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Mechanical Properties of Post-Cured Eggshell-Filled Glass-Fibre-Reinforced Polymer Composites

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Abstract: Eggshells are a potentially polluting industrial waste that are disposed of as landfill which has proven to be hazardous to the environment. The usage of chicken eggshells as a biofiller for polymer matrix composites instead of its disposal as landfill has proven advantageous in various studies. On the other hand, using eggshells as a filler material to replace inorganic calcium carbonate usage would be another environment friendly act. The present study is focused on studying the effects of eggshell filler addition and post-curing on polymer composites which could be utilised for domestic applications. Herein, uncarbonised and carbonised eggshell filler material were processed from waste eggshells. Hybridisation of the carbonised and uncarbonised eggshell filler was carried out. All three variants of eggshell fillers (10 wt.%) were used in the fabrication of composites. A hand lay-up technique was employed in the fabrication of unfilled composites along with three variants of filled composites, namely, uncarbonised, carbonised, and hybrid eggshell filled composites. The fabricated and cured composites were further subjected to post-curing at a temperature of 60 °C for a period of 2 h. All four variants of post-cured composites were then subjected to mechanical testing according to American Society for Testing and Materials (ASTM) standards. The tests revealed that all three variants of filled composites possess better mechanical properties in comparison with unfilled composites. Further, in comparison with unfilled composites, the carbonised eggshell filled composites showcased 42% and 49% improvement in flexural and tensile properties, respectively. The modes of failure of the specimens were observed and tabulated. SEM imaging revealed that the eggshell filler contributed to the strengths of the composites by means of arresting and deviating cracks. It was also observed that the post-cured specimens displayed improved properties when compared with our previous studies on non-post-cured specimens. In summary, the study showcased the benefits of eggshell filler addition and the post-curing of polymer composites.

Keywords: eggshells; eggshell filled composite; post-curing; GFRP; carbonization; hybrid composite; filler material; mechanical characterization; polymer matrix composites; modes of failure

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1. Introduction

Polymer matrix composites (PMC) have a wide spectrum of applications varying from the automotive sector to construction materials to electrical industries and even to children's toys. Polymer composites exhibit properties such as a high strength, high stiffness, being lightweight, and possessing a high resistance to corrosion. Composites find their application in a wide array of industries such as aerospace, construction, automotive, and even sporting [1–3].

Glass-fibre-reinforced plastics (GFRP) are the most popular and widely used PMCs owing to the low cost and ease of availability of glass fibre [4]. Apart from having a good tensile strength, they also possess superior corrosion resistance, resistance to chemicals, and resistance to microbial attack, and are lightweight in construction [5,6]. The 'E' type of glass fibre is the most commonly utilised type of glass fibre owing to its good physical, mechanical, and electrical properties [7].

Fillers are defined as additives in solid form that differ from the plastic matrix with respect to their composition and structure [8]. Filler materials play a vital role in the polymer industry. Filled polymer matrix composites have the potential to replace orthodox materials [9,10]. The major advantage associated with the usage of fillers is the reduction in the overall cost of the composites owing to the reduction in the resin requirement [11]. In addition, filler materials can add benefits to the materials in terms of improved processing, density control, optical, and thermal properties improvements, thermal expansion control, flame retardancy, and improvements in magnetic and electrical characteristics, in addition to promoted mechanical properties, such as fatigue resistance, wear resistance, and hardness [12,13]. The filler materials used can be either organic or inorganic. Some of the commonly used inorganic filler materials are calcium carbonate, aluminium silicate, calcium sulphate, and alumina trihydrate. The replacement of inorganic fillers with organic fillers such as chicken eggshells has become a new trend among the research fraternity due to their advantageous properties such as low densities, high filling levels, non-abrasiveness, renewable nature, and even cost-effectiveness [12,14,15].

Chicken eggshells are comprised of a network of protein fibres, associated with crystals of calcium carbonate (96% of shell weight), magnesium carbonate (1%), and calcium phosphate (1%), and also of organic substances and water [16,17]. Chicken eggshell comprises an extremely regular ultrastructure which is made up of polycrystalline calcium carbonate ceramic consisting of only one polymorph, calcite [14]. Eggshells are a potentially polluting industrial waste when not properly managed because they support microbiological action [17]. Eggshell wastes are generally untreated and disposed of as landfill. Considerable cost is also involved in the process. The eggshell waste disposal is a significant problem as it is directly related to public health. Eggshell landfills are responsible for waste contamination, soil pollution, and other environmental hazards [18,19]. Hence, an environment-friendly solution for the problem is necessary.

The usage of chicken eggshells as a biofiller for polymer matrix composites is one of the solutions to the problem at hand. Various biodegradable materials such as LLDPE/MPP and HDPE composites have proven to be beneficial in terms of mechanical and flame-retardant properties [20,21]. Similarly, various studies have showcased the effective usage of eggshells as a filler to improve the properties of polymer composites [22,23]. Investigating the effects of three eggshell filler variants on the mechanical properties of post-cured glass fibre/polyester composites is the intent of this particular study.

"Curing is an irreversible reaction where chemical covalent crosslinks are formed that are thermally and mechanically stable". The ultimate mechanical and chemical properties of a material can be achieved with the help of a curing process. Incomplete curing reduces the performance of the material. Post-curing at elevated temperatures can deliver a significant solution to such problems [24]. Temperature variation significantly influences the mechanical properties of PMCs, as PMCs are viscoelastic materials. Post-cured samples exhibit better results in comparison with non-post-cured samples [25].

The post-cure process is defined by several parameters. Temperature and time duration are the key variables that need to be considered in post-curing. It is stated in various sources in the literature that the vital factor that defines the magnitude of cross-linking is the temperature at which the post-curing process is performed [24].

