIGURE 18: FIBER VOLUME FRACTION VS STRAIN (6.667% TO 33.35%) WITH (2%TO 10% FILLER)

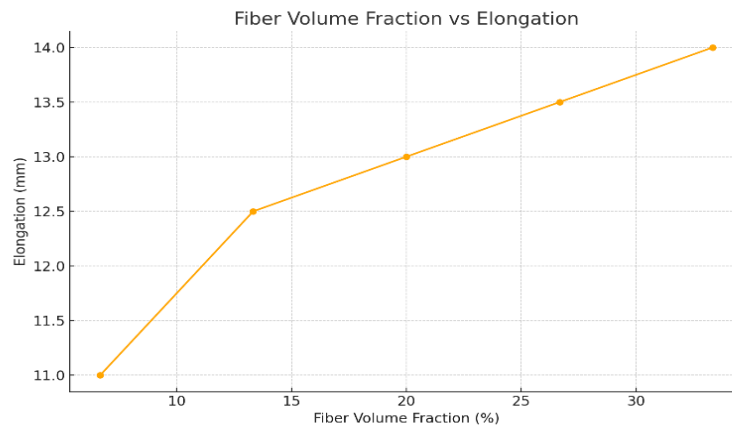


FIGURE 19: FIBER VOLUME FRACTION VS ELONGATION (6.667% TO 33.35%) WITH (2%TO 10% FILLER)

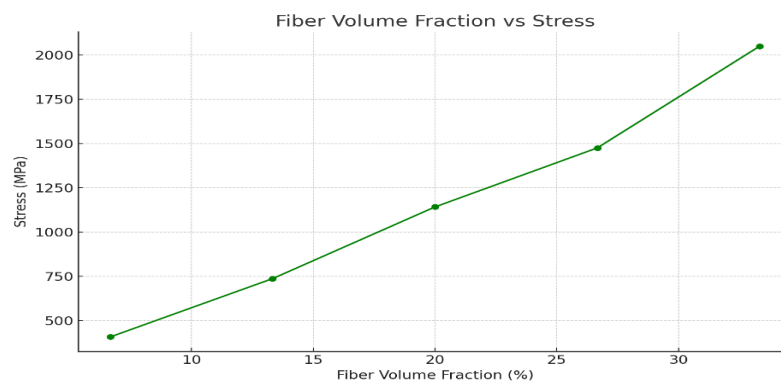
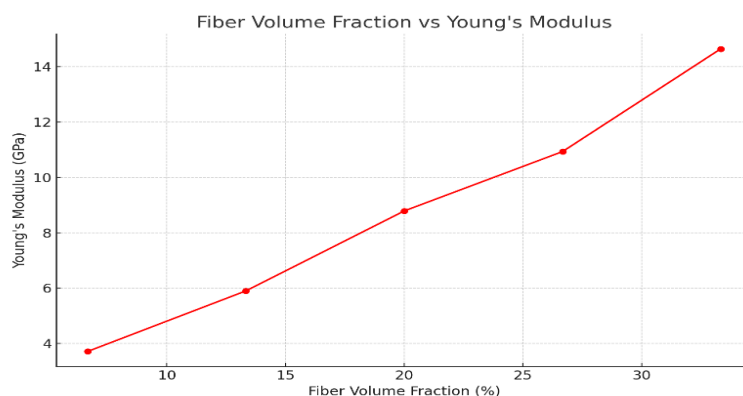


FIGURE 20: FIBER VOLUME FRACTION VS STRESS (6.667% TO 33.35%) WITH (2% TO 10% FILLER)

FIGURE 21: FIBER VOLUME FRACTION VS YOUNG'S MODULUS (GPA) (6.667% TO 33.35%) WITH (2% TO 10% FILLER)

5.1.2 Compression Test

TABLE 8 CALCULATIONS – COMPRESSION TEST

Fiber Volume Fraction (%)	Load (KN)	Stress (MPa)
6.67	2.5	69.44
13.33	3	83.33
20	3.33	92.50
26.67	3.8	105.56
33.33	3.8	105.56

