



Article

Comparative Study of Unhatched and Hatched Chicken Egg Shell-Filled Glass Fibre/Polyester Composites

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Abstract: The incorporation of filler materials to enhance the properties of fibre-reinforced plastics is a prevalent practise in materials science. Calcium carbonate is a commonly used inorganic filler in composite fabrication. Eggshell, a rich source of calcium carbonate, offers an organic alternative to conventional inorganic fillers. This study investigates the efficacy of different types of eggshells as filler materials. Three variants, viz., unhatched raw eggshell, unhatched boiled eggshell, and post-hatched eggshell, were used to fabricate composite variants, which were then subjected to mechanical characterization and compared with unfilled composites. The results indicated that composites filled with unhatched eggshells outperformed those with post-hatched eggshells. Tensile testing revealed a significant enhancement in the tensile properties of all eggshell-filled composites in comparison to the unfilled ones. The composite variant filled with unhatched raw eggshell filler showcased the utmost tensile modulus and strength, with a notable 36% improvement in comparison with the unfilled variant. Similarly, flexural tests demonstrated a 53% increase in flexural strength for unhatched raw eggshell-filled composites over unfilled composites. SEM imaging confirmed these findings by showing crack arrests, deviations, particle distribution, and strong interfacial bonding in the eggshell-filled composites.

Keywords: boiled eggshell; GFRP; hybrid composites; polyester; filler material



Citation: Kowshik, S.; Sharma, S.; Rao, S.; Shetty, S.V.U.K.; Jain, P.; Hiremath, P.; Naik, N.; Manjunath, M.

Comparative Study of Unhatched and Hatched Chicken Egg Shell-Filled Glass Fibre/Polyester Composites. *J. Compos. Sci.* **2024**, *8*, 432. <https://doi.org/10.3390/jcs8100432>

Compos. Sci. **2024**, *8*, 432. <https://doi.org/10.3390/jcs8100432>

Academic Editor: Pietro Russo

Received: 14 August 2024

Revised: 20 September 2024

Accepted: 21 September 2024

Published: 17 October 2024



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1. Introduction

The development of advanced materials with superior mechanical properties is a fundamental goal in materials science, particularly in the field of fibre-reinforced plastics (FRPs). Fibre-reinforced polymer (FRP) composites have gained widespread popularity in various industries, including aerospace, automotive, and construction, due to their exceptional strength-to-weight ratio, corrosion resistance, and design flexibility [1,2]. To further enhance the properties of FRP composites, researchers have explored the incorporation of filler materials into the polymer matrix. Fillers can improve mechanical properties, reduce costs, and modify the thermal and electrical characteristics of the composite [3,4].

Traditionally, inorganic fillers like calcium carbonate have been extensively used in composite fabrication to achieve these enhancements. Calcium carbonate (CaCO₃) is readily available, cost-effective, and can improve the mechanical and thermal properties of the composite. However, the use of inorganic fillers has raised concerns about their environmental impact and sustainability [5]. As a result, researchers have been exploring alternative filler materials, particularly those derived from natural sources.

Eggshell, a by-product of the poultry industry, is a promising alternative to conventional inorganic fillers. Comprising primarily calcium carbonate (94%), eggshells also contain minor amounts of organic matrix, which can potentially enhance the composite properties differently than pure inorganic fillers [6]. The utilization of eggshells not only provides a sustainable use for this common waste product but also aligns with the broader environmental goals of reducing waste and promoting recycling [7].

The use of eggshell as a filler in different polymer matrices, including epoxy, polyester, and polypropylene, has been studied in the past. The effects of various particle sizes and eggshell filler content on the flexural and tensile characteristics of glass fibre-reinforced polymer (GFRP) composites were investigated by [8]. The eggshells were processed to obtain particle sizes of 53 and 150 microns. Using the wet hand lay-up method, four layers of plain-woven fabric (800 GSM) and different amounts of eggshell powder (ESP) fillers (0, 10, 25, and 40 wt.%) were used to create epoxy composite panels. The appropriate standards prescribed by ASTM were followed when conducting the mechanical testing. The findings demonstrated the tensile and flexural characteristics declined as the filler loading rose from 10 to 40 weight percent among both filler particle sizes considered. The optimal filler loading was identified as 10 percent for both 53 micron and 150 micron-sized particle-filled composites.

A similar trend was observed in another study carried out by [9] wherein PVC resin was used as the matrix and eggshell fillers of 0.2 and 7 micron sizes were used for reinforcement. The test results showed that the tensile strength of the composite improved with increased filler content and reduced filler particle size in comparison with the unfilled composite. However, the best results were observed with the composite consisting of 10 wt.% eggshell powder with a 0.2 μm particle size. It was further observed that, with an increase in filler content, the tensile modulus enhanced. However, composites with a 0.2 μm particle size exhibited better tensile modulus in comparison with the ones filled with a 7 μm particle size.

Researchers [7] explored the mechanical properties of eggshell-filled polypropylene (PP) composites. Two composite variants were prepared and compared to neat PP. One composite variant consisted of 30 wt.% eggshell filler with 70 wt.% of PP. The other variant contained 65 wt.% PP, 30 wt.% eggshell powder, and 5 wt.% maleic anhydride-grafted polypropylene (MAPP). The composites were manufactured via the extrusion process. Further, the specimens were prepared according to ASTM standards for testing. The results showed that the composite without MAPP improved the flexural modulus by 30.59%, while the composite with MAPP showed a 35.5% improvement compared to neat PP.