Although there have been few studies regarding the effectiveness of eggshell filler in polymer composites, there is significant scope for research. The know-how regarding carbonised eggshell fillers is certainly limited, and there is space for exploring the area. In addition, knowledge of hybrid eggshell fillers—especially the hybridisation of carbonised and uncarbonised eggshells—is unexplored, proving itself to be a niche area of research and hence has been undertaken in the course of this study. Further, the effects of post-curing on the mechanical properties of composites, especially eggshell filled composites, is another area to be explored and hence has been undertaken in the present study.

The current study was also undertaken with a view that the composite material under consideration can be used for domestic applications. Hence, the understanding of the strength and stability of the material is of great significance given the fact that composite materials are required to operate in a post-critical state [26]. Thus, the material was subjected to mechanical characterisation.

2. Materials and Methods

The complete methodology adopted in the present research work is represented and depicted in Figure 1.

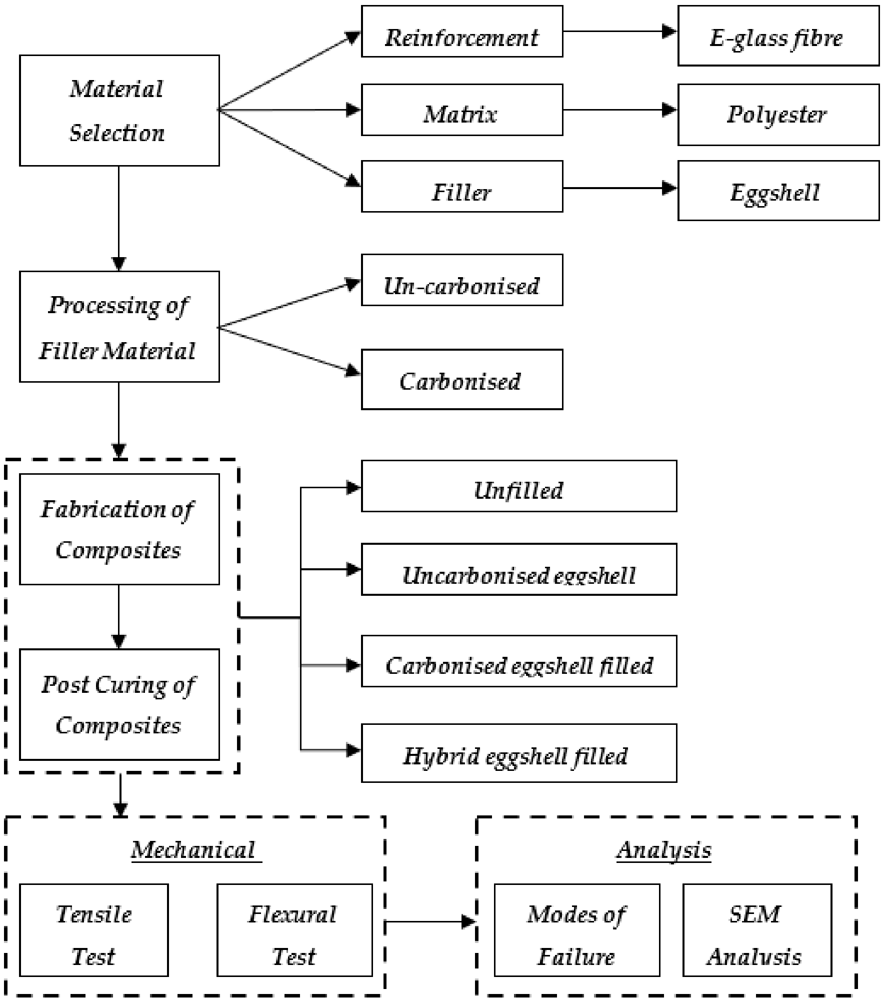

Figure 1. Methodology.

The reinforcement and matrix were chosen based on the application. Glass fibre/polyester composites are widely used in domestic applications. Chicken eggshell was chosen as the filler material. Uncarbonised and carbonised eggshell fillers were obtained by processing waste eggshells procured from various locations. The uncarbonised and carbonised eggshell fillers were utilised in the fabrication of different variants of composites. Tensile and flexural tests of the fabricated composites were undertaken as per the ASTM standards D3039 and D7264, respectively [16,27]. The failed specimens were further subjected to microscopic analysis to understand and correlate the test results. Modes of failure were also observed, documented, and analysed.

2.1. Material Selection

Two major constituents of composite materials are matrix and reinforcement. Boron-free E-glass fibre was used as the reinforcement material and unsaturated polyester was utilised as the matrix material in the current study. Chicken eggshell is a potential organic filler material that has the ability to replace the widely used inorganic mineral calcium carbonate [12,28]. Hence, chicken eggshells were used as a filler material in the fabrication of the composites. The physical, mechanical, and chemical properties of E-glass fibre, unsaturated polyester, and eggshells are tabulated in Tables 1 and 2.

Table 1. Properties of E-glass fibre.

Property	Unit	E-Glass Fibre
Density	g/cm^3	2.54
Tensile strength	MPa	3425
Tensile elongation	%	2.75
Modulus of elasticity	GPa	75
Fibre diameter	μm	11
Chemical composition	%(weight)	51.6 SiO_2 15.9 Al_2O_3 9.6 B_2O_3 5.5 MgO 16.6 CaO 0.8 Other

Table 2. Properties of Unsaturated Polyester.

