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Mechanical Performance Evaluation of Brachyuran Shell Particle-Infused S-Glass Fibre Epoxy Polymer Composites

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Abstract

Epoxy composites bio-filled with brachyuran crab shell powder and reinforced with S-glass fibres at different loadings (2%, 4%, and 6%) are tested for their mechanical properties in this work. Using modest amounts of filler significantly improved hardness, ultimate tensile strength, and flexural strength in the empirical data. The largest increase in hardness was 64.42% at 4% filler, up from 26.22% at 2%; however, there was a dramatic decrease to 13.11% at 6% filler. For 4% filler content, the ultimate tensile strength also peaked at 25.40%, following an 18.76% increase at 2% and a subsequent decline to 20.05% at 6%. This pattern was also observed in flexural strength, which peaked at 23.79% at 4% after first increasing by 19.47% at 2% and then declining by 19.47% at 6%. A filler concentration of 4% is optimum, according to these trends, because it maximises mechanical benefits via increased filler-matrix stress transmission and microstructural reinforcement. When this happens, the qualities start to deteriorate due to stress concentration locations and compromised composite integrity caused by filler agglomeration and inadequate interfacial bonding. In order to achieve a balanced improvement in both material reinforcement and manufacturing feasibility, it is necessary to optimise the filler concentration. This research shows that crab shell powder is an efficient natural filler for improving the mechanical strength of S-glass fibre-epoxy composites. By strengthening the link between shell particles and S-glass fibres, brachyuran shell reinforcement makes materials more rigid, pliable, impact-resistant, and tension-strong. Compared to standard S-glass epoxy and other natural fibre/epoxy options, the composites are far more durable, rigid, and long-lasting. Based on these findings, structural composites produced from bio-waste offer great promise for applications in the engineering field. Sustainability in advanced material design is promoted, and critical mechanical metrics are improved upon compared to present natural fibre-epoxy composites. The creation of long-lasting, sustainable composite materials designed for innovative engineering applications can be aided by these insights.

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INTRODUCTION

A bio-based filler material that has scientific attention for reinforcing polymer composites is brachyuran shell particles, which are generated from crab shells. A naturally mineralised composite with excellent tensile and thermal qualities, crab shells are mostly made up of chitin, proteins, and calcium carbonate. These shells, when ground into a fine powder, can be used as particle fillers in polymer matrix composites, which could improve their mechanical, thermal, and fire-retardant characteristics. Shell waste valorisation in composite manufacturing is being investigated by academics due to the growing demand for sustainable materials and eco-friendly reinforcements.

Because of their exceptional strength-to-weight ratio, resistance to corrosion, and dimensional stability, S-glass fibre-reinforced epoxy composites find extensive application in the aerospace, automotive, and marine sectors. Longevity and safety under extreme conditions are both enhanced by composites that are harder, more impact resistant, and fire retardant. An interesting hybrid technique to enhance composite performance and make use of ample crustacean waste is to fill S-glass epoxy composites with brachyuran shell powder.

Researchers are progressively incorporating marine-derived particles as bio-fillers into high-quality composites in an effort to create materials with improved mechanical strength, lifespan, and environmental impact all at once. This novel approach improves the composites' qualities and also promotes sustainability through waste reduction. There will probably be more eco-friendly materials used in a variety of sectors, thanks to the expanding use of such bio-fillers as research progresses. For example, there is crab shell powder. Composite matrices made from brachyuran shell particles—which come from crab exoskeletons—may have better mechanical and functional properties than those made from other materials because of the unique blend of mineral-rich microstructure and natural biopolymer phases. Improving thermal, flexural, and tensile characteristics and encouraging environmental responsibility through the vaporisation of bio-waste are achieved by combining these bio-derived fillers with S-glass fibre-reinforced epoxy resins. Lightweight, long-lasting, and environmentally friendly materials are of utmost importance in various engineering domains; this study is the first of its kind to investigate the mutually beneficial effects of brachyuran shell particles on the mechanical, physical, and microstructural properties of S-glass/epoxy composites.

Researchers Teja MS et al. [1] and Mohana Krishnudu et al. [2] studied the effects of filler loading on the mechanical and thermal properties of fibre-reinforced composites. Using E-glass chopped strand fibres and diverse amounts of crab shell powder as space filler, Shenoy and colleagues created hybrid composites. According to the results of mechanical tests, increasing the proportion of shell powder to reach around 7.6 weight percent resulted in improvements in the flexural, tensile, compression, and impact strengths. According to the findings of their research, the use of crab shell powder as a bio-waste addition has the potential to enhance the mechanical performance of composites while simultaneously lowering their construction costs.