The improvement due to eggshell filler was observed with the addition of nano eggshell fillers. Research conducted by [10] explored the utilization of nano eggshell powder as well as methods for effectively integrating nano fillers into polymer composites to create value-added products. Four types of composites, varying in weight proportions of nano eggshell powders, were prepared using the hand lay-up technique for mechanical and thermal characterizations. Various mechanical properties, including tensile strength, flexural strength, impact behaviour, and thermal properties via TGA and DMA analysis, were investigated. The results indicated that incorporating the optimal amount of nano fillers significantly improves the overall strength of glass fibre-reinforced composite materials, leading to cost savings of over 30%. This suggests that nano eggshell fillers hold great potential in composite manufacturing, particularly for substituting high-cost glass fibre in low-load-bearing applications.

Over the years, similar studies have demonstrated that eggshell fillers can improve the tensile strength, flexural strength, and impact resistance of the composites [4,11–15]. However, the effectiveness of eggshell fillers may vary depending on factors, such as the type of eggshell used, surface treatment, and the compatibility between the polymer matrix and filler material.

Although many researchers have explored the possibility of using eggshell as a filler material, this novel study aims to investigate the efficacy of different types of eggshells as

filler materials in fibre-reinforced composites. Specifically, we examined the mechanical properties of composites filled with unhatched raw eggshells, unhatched boiled eggshells, and post-hatched eggshells. By comparing these variants with unfilled composites, we seek to determine the optimal type of eggshell filler and its impact on composite performance.

2. Materials and Methods

The reinforcement and the matrix are the two main constituents of composite materials. In this research study, E-glass fibre and unsaturated polyester were utilized as reinforcement and matrix, respectively. According to earlier studies, calcium carbonate, a common inorganic mineral, may be replaced with chicken eggshells as an effective organic filler [7]. Chicken eggshells were, therefore, identified as the filler in the composite fabrication.

Figure 1 illustrates the methodology followed for the study. Three varieties of waste eggshells were obtained and processed so that they could be used as filler material. The hand lay-up technique was employed to fabricate four different variants of composites. Mechanical characterisations of composite specimens were undertaken as per their respective ASTM standards. Further, specimens of all the composite variants were subjected to SEM imaging.

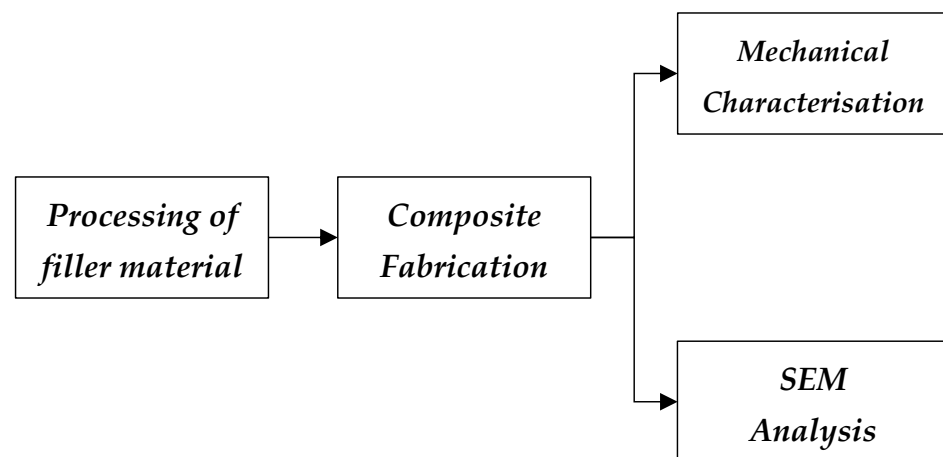


Figure 1. Methodology.

2.1. Processing of Filler Material

The type of chicken eggshell waste generated varies depending on the consumption/utilization of chicken eggshells. Egg yolk is one way of consuming raw eggs, i.e., before the eggs hatch. Unhatched eggs are also consumed after boiling, such as boiled eggs, mashed eggs, etc. Eggshell wastes are also obtained from hatched eggs in poultry. All three types of eggshell wastes, viz., unhatched raw eggshell, unhatched boiled eggshell, and post-hatched eggshell, are considered the filler materials in the current study. Figure 2 depicts the steps incorporated for processing all three eggshell variants.

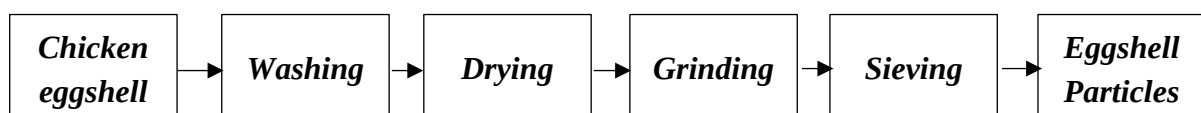


Figure 2. Eggshell filler processing.

The eggshells were cleaned with warm deionized water to remove any protein, albumen, or other impurities remaining before being put to use. To get rid of moisture, the shells were washed and then left to air dry for a whole day. The dried eggshells were then reduced in size by mechanically grinding using a ball milling machine, as shown in Figure 3. To ensure that the particle sizes range between 45 and 37 microns, the ground

eggshells were then put through a 45-micron mesh sieve. The resultant particles were gathered and stored.



Figure 3. Ball milling.

2.2. Composite Preparation

Composite variants, namely, unfilled (UF), unhatched raw eggshell (UHR)-filled, unhatched boiled eggshell (UHB)-filled, and post-hatched eggshell (PHES)-filled were fabricated. Table 1 provides a detailed breakdown of the composition of the four composite variants. These variants were fabricated using a hand lay-up.