Property	Unit	Unsaturated Polyester
Density	g/cm^3	1.2
Tensile strength	MPa	62
Tensile elongation	%	2
Modulus of elasticity	GPa	3.2
Flexural strength	MPa	40

2.2. Processing of Filler Material

Waste eggshells from various sources such as canteens, restaurants, etc., were obtained. These eggshells were then processed to obtain two variants of eggshells—namely, uncarbonised and carbonised. The various activities involved in the processing of eggshells to obtain uncarbonised and carbonised eggshell fillers are explained in detail in the subsequent sections.

2.2.1. Processing for Uncarbonised Eggshell Filler

The processing of eggshells to obtain uncarbonised eggshell filler is shown in Figure 2. The waste chicken eggshells obtained were first washed with warm demineralised water to remove any leftover albumen and/or other protein material and/or impurities adhered. The washed eggshells were dried for 24 h (by natural phenomena) in order to remove the moisture content.

The dried eggshells were then ground with a mechanical grinder. The ground eggshells were sieved with a mechanical sieve of 45 microns grit size to obtain a particle size distribution between 45 and 37 microns. The obtained eggshell particles were collected and stored in an airtight container.

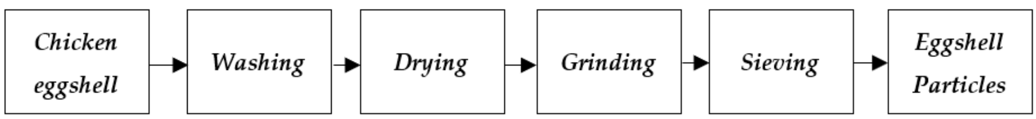

Figure 2. Processing for uncarbonised eggshell filler.

2.2.2. Processing for Carbonised Eggshell Filler

The steps involved in the processing of eggshells to obtain carbonised eggshell filler are shown in Figure 3.

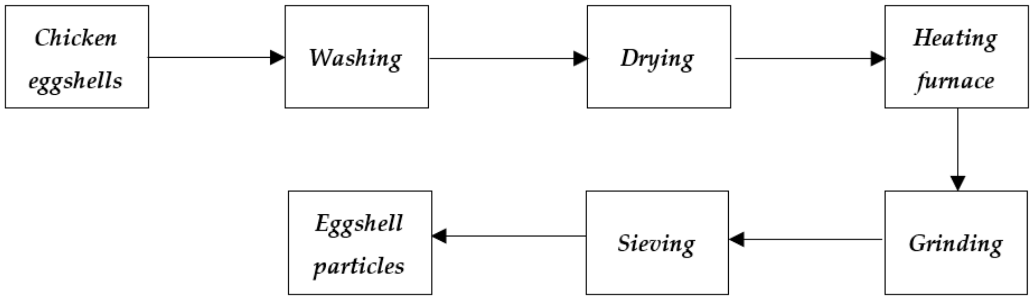

Figure 3. Processing for carbonised eggshell filler.

In order to remove any leftover albumen and/or impurities, the waste chicken eggshells were washed with warm demineralised water. The washed eggshells were dried for 24 h (by natural phenomena) in order to remove the moisture content. In order to carbonise the eggshells, they were first chipped and filled into a graphite crucible. Further, powered graphite was added into the eggshell-filled crucible and packed thoroughly. The decomposition temperature of calcium carbonate is known to be around 900 °C. Hence, a muffle furnace was used to heat the eggshells and graphite powder filled crucible to a temperature of 850 °C for one hour in order to obtain decent decomposition without build-up of soot on the eggshells. Later, the carbonised eggshells were ground with a mechanical grinder and sieved through 45 microns grit size sieve using a mechanical sieve to obtain a particle size distribution between 45 and 37 microns. The carbonised eggshells were collected and stored in an airtight container.

2.3. Fabrication of Composites

Four different composite variants—namely, unfilled (UF), uncarbonised eggshell (UCES) filled, carbonised eggshell (CES) filled, and hybrid (HY)—were prepared. The details regarding the variants and their compositions are shown in Table 3.

The four variants of composites were fabricated by employing the hand lay-up technique. E-glass fibre mats consisting of chopped glass fibre strands with a random orientation having 450 GSM were utilised as reinforcement. The matrix material utilised for fabrication was polyester resin. The hardener used in the process was methyl-ethyl-ketone peroxide (MEKP). The hardener and resin were mixed according to the hardener–resin ratio of 12:1. Chicken eggshell fillers were mixed with polyester resin using a mechanical stirrer. Table 3 shows the proportion of mixing. Composite laminates of 300 mm × 300 mm with an average thickness of 3 mm were fabricated.

Table 3. Composite variants and their composition.

Composite Variant	Glass Fibre (wt.%)	Polyester (wt.%)	Uncarbonised Eggshell (wt.%)	Carbonised Eggshell (wt.%)
Unfilled (UF)	34	66	0	0
Uncarbonised eggshell filled (UCES)	34	56	10	0
Carbonised eggshell filled (CES)	34	56	0	10
Hybrid eggshell filled (HY)	34	56	5	5

2.4. Post-Curing of Composites

The ultimate mechanical and chemical properties of a material can be achieved with the help of the curing process. Incomplete curing reduces the performance of the material. Post-curing at elevated temperatures can deliver a significant solution to such problems.

The post-cure process is defined by several parameters. Temperature and time duration are the key variables that need to be considered in post-curing. It is stated in various literature sources that the vital factor that defines the magnitude of cross-linking is the temperature at which the post-curing process is performed. Thus, after fabrication and curing, all variants of the composites were subjected to post-curing in a hot-air oven. Post-curing was performed at 60 °C for a duration of 2 h in the hot-air oven.

2.5. Tensile Test

The tensile properties of the specimens were determined as per the ASTM D3039 standard. Each specimen was cut to the standard dimensions, 250 mm × 25 mm × 3 mm. The tensile test was performed on five such specimens of each composite variant. A Zwick–Roell universal testing machine was employed for the testing. The test was conducted at a test speed of 2 mm/min, and the values of ultimate tensile strength and the strain at break were recorded for all specimens.