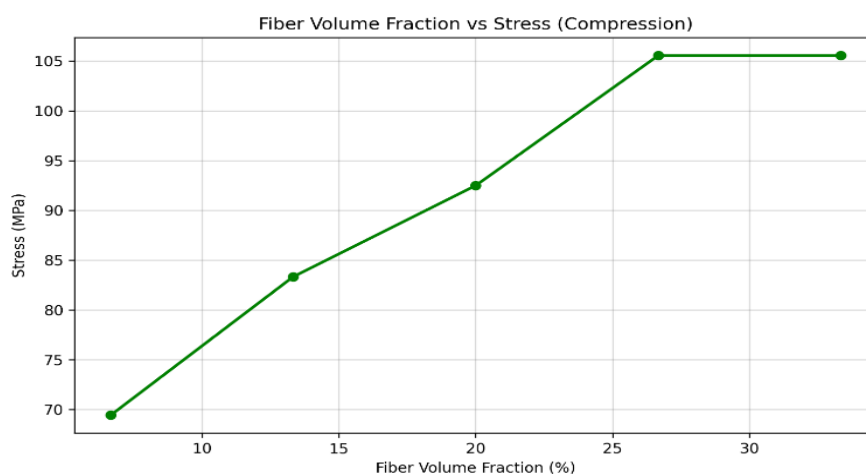


FIGURE 22: FIBER VOLUME FRACTION VS STRESS (6.667% TO 33.35%) WITH (2% TO 10% FILLER) (COMPRESSION)

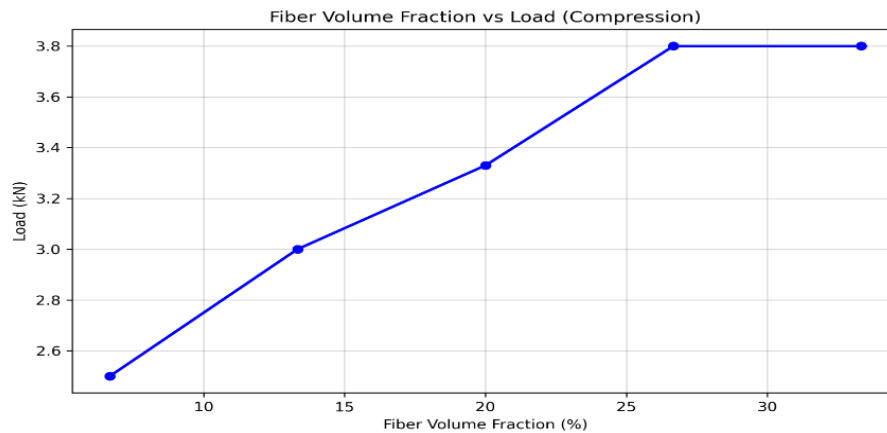


FIGURE 23: FIBER VOLUME FRACTION VS LOAD (KN) (6.667% TO 33.35%) WITH (2% TO 10% FILLER) (COMPRESSION)

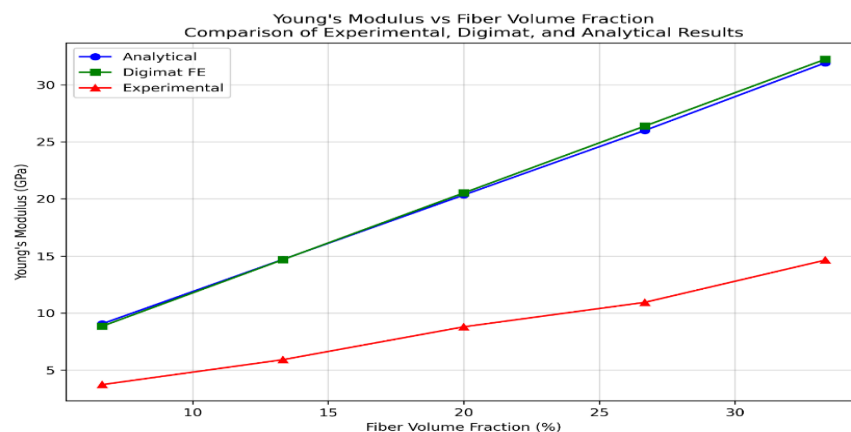


FIGURE 24: YOUNG'S MODULUS VS FIBER VOLUME FRACTION: COMPARISON OF EXPERIMENTAL, DIGIMAT, AND ANALYTICAL RESULTS.

5.2 Thermal Test (Lee Disc)

Thermal conductivity decreased as the eggshell fraction increased:

- Measured trend:** Average thermal conductivity values dropped from about $0.38 \text{ W/m}\cdot\text{K}$ (4.6 % Vf, 2 % filler) to $\approx 0.17 \text{ W/m}\cdot\text{K}$ (23 % Vf, 10 % filler) This shows that **eggshell acts as an effective thermal insulator**, making the composite better at resisting heat transfer.
- Reason:** Eggshell's CaCO_3 structure and the additional interfaces it introduces reduce heat flow through the resin phase. Increased filler lowers the continuous polymer fraction, creating a more thermally resistive path.
- Optimal balance:** A filler content of about 4–6 % with moderate fiber Vf maintained mechanical integrity while still lowering conductivity significantly