Table 1. Compositions of composite variants.

Composite Variant	Composite Code	Glass Fibre (wt.%)	Polyester (wt.%)	Eggshell (wt.%)
Unfilled	UF	34	66	0
Unhatched raw eggshell-filled	UHR	50	40	10
Unhatched boiled eggshell-filled	UHB	50	40	10
Post hatched eggshell-filled	PH	50	40	10

For reinforcement, 450 GSM of randomly oriented E-glass fibre mats with chopped glass fibre strands were used. Polyester resin was used as the matrix material. The hardener, Methyl-Ethyl-Ketone Peroxide (MEKP), was combined with the resin in a 12:1 hardener-to-resin ratio. A mechanical stirrer was used to combine the polyester resin with the eggshell filler material. Table 1 displays the compositions of the composite variants. An average 4 mm-thick square composite plate dimensioning $300 \times 300 \text{ mm}^2$ was produced.

2.3. Tensile Test

The mechanical characteristics expressed in terms of Young's modulus (E) and ultimate tensile strength (σ) were established as per the ASTM standard D3039. Five $250 \times 25 \times 4 \text{ mm}^3$ sized samples of each variety were subjected to tensile testing. For specimen testing, a universal testing machine (Zwick-Roell), as shown in Figure 4, was employed at a 2 mm/min test speed. The tensile test specimens of all composite variants are shown in Figure 5. The highest loads that the specimens could support before failing were used to calculate their ultimate strength. The Young's moduli of the specimens were determined by noting the stress–strain responses.



Figure 4. Tensile testing in UTM.



Figure 5. Tensile test specimens of (a) unfilled, (b) unhatched raw eggshell-filled, (c) unhatched boiled eggshell-filled, (d) post-hatched eggshell-filled composite variants.

2.4. Flexural Test

Flexural testing was conducted in compliance with the ASTM standard D7264. Five $128 \times 13 \times 4 \text{ mm}^3$ sized samples of each variety were tested, and the universal testing machine (Zwick-Roell), as shown in Figure 6, was employed at a 2 mm/min test speed. The flexural test specimens of all composite variants are shown in Figure 7. Testing yielded results on the modulus and flexural strength. Additionally, the required stress–strain graphs were plotted.

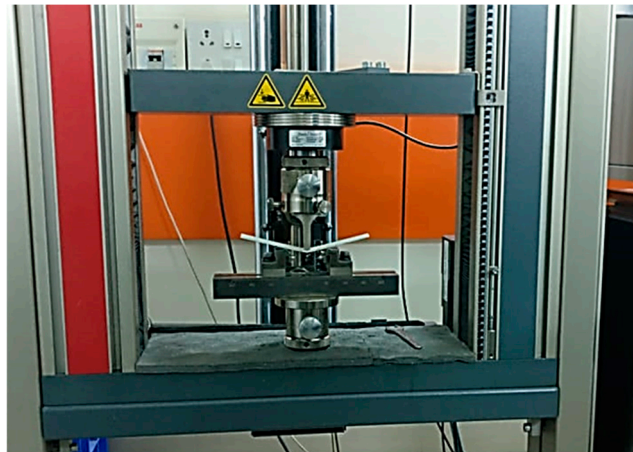


Figure 6. Flexural strength testing in UTM.



Figure 7. Flexural test specimens of (a) unfilled, (b) unhatched raw eggshell-filled, (c) unhatched boiled eggshell-filled, (d) post-hatched eggshell-filled composite variants.

2.5. Microscopic Imaging

To comprehend the failure mechanism, specimens of all fabricated composite variants were subjected to scanning electron microscopy (SEM) investigations. The SEM imaging was executed using the Zeiss EVO MA18 instrument. The specimen holder of the microscope was loaded with the specimens ($10 \times 6 \text{ mm}^2$) of all composite variants. In order to enable improved imaging, the electrical conductivity of the specimens was enhanced via the deposition of silver on the surfaces of the specimens via low-vacuum sputtering.

3. Results and Discussion

The results of tensile and flexural tests are clearly documented in this section. Five samples of each composite variant were tested in accordance with the relevant ASTM standards. This section contains a detailed documentation of the test outcomes.

3.1. Tensile Strength Test

Figure 8 illustrates the spectrum of the tensile strengths of the tested variants. Amongst these variants, the unhatched raw eggshell-filled composite demonstrated the highest tensile strength of 120 MPa. Following this, the unhatched boiled eggshell-filled composite showcased a 105 MPa tensile strength. The post-hatched eggshell-filled variant exhibited an utmost tensile strength of 96 MPa, while the unfilled composite had the lowest tensile strength of 88 MPa among the variants considered.