2.6. Flexural Test

A three-point bending test was performed according to ASTM D7264 in order to determine the flexural modulus and strengths of the specimens. Each specimen was cut to the dimensions 128 mm × 13 mm × 3 mm. Five specimens of each variant were subjected to the three-point bending test. The pre-test conditions were maintained for the specimens. A Zwick–Roell universal testing machine was employed for the testing. The test was conducted at a test speed of 2 mm/min. Further, the necessary stress–strain curves were plotted and compared.

2.7. Microscopic Analysis

Scanning electron microscope (SEM) imaging of all four composite variants was performed to understand the failure mechanisms. A Zeiss EVO MA18 instrument was used to perform the SEM imaging. Specimens were diced to dimensions of 10 mm length and 6 mm width in order to equip them in the specimen holder of the microscope. Further, in order to produce effective imaging, the specimen surface was required to be electrically conductive. Thus, the specimen surfaces were deposited with silver using a low vacuum sputtering system.

3. Results and Discussion

This section details the results of the mechanical testing—namely, flexural and tensile tests. As mentioned earlier, the tests were performed as per their respective ASTM standards.

3.1. Tensile Test Results

The variation of tensile strengths among all the post-cured composite variants are represented in Figure 4. The highest tensile modulus and strength among the composite variants were exhibited by the carbonised eggshell filled composites. The hybrid composite exhibited the next best values, followed by the uncarbonised eggshell filled variant. The lowest tensile strength and modulus were observed with the unfilled composite.

The uncarbonised eggshell filled composite variant exhibited a 9% improved strength when compared with the unfilled variant. Further, the carbonised eggshell filled composites exhibited a 49% higher tensile strength when compared with unfilled composites. Hybrid composites also showcased a 19% higher tensile strength compared with unfilled composites.

The higher strength could be due to a transfer of tensile stress from the polyester matrix to the eggshell filler material [29]. Further, the higher surface area of carbonised eggshell filler particles in the resin in comparison with the surface area of uncarbonised eggshell filler particles in resin could be attributable for the better performance of the carbonised eggshell filled composite variant [30].

The variation in tensile modulus among all the composite variants is represented in Figure 5. The addition of uncarbonised eggshells produced an 18% higher tensile modulus in comparison with unfilled composites. Further, the carbonised eggshell filled composites and hybrid composites respectively exhibited 72% and 33% higher tensile moduli in comparison with unfilled composites. The improvement in the Young's modulus could be due to the improved stiffness and brittleness of eggshell filled composites [31].

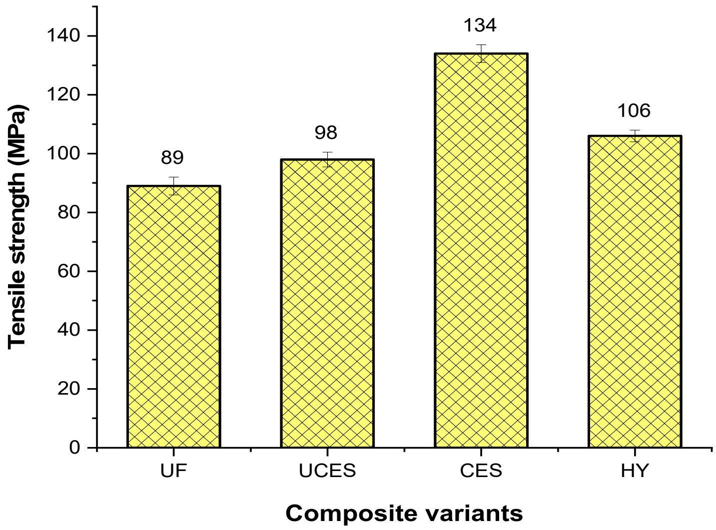

Figure 4. Tensile strength comparison of composite variants.

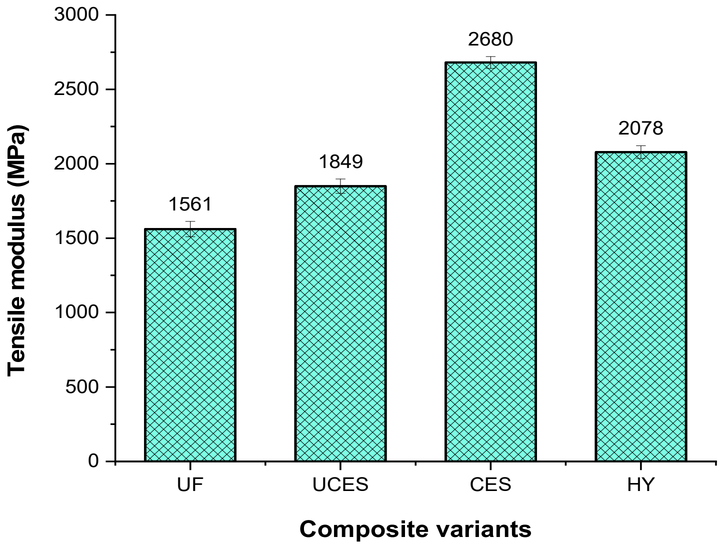

Figure 5. Tensile modulus comparison of composite variants.

The trend observed in the present study is similar to that of our previous study, wherein the same variants of non-post-cured composites were subjected to mechanical testing. However, a significant improvement in the tensile strength and modulus of the post-cured specimens in the current study was observed in comparison with the results of our previous study of non-post-cured composites [32].