Thermal Conductivities for all specimens

TABLE 9 CALCULATIONS – THERMAL CONDUCTIVITIES

Volume Fraction (%)	Thermal Conductivity [$W/m \cdot K$]			
	Specimen 1	Specimen 2	Specimen 3	Average
4.6% Vf	0.386	0.375	0.383	0.381
9.2% Vf	0.314	0.303	0.296	0.304
13.8% Vf	0.258	0.257	0.262	0.259
18.4% Vf	0.203	0.211	0.214	0.209
23% Vf	0.169	0.169	0.17	0.169

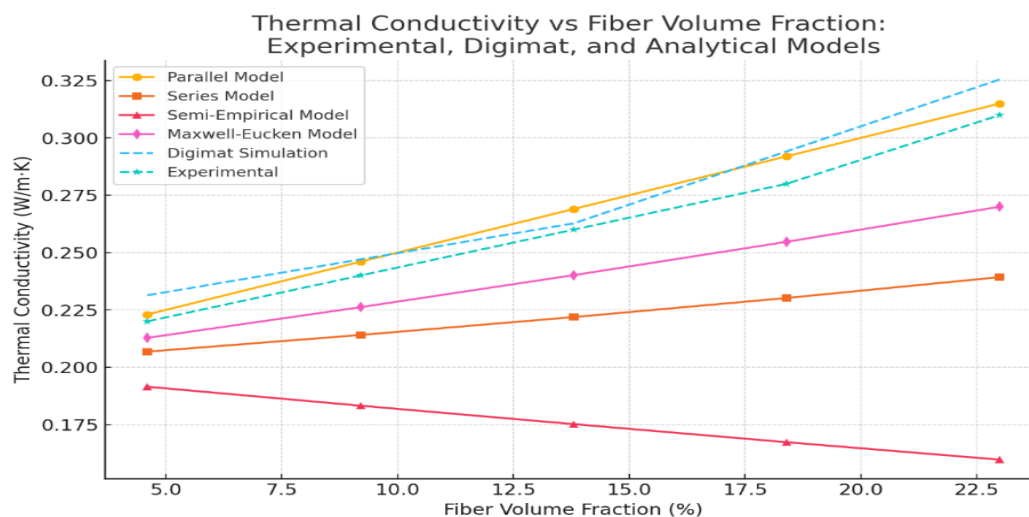


FIGURE 25: THERMAL CONDUCTIVITY VS FIBER VOLUME FRACTION WITH FILLER:
EXPERIMENTAL AND DIGIMAT SIMULATION COMPARISON

VI. CONCLUSION

This study successfully examined the influence of eggshell powder as a natural filler on the **mechanical and thermal performance of basalt fiber reinforced polyester composites**. By systematically varying the fiber volume fraction and filler content, a clear understanding of how eggshell particles affect strength, stiffness, and heat transfer behavior was obtained. Both **analytical calculations and Digimat simulations** were compared with experimental findings to ensure reliability.

Mechanical Properties: The inclusion of eggshell filler up to 6% ($\approx 20\%$ Vf) improved stiffness and strength, with Young's modulus reaching around 11.8 GPa. However, beyond 8–10% filler ($\approx 26.7\text{--}33.3\%$ Vf), mechanical properties began to decline due to filler agglomeration and reduced fiber–matrix adhesion. This indicates that eggshell is effective as a reinforcing filler only up to a certain threshold.

Thermal Properties: The thermal conductivity of the composites decreased with higher eggshell content, highlighting its role as an insulating filler. At **4.6% Vf**, thermal conductivity values were moderate, while at **23% Vf with 10% filler**, the conductivity was significantly lower, demonstrating improved thermal resistance. This trend confirms that eggshell addition helps the composite act as a better thermal barrier.

Optimal Fiber Volume Fraction: The most balanced performance was observed at **13.3–20% fiber volume fraction with 4–6% eggshell filler**, where mechanical integrity was retained while thermal insulation improved. This range can be considered optimal for multifunctional applications requiring both strength and insulation.

Sustainability and Applications: Using eggshell powder as a filler not only reduces production costs but also addresses waste management by recycling a natural by-product. These eco-friendly composites are promising for **construction panels, automotive interiors, and thermal insulation materials**, where both durability and environmental responsibility are valued.

Simulation Reliability: The **Digimat FE predictions** showed close agreement with experimental and analytical results. Differences were typically within **5% for mechanical properties** and **4–6% for thermal behavior**, validating simulation as a dependable tool for predicting the performance of natural filler-based composites.

Overall, this project highlights that integrating eggshell filler into basalt fiber reinforced polyester composites provides a sustainable pathway for producing materials with **enhanced insulation capacity and competitive strength**. Future research may focus on optimizing filler particle size, improving dispersion methods, and exploring hybrid resin systems to further enhance performance.

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