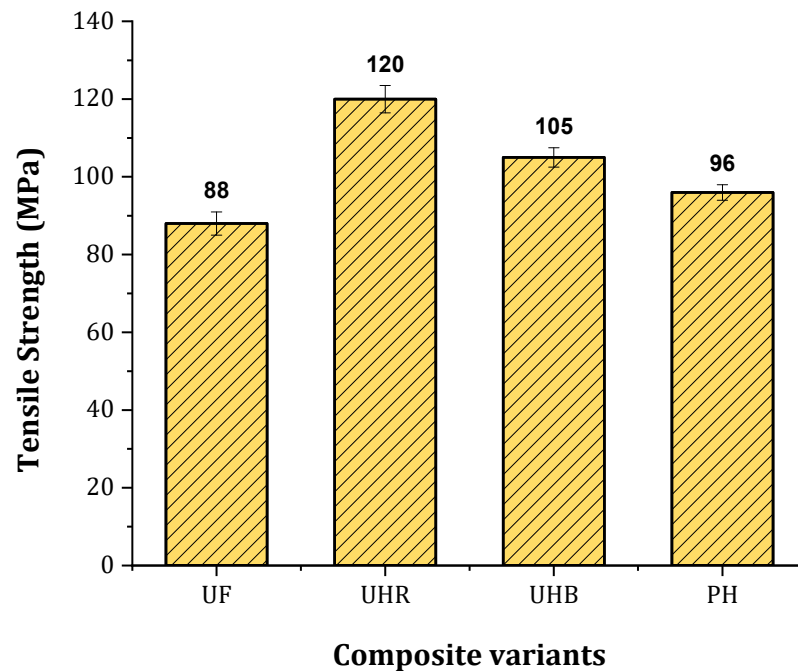


Figure 8. Comparison of tensile strengths.

The experimental data clearly indicate that the tensile strength of the unhatched raw eggshell-filled composite variant is 36% higher than that of the unfilled composite. Similarly, the unhatched boiled eggshell composites and post-hatched eggshell-filled composites show a 19% and 9% increase in strength, respectively, compared to the unfilled composites.

In addition to the reinforcement offered by glass fibres, the increased strength seen in the eggshell-filled composites may be the result of the tensile stress transfer to the eggshell fillers from the polyester matrix [16,17]. The combination of eggshell fillers with glass fibre reinforcement creates a synergistic effect. While the glass fibres provide tensile strength and rigidity, the eggshell fillers improve the toughness and resistance to crack propagation, resulting in higher tensile strengths [18].

Boiling eggshells can lead to chemical changes, such as the denaturation of proteins or alterations to the mineral content [19]. These changes could affect the interaction between the eggshell particles and the polymer matrix, potentially diminishing the bonding strength and the overall mechanical properties of the composite, thus leading to reduced performance in comparison to raw eggshell-filled composites.

It is observed that post-hatched eggshell-filled variant exhibits the least strength. Unhatched eggshells have a more uniform microstructure compared to post-hatched eggshells. Variations in microstructure, such as differences in pore size and distribution, can affect the mechanical properties of the eggshell particles and their interactions with the polymer matrix [20]. A more uniform microstructure in unhatched eggshells may have resulted in better load transfer and improved tensile strength in the composite.

Figure 9 shows the variations in the tensile modulus of the composite variants considered. With a value of 2449 MPa, the unhatched raw eggshell-filled composite exhibited the highest modulus. Subsequently, the composite consisting of unhatched boiled eggshells exhibited a modulus of 2020 MPa. Of all the variants tested, the unfilled composite had the lowest tensile modulus of 1600 MPa, while a tensile modulus of 1812 MPa was showcased by the post-hatched eggshell-filled composite variant.

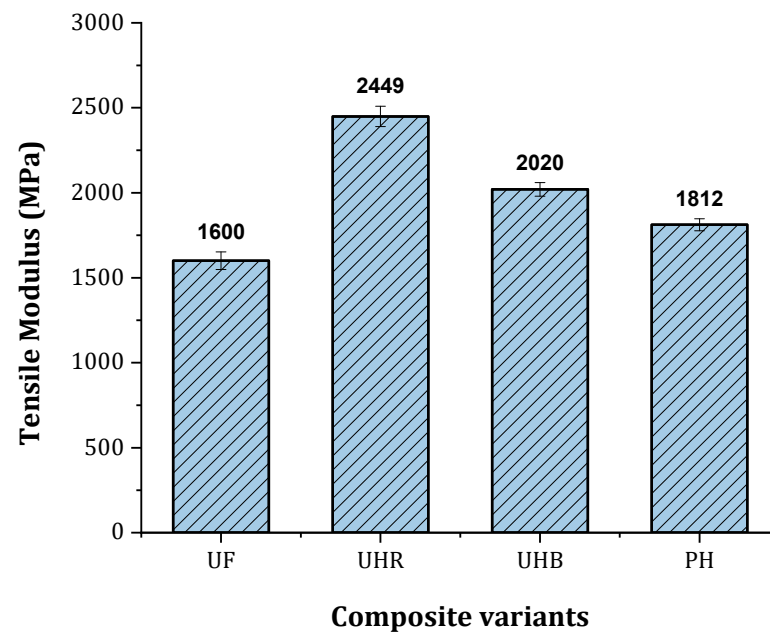


Figure 9. Comparison of tensile modulus.

The experimental data clearly indicate that the tensile modulus of the unhatched raw eggshell-filled composite is 53% higher than that of the unfilled composite. Similarly, the unhatched boiled eggshell composites and post-hatched eggshell-filled composites show a 26% and 13% increase in modulus, respectively, compared to the unfilled composites.

Eggshell particles are composed of calcium carbonate, which has a high stiffness. When these particles are incorporated into the composite, they contribute significantly to the overall rigidity, leading to a higher tensile modulus [21].

Figure 10 shows the stress–strain curve with the maximum recorded values for each of the four variants of composites. The plotted curve clearly represents the brittle nature of the prepared composite, leading to catastrophic failure without any discernible yield points prior to fracture [22]. Additionally, Figure 5 highlights that composites filled with unhatched raw eggshells demonstrate the lowest strain at break, whereas the unfilled variant of the composites exhibits the utmost strain at break. The inclusion of rigid eggshell particles makes the composite more brittle, which is typically associated with higher stiffness. This brittleness results in a higher tensile modulus as the composite resists deformation more effectively [23]. Further, discontinuities or irregularities in the shape and distribution of eggshell particles within the composite can act as stress concentrators [24]. Under applied load, these stress concentrations can lead to localized areas of high stress, exacerbating the propensity for brittle fracture and reducing the overall strain at break.