The stress–strain curves of all the four variants of composites can be compared and contrasted with the help of the stress–strain curve represented in Figure 6. The stress–strain curves clearly indicate the catastrophic failure of the specimens owing to their brittle nature. It can be observed that there are no yield points before the fracture mechanism. It can also be observed from the graph that carbonised eggshell filled composites exhibited the least strain at break, while the unfilled composites exhibited the highest strain at break. A reduction in strain can be observed with an increase in tensile stress. This could be due to the increase in composite stiffness owing to the addition of the eggshell filler material [31].

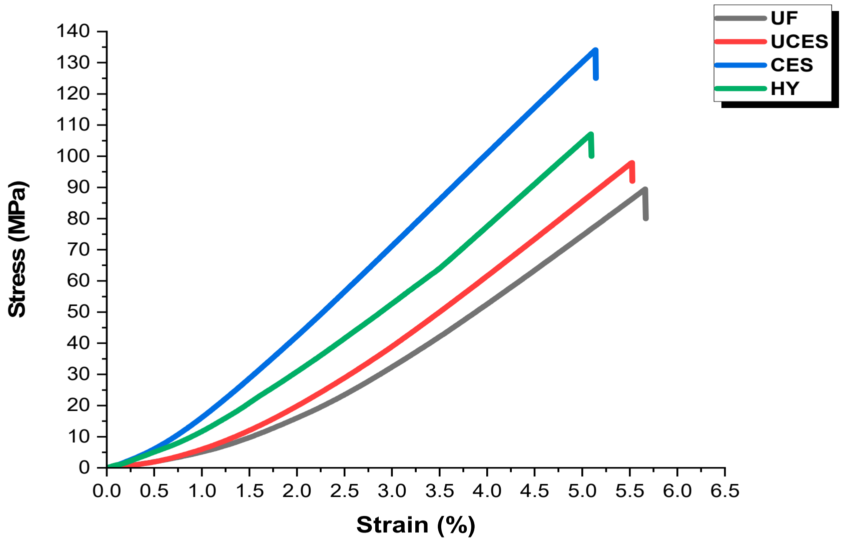

Figure 6. Stress–strain variation comparison of composite variants.

3.2. Flexural Test Results

The variation of flexural strengths among all the composite variants is represented in Figure 7. The highest flexural modulus and strength among the composite variants were exhibited by the carbonised eggshell filled composites. The hybrid composite exhibited the next best values, followed by uncarbonised eggshell filled variant. The lowest flexural strength and modulus were observed with the unfilled composite.

The uncarbonised eggshell filled composite variant exhibited a 15% increased flexural strength in comparison with unfilled composites. Further, the carbonised eggshell filled and hybrid composites respectively exhibited 42% and 22% higher flexural strengths in comparison with unfilled composites. Further, the higher surface area of carbonised eggshell filler particles in the resin in comparison with the surface area of uncarbonised eggshell filler particles in resin could be attributable for the better performance of the carbonised eggshell filled composite variant [30].

The variation of flexural modulus among all the composite variants is represented in Figure 8. The addition of uncarbonised eggshells exhibited a 23% higher flexural modulus in comparison with unfilled composites. Further, the carbonised eggshell filled and hybrid composites respectively exhibited 64% and 36% higher flexural moduli in comparison with unfilled composites. The improvement in the modulus could be due to the improved stiffness and brittleness of eggshell filled composites [31].

The trend observed in the present study is similar to that of our previous study, wherein the same variants of non-post-cured composites were subjected to mechanical testing. However, a significant increase in the flexural strength and modulus of the post-cured specimens in the current study was observed in comparison with the results of our previous study [32].

The stress–strain curves of all the four variants of composites can be compared and contrasted with the help of the stress–strain curve represented in Figure 9. The obtained stress–strain curves indicate that the carbonised eggshell filled composites exhibit the least strain, while the unfilled composites exhibit the highest strain. Further, it can also be observed that all eggshell filled composite variants exhibit a reduced strain in comparison with the unfilled composite. A reduction in strain can be observed with an increase in stress. This could be due to the increase in composite stiffness owing to the addition of the eggshell filler material [31].

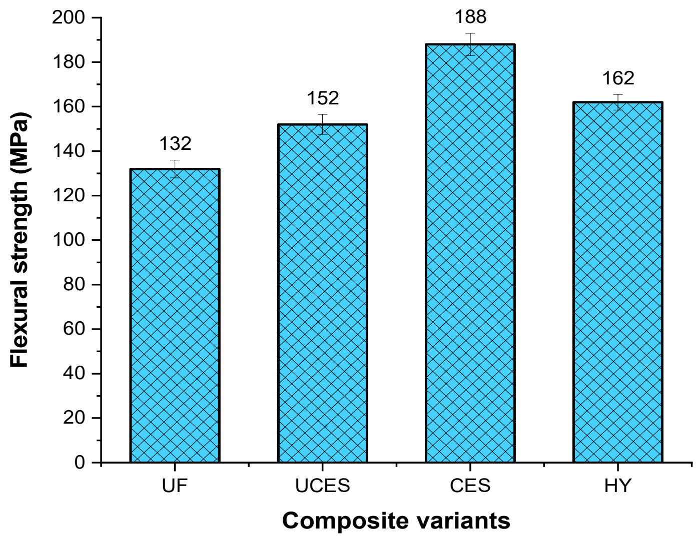

Figure 7. Flexural strength comparison of composite variants.