Researchers Chandrakal et al. [3] observed hybrid composites by mixing chopped strand E-glass fibre-reinforced epoxy with varying amounts of crab shell powder. This results in the formation of hybrid substances. Crab shell powders and epoxy composites reinforced with E-glass fibres were the subjects of experimental characterisation by Nayak SY et al. [4]. They discovered that bio-filled composites beat clean epoxy/glass fibre laminates in terms of hardness, impact resistance, and flexural strength. This was the conclusion by the researchers. According to the findings of the study, the integration of particle reinforcement shows the way to the development of effective mechanisms for energy absorption and fracture deflection.

By adding filler material to composites, their hardness, flexural strength, impact strength, and tensile strength are all enhanced. Researchers Rallabandi SR and colleagues [5] employed state-of-the-art methods in their investigation of bio-fibre composites. The mechanical and physical properties of glass fibre-reinforced epoxy composites are much improved upon adding brachyuran shell particles, according to a large body of research. The tensile, flexural, and impact strengths were found to be improved when five percent by weight of crab shell powder was an extra to these composites. It made no distinction as to what type of composite it was. Due to the sturdy bond between the epoxy matrix and the hydrophilic shell particles, the load may be more effortlessly moved. The reason for this, according to them, was that the material was more long-lasting and sturdy. Agglomeration, stress concentration, and a little reduction in features over the ideal range were among the several effects shown by high particle loading. Research in the scientific community has shown these consequences.

In an attempt to improve the mechanical performance and fire resistance of glass fibre reinforced polymer composites, Rakhman et al. [6] investigated the mechanical characteristics of these composites that have crab shell particles included in them. According to the study, the flame resistance significantly improved with the use of these bio-fillers. The shells' calcium carbonate composition likely contributes to the formation of char and the heat barrier effect. The optimal particle concentration was found to develop peak stiffness and tensile strength in mechanical tests.

A significant experimental study was carried out by Prasad et al. [7] that described the impact, flexural, and tensile strengths of glass fibre epoxy composites containing brachyuran shell particles. For this mechanical enhancement, the authors zero in on the processing factors and microstructural processes. Because additional factors are considered with seashell powder, Krishna et al. [8] broaden the applicability of this approach, which improves mechanical characteristics and offers comparative insights into particle dispersion and interfacial bonding. In their quantitative evaluation of brachyuran shell and other bio-fillers in glass fibre epoxy systems, Kabir et al. [9] show that marine-derived fillers perform better in terms of modulus and fracture resistance. The mechanical and thermal analysis presented by Oladele et al. [10] is sustainability-orientated; it compares different types of bio-filler and highlights the technical and environmental benefits of shell-based composites in various fields of application. Noteworthy gains in toughness and fracture resistance are reported by Ifuku et al. [11] when they concentrate on nano chitin that is collected from crab shells. They discuss chemical modification approaches that increase compatibility and performance inside composite matrices.

In their review of the state of the art in hybrid fibre polymer composites, Mohanraj et al. [12] synthesise data from several biofiller investigations and propose criteria for the best mechanical reinforcement, taking into account hybridisation methodologies and filler selection. In their study, Arul et al. [13] compare the effects of several bio-fillers, such as natural fibres derived from shells, and show how designing the interface between the filler and matrix can improve mechanical properties. Improving mechanical characteristics while maintaining processability and enduring stability is an ongoing challenge. To further appreciate the benefits and drawbacks in real-world situations, more research should focus on improving particle treatment and distribution procedures and conducting life-cycle and application-specific evaluations. Fibre-reinforced polymer composites could benefit greatly from the addition of brachyuran shell particles, which would improve their performance and make them more environmentally friendly.

Thermal and morphological activities, together with mechanical properties, are the focus of investigations. Recent research on epoxy-seashell composites has shown that increasing the filler content to 30 weight percent greatly enhances the flexural modulus and thermal stability of the material. Composites reinforced with bio-fillers have higher glass transition temperatures and better heat resistance due to the stiffening effect and decreased chain mobility. Brachyuran shell particles must be uniformly distributed and bind strongly to the epoxy matrix in order for the stress transmission and fracture arresting processes to work, which are the basis of mechanical benefits. The shells' mineralisation gives them natural hardness and structural strength, and chitin makes them resistant and lightweight.

PREPARATION OF CRAB SHELL POWDER

The carapace, or the hard outer shell of the crab composed primarily of chitin, is collected in large quantities from seashores. The shells are first dried under sunlight for 2 to 3 days to reduce moisture content. After drying, they are thoroughly washed and cleaned to remove residual odours, salts, and any remaining moisture. Once cleaned, the crab shells are manually broken into smaller pieces by hammering on a flat surface. These pieces are then milled using a ball mill for approximately one hour to produce fine powder. The resulting powder is carefully moved and passed through a standard sieve shaker equipped with a British Standard Sieve (BSS) mesh size of 70, sieving for 15 minutes to obtain a uniform particle size suitable for composite fabrication.