The stress–strain curve demonstrates that the unhatched raw eggshell-filled composites have the least strain to break, followed by the boiled eggshell-filled variant, and further followed by the post-hatched eggshell-filled variant. The highest strain to break is observed with the unfilled composite variant. Unhatched raw eggshell-filled composites tend to be more brittle compared to the boiled eggshell-filled variant. The heat treatment involved in boiling eggshells alters their microstructure, making them slightly more ductile [25]. As a result, the composites filled with boiled eggshell filler material may demonstrate slightly higher strain at break compared to composites filled with raw eggshells. Post-hatched eggshells are typically more porous as they would have undergone natural processes that would make them less brittle. The hatching process can cause the eggshell to develop microstructural changes, potentially making it less prone to cracking [26]. This could be the reason for higher strain at the break of post-hatched eggshell-filled composites.

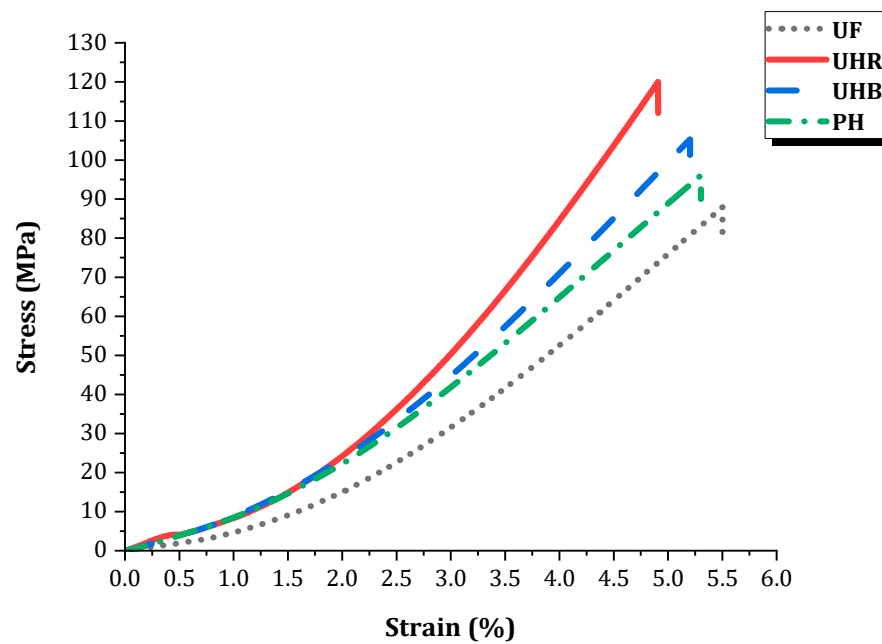


Figure 10. Comparison of tensile stress–strain variation.

3.2. Flexural Strength Test

Figure 11 illustrates the range of flexural strengths among the various composite types analyzed. The specimens filled with raw eggshell, prior to hatching, demonstrated the highest flexural strength at 225 MPa. In close succession, the composite variant filled with boiled eggshell filler demonstrated a flexural strength of 211 MPa. In comparison, the post-hatched eggshell-filled variant showed a maximum flexural strength of 195 MPa, while the unfilled composite displayed the lowest strength at 176 MPa. The experimental results highlight that the flexural strength of the raw eggshell-filled composite variant surpasses that of the unfilled composites by 28%. Similarly, the boiled eggshell-filled composites and post-hatched eggshell-filled composites show strength increases of 20% and 11%, respectively, when compared to the unfilled composites.

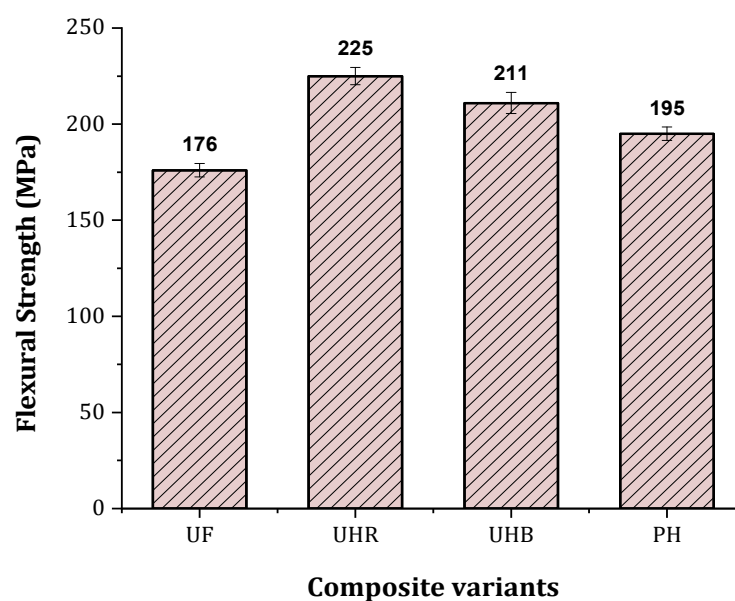


Figure 11. Comparison of flexural strength.

The structure of eggshells consists of calcium carbonate crystals arranged in a complex matrix of proteins, which can enhance the mechanical properties of the composite when dispersed throughout the matrix. This reinforcement contributes to increased resistance to bending forces, resulting in higher flexural strength in the eggshell-filled composites [27]. The highest flexural strength observed in raw eggshells can be attributed to their natural structure, including the intricate arrangement of calcium carbonate crystals, which can provide effective reinforcement when incorporated into the composites [28].