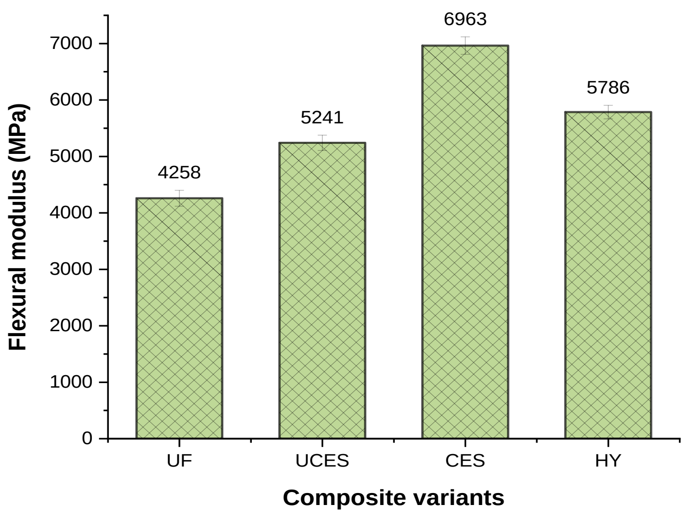

Figure 8. Flexural modulus comparison of composite variants.

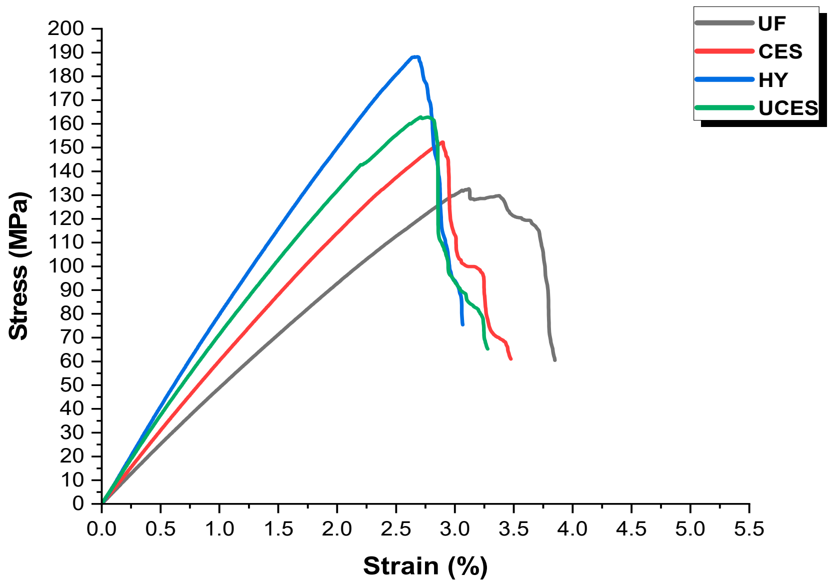

Figure 9. Stress–strain variation comparison of composite variants.

3.3. Modes of Failure

The failure modes of all the specimens according to ASTM D3039 are tabulated in Tables 4–7. The modes of failure of the post-cured specimens subjected to tensile testing can be observed in Figure 10.

Table 4. Modes of failure—unfilled composite specimens.

Specimen Number (Top to Bottom)	Mode of Failure as per the ASTM Standard	First Character (Failure Type)	Second Character (Failure Area)	Third Character (Failure Location)
1	LAT	Lateral	At grip	Top
2	AGM	Angular	Gauge	Middle
3	LGM	Lateral	Gauge	Middle
4	LAT	Lateral	At grip	Top
5	LGM	Lateral	Gauge	Middle

Table 5. Modes of failure—uncarbonised eggshell filled composite specimens.

Specimen Number (Top to Bottom)	Mode of Failure as per the ASTM Standard	First Character (Failure Type)	Second Character (Failure Area)	Third Character (Failure Location)
1	AAT	Angular	At grip	Top
2	AGM	Angular	Gauge	Middle
3	AGM	Angular	Gauge	Middle
4	LGM	Lateral	Gauge	Middle
5	LGM	Lateral	Gauge	Middle

Table 6. Modes of failure—carbonised eggshell filled composite specimens.

Specimen Number (Top to Bottom)	Mode of Failure as per the ASTM Standard	First Character (Failure Type)	Second Character (Failure Area)	Third Character (Failure Location)
1	AGM	Angular	Gauge	Middle
2	AGM	Angular	Gauge	Middle
3	AGM	Angular	Gauge	Middle
4	LAT	Lateral	At grip	Top
5	LGM	Lateral	Gauge	Middle

Table 7. Modes of failure—hybrid eggshell filled composite specimens.

Specimen Number (Top to Bottom)	Mode of Failure as per the ASTM Standard	First Character (Failure Type)	Second Character (Failure Area)	Third Character (Failure Location)
1	LGM	Lateral	Gauge	Middle
2	LGM	Lateral	Gauge	Middle
3	LGM	Lateral	Gauge	Middle
4	LAT	Lateral	At grip	Top
5	LGM	Lateral	Gauge	Middle