Material Selection and Characterization

As a primary reinforcement, taken S-glass fibre of cross-section area 200*200 mm was taken. The density of the S-glass is 2.49 gm/cm³, and the crab shell powder is used as a secondary reinforcement with multiple filler loadings such as 0%, 2%, 4% and 6% weight fractions. Along with hardener and epoxy resin, we also used epoxy resin LY556 , Hardener- HY951 (100 g), S-glass fibre (300 g), Mansion wax polish (white), clear firm (for finishing purposes), and a squeezer (to remove air bubbles).

Composite Manufacturing

Taken the S-glass fibre and cut it into 200*200 mm. Crab powder for multiple filler loadings with weight fractions such as 0%, 2%, 4% and 6%. The S-glass has high strength by adding crab powder to make S-glass stronger, and the thickness of S-glass is 0.4 mm. We have to prepare the mixture from crab powder, epoxy resin and hardener in the ratio given below.

- *Epoxy resin:* Hardener=10:1 (gm),
- *S-glass:* Epoxy=1:1 (gm)
- *S-glass:* Hardener=10:1 (gm)

Take a jar and pour epoxy resin and hardener in a 10:1 ratio and stir manually for proper mixing for about 3–5 minutes. To this mixture, add the crab shell powder in the proportions, i.e., 0%, 2%, 4% and 6%, as mentioned earlier, and stir with a glass rod manually. After getting the matrix mixture, take a clear firm on the work table and apply the mansion polish to get the workpiece for smooth finishing and easily remove the workpiece without any damage or cracks.

Apply the resin mixture evenly onto a clean, firm surface. Continuously place S-glass fibre mats as layers over the resin until the desired composite thickness of 5 mm is achieved. This hand lay-up fabrication process typically requires 12 layers of S-glass fibre mats to reach the specified thickness. During fabrication, a squeezer is used to remove trapped air bubbles and minimise porosity, ensuring improved consolidation and mechanical integrity of the composites. To get solidification of the composite/workpiece, leave the workpiece for 24 hours in sunlight. After curing for the 24 hours, it has to remove the clear film for every proportion, i.e., 0%, 2%, 4% and 6%. For making a workpiece into a number of samples as per the required dimensions and shape Figure 1 shows the preparation of glass fibre, crab shell powder, mats and prepared samples for testing.

RESULT AND DISCUSSION

Mechanical Properties

Hardness

Using the Rockwell hardness test, hardness values of composites with different bio-filler proportions (0%, 2%, 4%, and 6%) were measured at room temperature. A load of 150 kgf was applied with a dwell time of 10 seconds. Indentations were made using a square-based diamond indenter. The average hardness value from multiple indentations was recorded as the Rockwell hardness number for each composite sample. Results (depicted in Figure 2) show that micro Rockwell hardness increases progressively from the unfilled composite to the 4% bio-filler (crab shell) addition, reaching a peak hardness number of 20.06. This enhancement is attributed to strong interfacial bonding between the fillers and the epoxy matrix, leading to increased resistance against indentation. However, at 6% filler content, the hardness decreases due to agglomeration of crab shell particles, which weakens the matrix.filler interface compared to the control (0%). Despite this drop, composites with bio-filler performed better than the unfilled material overall.

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[redacted]1. Preparation of brachy[redacted]ell particle-infused S-gla[redacted] epoxy polymer composite specimens. (a) Crab shells; (b) S Glass fibre; (c) Powder; (d) Sample mat; (e) Samples for testing; (f) Samples after testing.

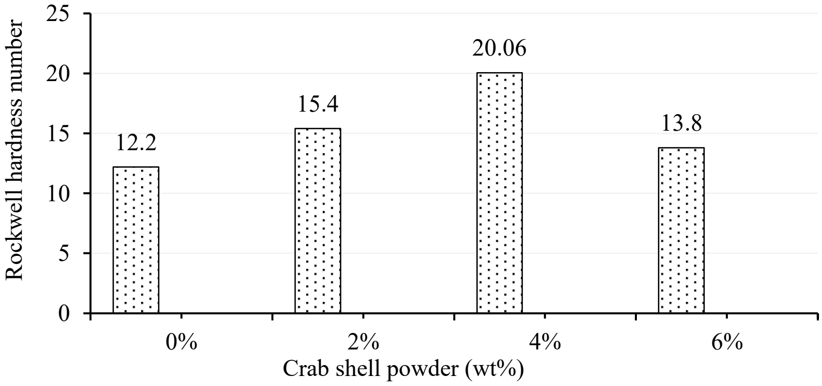

Figure 2. Hardness with variation in brachyuran shell particle S-glass fibre epoxy composites.