Figure 12 shows the variations in the flexural modulus of the composite variants considered. The utmost flexural modulus of 7266 MPa was observed in the unhatched raw eggshell-filled composite specimens. The unhatched boiled eggshell-filled composite had the next highest value at 6800 MPa. The post-hatched eggshell-filled variant showed a flexural modulus of 6488 MPa. The lowest flexural modulus among the variants was found in the unfilled composite, with a value of 6004 MPa.

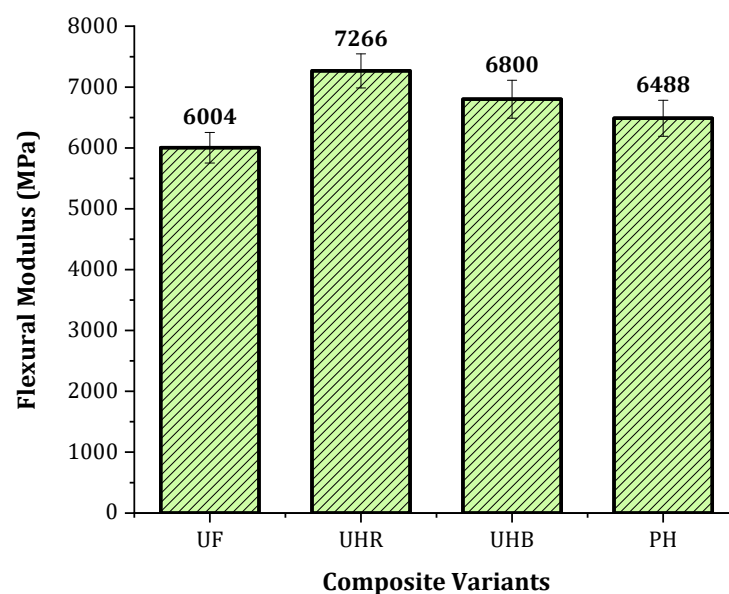


Figure 12. Comparison of flexural modulus.

The experimental data clearly indicate that the strength of the unhatched raw eggshell-filled composite variant is 21% higher than that of the unfilled composites. Similarly, compared to the unfilled composites, the unhatched boiled eggshell composites and the post-hatched eggshell-filled composites show increases in modulus of 13% and 8%, respectively. The enhanced stiffness and brittleness of the filled composites may be the cause for an upward trend in flexural modulus [29]. The presence of eggshell fillers within the composite matrix can improve the microstructure by reducing voids and defects. This densification enhances the stiffness and overall mechanical properties of the composite [23]. Further, the interaction between the polyester matrix and the eggshell particles can lead to a stronger interfacial bond. This strong bond restricts the movement of the polymer chains, thereby increasing the stiffness and tensile modulus of the composite [30].

The stress–strain behaviour of the composite variants, emphasizing their ultimate stress and strain values, is presented in Figure 13. The curves demonstrate that composites containing unhatched eggshell filler exhibit the lowest strain at failure, while unfilled composites achieve the highest strain. Notably, all eggshell-filled variants display a reduction in strain compared to the unfilled counterpart. This enhanced stiffness, evident from the reduced strain under increasing stress, can again be attributed to the reinforcing effect of the eggshell filler within the composite matrix.

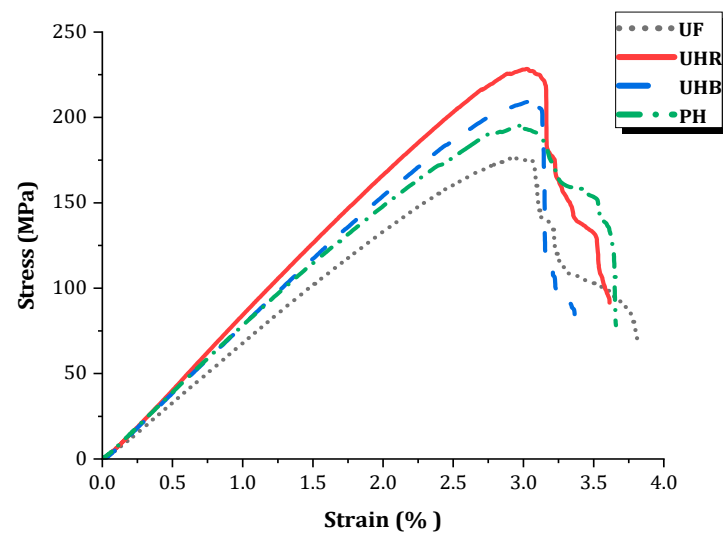


Figure 13. Comparison of flexural stress–strain variation.

3.3. Microscopic Image Analysis

In order to explicate the mechanisms governing failures in the four composite variants, a comprehensive analysis was undertaken using scanning electron microscopy (SEM). Scanning electron microscope (SEM) analysis was conducted on all four composite variants to comprehend the failure mechanisms. Figure 14a–h show the SEM images of all the composite variants.

Figure 14a reveals the unobstructed propagation of a crack within the matrix of the unfilled composite. This lack of resistance to the propagation of a crack likely contributes to the composite's rapid failure, reflecting its inherently lower strength. From Figure 14b, it can be seen that the interfacial bonding in the unfilled composites is lower compared to filled composites, as shown in Figure 14c,e.