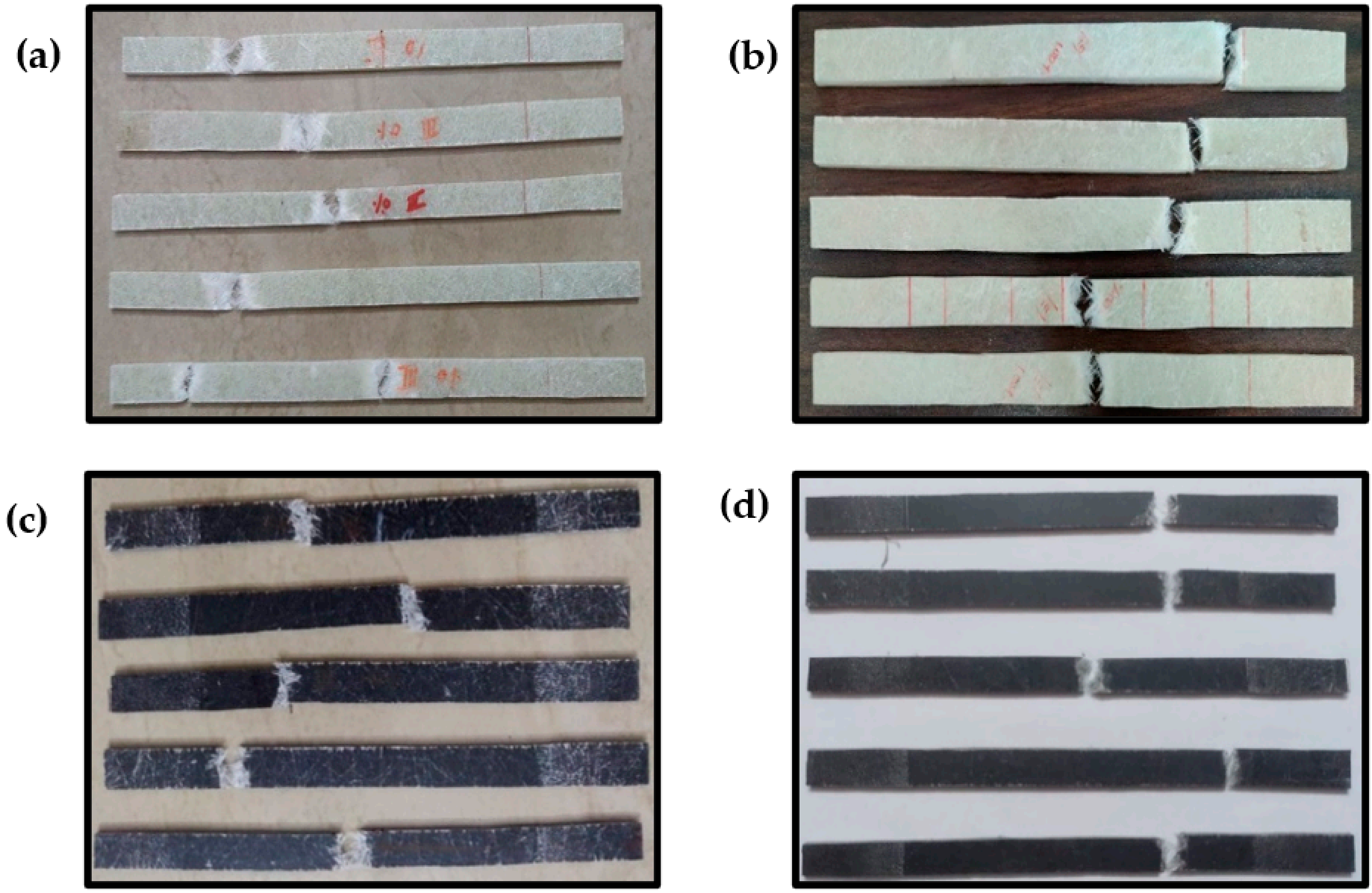

Figure 10. (**a**) Unfilled specimens; (**b**) uncarbonised eggshell filled specimens; (**c**) carbonised eggshell filled specimens; (**d**) hybrid specimens.

Specimens in both unfilled and filled composites have failed in the top portion. The failure could have been due to the accumulation of stress in the top region owing to the development of the main chap in the area. However, the formation of the main chap in the top region of the specimens constrains the formulation/progression of chaps to other regions. It is also observed that the specimens have failed in the middle portion (within the gauge length). Some specimens have also displayed angular failure in the gauge region. The anisotropic property of the composite specimens due to the usage of a randomly oriented fibre could be the cause for such angular failure.

3.4. Microscopic Analysis

Scanning electron microscopy (SEM) was employed to investigate the fracture mechanisms of the four composite variants. It can be observed in the SEM image of the unfilled composite shown in Figure 11a,b that the crack propagation in the matrix is not restricted and thus has led to the faster failure of the composite, depicting its lower strength.

The SEM image of the uncarbonised eggshell filled composite shown in Figure 11c reveals the crack deviation and arrest due to the addition of the eggshell filler material. The good interfacial bonding of the matrix and fibre can also be observed in Figure 11d. The above-mentioned reasons could have led to the better strength of the UCES filled composites.

The SEM image of the carbonised eggshell filled composite shown in Figure 11e reveals the crack deviation and arrest due to the addition of the eggshell filler material. The good interfacial bonding of the matrix and fibre can also be observed in Figure 11f. The above-mentioned reasons could have led to the higher strength of the CES filled composites.

It may also be observed that the crack deviation and arrest is also better than uncarbonised eggshell filled composites.

The SEM image of the hybrid eggshell filled composite shown in Figure 11g,h also reveals the crack deviation and arrest due to the addition of eggshell filler material. However, it may be observed that the crack arrest and deviation are better than that of uncarbonised eggshell filled composite but inferior compared with carbonised eggshell filled composite.