SEM imaging of the unhatched raw eggshell composite (Figure 14d) reveals the promotion of crack arrest and crack deflection around the filler particles, indicating the presence of raw eggshell filler material. Figure 14c illustrates the strong interfacial bonding between the eggshell filler and the matrix in the composite. This strong interfacial bond ensures that stress is effectively transferred across the matrix and the fillers, enhancing the overall strength of the composite [31,32].

Further, it can be seen that the composites filled with raw eggshells have a more irregular surface morphology, providing better mechanical interlocking with the polymer matrix compared to boiled eggshells, which have smoother surfaces, as observed in Figure 14e,f, due to the potential dissolution or softening of the eggshell surface during boiling. This difference in morphology may have affected the load transfer efficiency and, ultimately, the tensile modulus of the composite [33]. This could be the reason for the earlier observation of superior strengths in raw eggshell-filled composites in comparison with a composite variant filled with boiled eggshells.

The SEM image of the boiled eggshell-filled composite shown in Figure 14e reveals that good interfacial bonding and crack deviation due to the presence of eggshell filler can be clearly observed in Figure 14f. Figure 14g,h clearly show the effective dispersion of eggshell particles throughout the composite matrix, ensuring the uniform distribution of reinforcement and minimizing the presence of voids or weak spots. This homogeneity enhances the overall structural integrity of the composite, leading to improved flexural strength compared to unfilled composites [34]. Crack deviations and arrests can be observed in the same SEM images. Further, it can be observed that the crack deviations in raw and boiled eggshells are better compared to post-hatched eggshell-filled composites, demonstrating the reason for the lower tensile and flexural strengths of the post-hatched eggshell-filled composite variants comparatively.

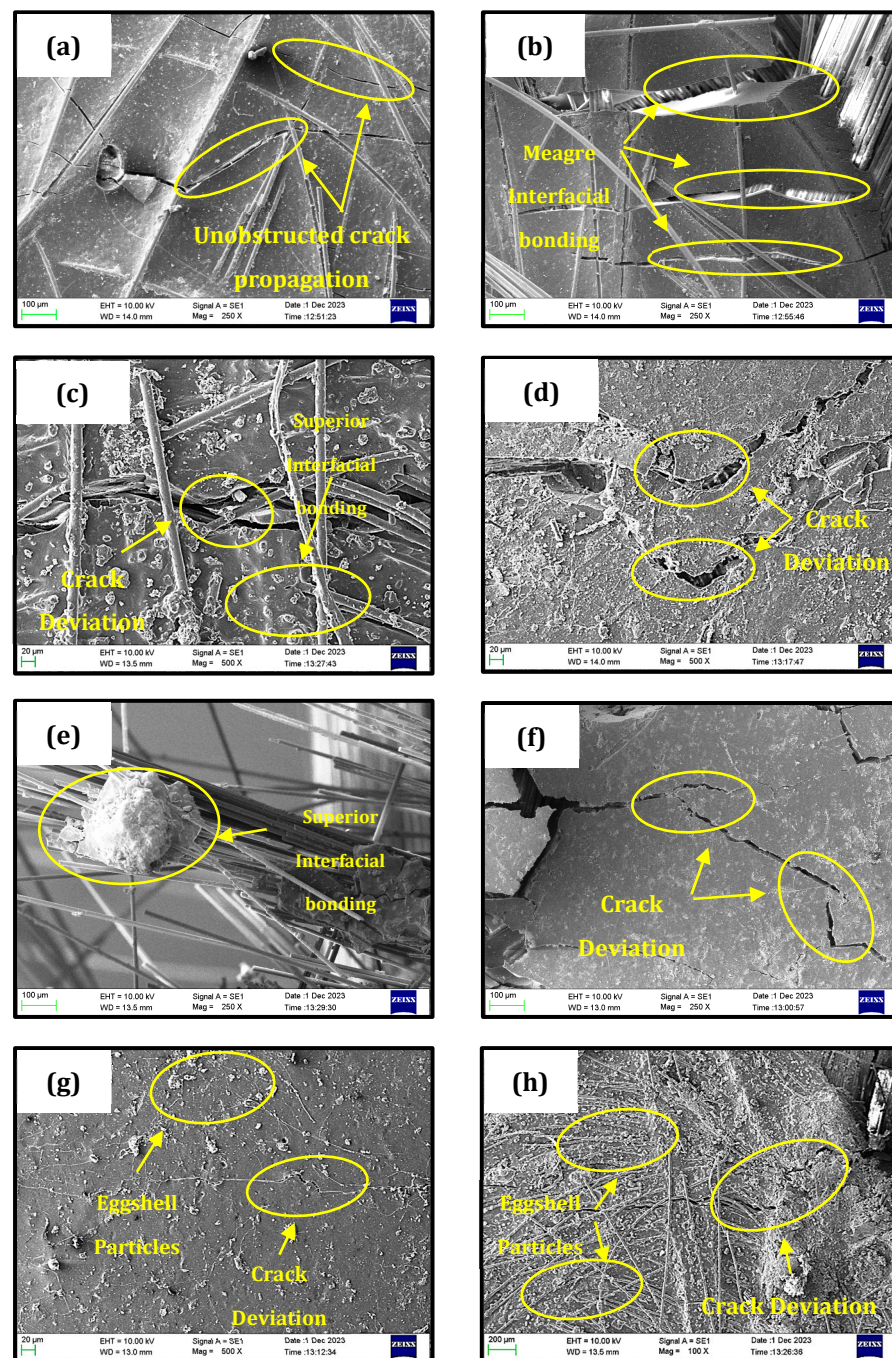


Figure 14. SEM images of (a) unobstructed crack propagation in unfilled composite; (b) meagre interfacial bonding of fibre and matrix in unfilled composite; (c) superior interfacial bonding and crack deviation in unhatched raw eggshell-filled composite; (d) crack deviation in unhatched raw eggshell-filled composite; (e) superior interfacial bonding in boiled eggshell-filled composite; (f) crack deviation in boiled eggshell-filled composite; (g) crack deviation in post-hatched eggshell-filled composite; (h) crack deviation in post-hatched composites.

3.4. Effect of Eggshell Composition and Structure on Mechanical Properties

The chemical makeup of eggshells is crucial in terms of their efficacy as filler materials. Eggshells mostly consist of calcium carbonate (CaCO_3), a mineral recognized for its significant stiffness and brittleness, resulting in enhanced tensile and flexural moduli when utilized as a reinforcement material in polymer composites. Unhatched raw eggshells have a more uniform distribution of calcium carbonate particles than post-hatched eggshells,

which display microstructural abnormalities resulting from the biological processes involved in hatching. The aforementioned anomalies presumably account for the comparatively diminished mechanical performance of the post-hatched eggshell-filled composites.

Furthermore, the organic matrix in unhatched eggshells, comprised of proteins and other organic substances, improves the interfacial adhesion between the filler and the polyester matrix. This high interfacial adhesion promotes the effective transmission of stress from the matrix to the filler during mechanical loading, leading to the reported 36% increase in tensile strength for the unhatched raw eggshell-filled composites compared to the unfilled form. The diminished performance of cooked eggshell-filled composites is due to protein denaturation and changes in mineral content resulting from boiling, which compromise interfacial bonding and decrease load transfer efficiency [35,36].

3.5. Comparative Analysis of Mechanical Properties

The tensile modulus of the unhatched raw eggshell-filled composite was measured as being 2449 MPa, which is a 53% increase over the unfilled composite, while the tensile modulus of the boiled eggshell-filled variant reached 2020 MPa. These results are consistent with the idea that the inclusion of high-stiffness calcium carbonate particles from the eggshell increases the rigidity of the composite. However, the lower stiffness in the cooked eggshell variant shows that the heat treatment involved in boiling alters the microstructure, diminishing its capacity to contribute to stiffness to the same degree as raw eggshells.

Additionally, the flexural strength of the unhatched raw eggshell-filled composite reached 225 MPa, the highest of all variants tested, while the boiling and post-hatched variants obtained 211 MPa and 195 MPa, respectively. The enhanced performance of the unhatched raw eggshell filler can be due to its intact microstructure and excellent particle size distribution, which allows for greater stress transmission under flexural loading. The post-hatched variant's decreased performance is a result of the bigger pores and weaker structure, which impaired its capacity to bear stresses effectively [37,38].

3.6. Chemical and Biological Interactions

The incorporation of eggshells as a filler material not only leverages their high calcium carbonate concentration but also provides the possibility for organic filler–polymer matrix interactions. The protein-rich organic matrix of unhatched raw eggshells may have led to greater bonding with the polyester matrix, further strengthening the composite. In boiling eggshells, however, the denaturation of proteins impairs this connection, resulting in reduced mechanical performance.

The biological processes involved in hatching result in major structural changes in eggshells, including modifications to pore size, density, and the crystalline structure of calcium carbonate. These alterations limit the eggshell's efficiency as a filler, which is seen in the reduced mechanical characteristics of the post-hatched eggshell-filled composites. Future research should examine the optimization of post-hatched eggshells, such as via surface treatments or particle size reductions, to increase their compatibility with polymer matrices [39,40].

4. Conclusions

Three types of eggshell-filled composites (unhatched raw, unhatched boiled, and post-hatched), along with an unfilled composite variant, were fabricated using unsaturated polyester as a matrix and E-glass fibre as the reinforcement via the hand lay-up technique. The material characterization of all of the composites under consideration revealed that eggshell-filled composites possessed greater tensile strength compared to that of the composites that were unfilled. Among the considered composite variants, the unhatched raw eggshell-filled variant demonstrated the greatest tensile and flexural properties. This variant showcased a 36% increase in tensile strength and a 53% increase in flexural strength in comparison with the unfilled variant. Thus, it can be inferred that the mechanical properties of polyester/glass fibre composites can be enhanced through

the use of eggshell fillers, which is in line with similar studies. The improved strength of the eggshell-filled composites likely results from effective stress transfer, better interfacial bonding, and reinforcement synergy. The most pertinent observation of this study is that the unhatched eggshell-filled variants outperformed the post-hatched variant, likely due to differences in mineral composition and microstructure. SEM imaging revealed crack arrests, deviations, particle distribution, and strong interfacial bonding in the eggshell-filled composites, validating the test results. Hence, it can be clearly inferred that although eggshells can be used as filler material to enhance the mechanical properties of GFRPs, the unhatched raw eggshell fillers performed better than post-hatched fillers.

Author Contributions: Conceptualization, S.K. and S.S.; methodology, S.R. and P.H.; software, M.M. and P.J.; validation, S.R., S.S. and P.H.; formal analysis, S.K. and M.M.; investigation, N.N. and S.V.U.K.S.; resources, P.J. and S.K.; data curation, M.M. and N.N.; writing—original draft preparation, S.K.; writing—review and editing, N.N. and P.H.; supervision, S.S. and S.R.; project administration, S.S. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data used in the current study are available from the first author and/or corresponding author and may be shared upon genuine request.

Conflicts of Interest: The authors declare no conflicts of interest.

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