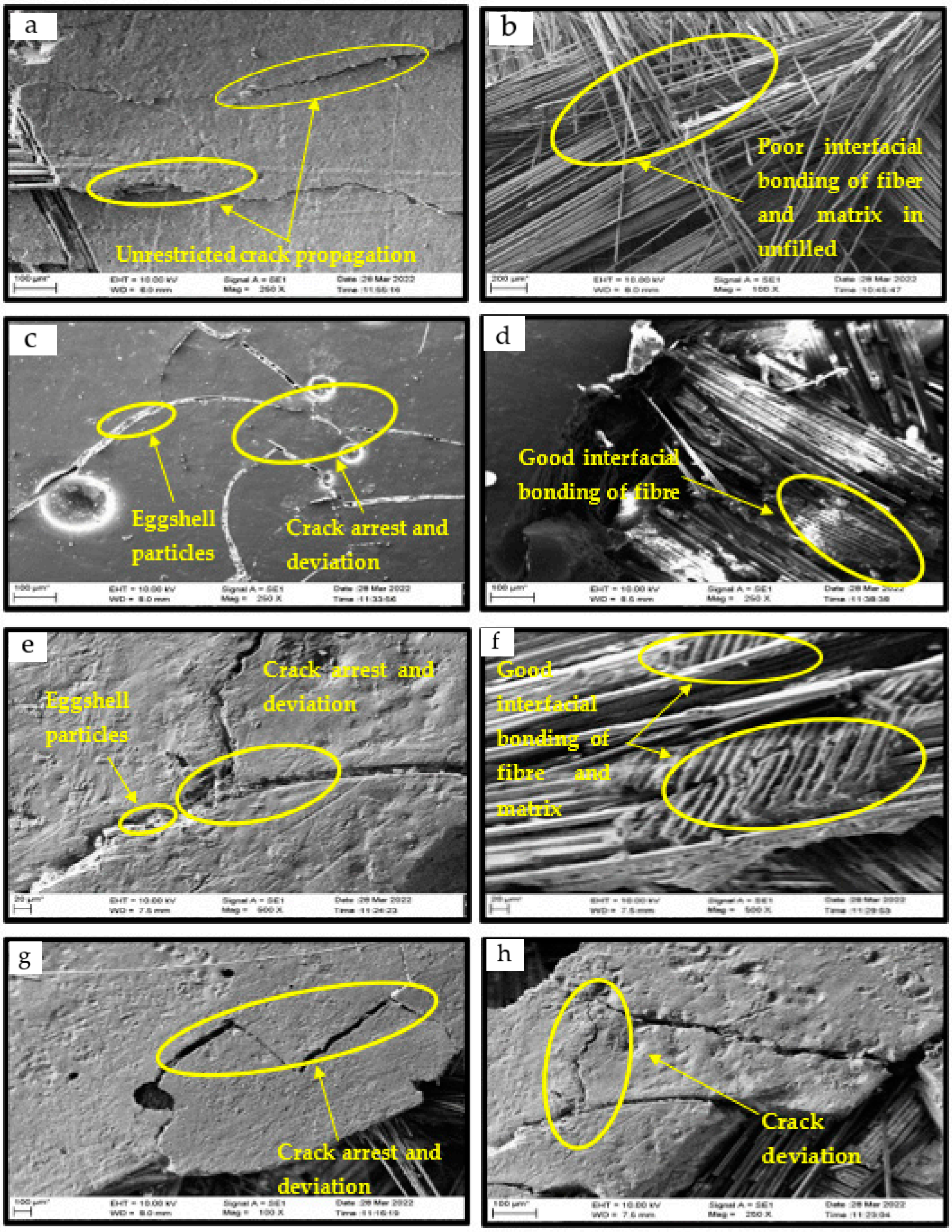

Figure 11. SEM images of composite variants. (**a**) Unrestricted crack propagation in unfilled composite; (**b**) poor interfacial bonding of fibre and matrix in unfilled composite; (**c**) crack arrest and deviation in uncarbonised eggshell filled composite; (**d**) good interfacial bonding in carbonised eggshell filled composite; (**e**) crack arrest and deviation in carbonised eggshell filled composite; (**f**) good interfacial bonding in carbonised eggshell filled composite; (**g**) crack arrest and deviation in hybrid eggshell filled composite; (**h**) crack deviations in hybrid composites.

The eggshell filler particles are homogenously distributed which contributes to the crack arrest and deviation. Similar results have been showcased in the study by [27], in which the authors have attributed the crack arrest to the homogenous distribution of eggshell filler particles. Interfacial bonding of eggshell filler and polyester resin can also be seen in the SEM images. Interfacial bonding of the filler and matrix plays a vital role in the strengthening of the material [33].

The bonding between the filler and matrix depends on various parameters such as particle size, shape, surface area, etc. [27]. The particles in this case are irregularly shaped, which has contributed to the higher level of adhesion with the resin. Further, various studies have shown that lower particle sizes contribute to higher strength owing to the increase in surface area [19,33]. Further, the obtained tensile and flexural strengths follow the same trend as the research conducted by [29].

4. Conclusions

In summary, three different variants of eggshell filled composites, namely, uncarbonised, carbonised, and hybrid eggshell filled, and an unfilled composite variant consisting of E-glass fibre reinforcement and unsaturated polyester matrix were fabricated using a hand lay-up technique, exposed to post-curing, and then subjected to mechanical testing.

The results of the tensile tests showcased that although all eggshell filled composites exhibited a higher tensile strength in comparison with unfilled composites, carbonised eggshell filled composites possessed the highest tensile strength and modulus. A 42% increase in tensile strength was observed in carbonised eggshell filled composites in comparison with unfilled composites. A similar trend was observed with the flexural test results. Carbonised eggshell filled composites showcased a 49% higher flexural strength in comparison with unfilled composites.

It can be inferred from the tensile and flexural tests that the addition of eggshells as a filler material contributes to the improvement in mechanical properties of glass fibre/polyester composites. The improved strength could be due to the increased surface area of eggshells and tensile stress transfer from the matrix to filler.

The SEM imaging showcased the crack arrests and deviations in eggshell filled composites which proved to be a validation of the test results. The modes of failure of the specimens were observed and tabulated which revealed the angular catastrophic failure of the majority of the filled specimens, indicating their higher strength and stiffness.

As the study showcases the augmented properties of post-cured composites, further research with respect to the post-curing of various composites would be beneficial to the materials research community.

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