Tensile Stress
Ultimate

Ultimate tensile strength observations are shown in Figure 3; the tensile test was conducted on the UTM (universal testing machine). The raw composite (0%) was shown to have less tensile strength compared to crab shell particle glass fibre reinforced composites. At 4% composite, it got maximum ultimate tensile strength (284.07 MPa) compared to raw composite and 0%, 2%, 4% and 6% filler composites.

Flexural Test

The flexural composites were evaluated on UTM, and the flexural strength values were measured. The crosshead speed was 0.1mm/min. The high flexural strength obtained at 4% reinforced composite compared to raw composite (0%).

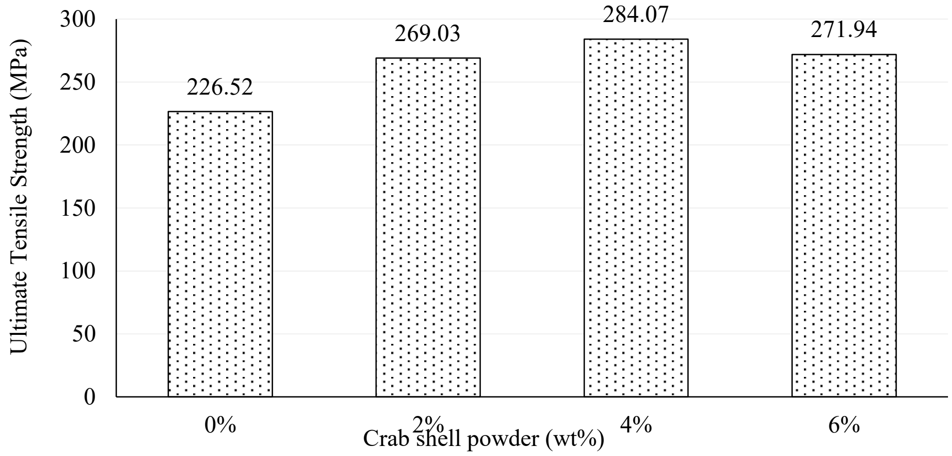

Figure 3. Ultimate tensile strength with variation in brachyuran shell particle infused S-glass fibre epoxy composites.

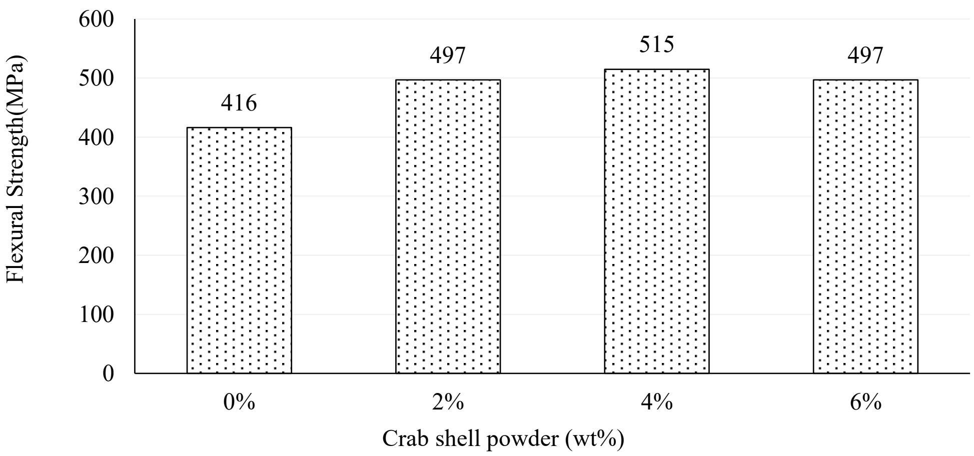

Figure 4. Flexural strength with variation in in brachyuran shell particle infused S-glass fibre epoxy composites.

The high flexural value found at 4% is 515 MPa. Flexural strength shows a direct correlation with increasing crab shell powder content up to 4%, where the particles are uniformly distributed, resulting in reduced porosity. Beyond this level, however, the flexural strength begins to decline, as seen at 6% filler content, due to the weakening of the interface caused by particle agglomeration. The variation in flexural strength across different samples is summarised and illustrated in Figure 4.

Impact Test

Charpy impact testing equipment was used to perform the impact test on the specimens in agreement with ASTM guidelines. To achieve precise impact loading, the samples were arranged horizontally, facing the edge of the hammer. Dividing the energy received by the cross-sectional area of the specimen yielded its impact strength. The lack of bio-filler was evident from the unfilled composite's lowest impact strength value at 70 J. The use of crab shell powder significantly enhanced the impact resistance. At a filler concentration of 4%, the maximum value reached 154 J. The bio-filler and matrix form strong interfacial bonds, which allow for effective energy absorption, which is the reason for this improvement. It is probable that filler agglomeration and weaker filler-matrix adhesion at increasing concentrations caused the impact strength to exhibit a trend of decline beyond 4%. Figure 5 provides a visual summary of the impact strength variance across different filler contents.

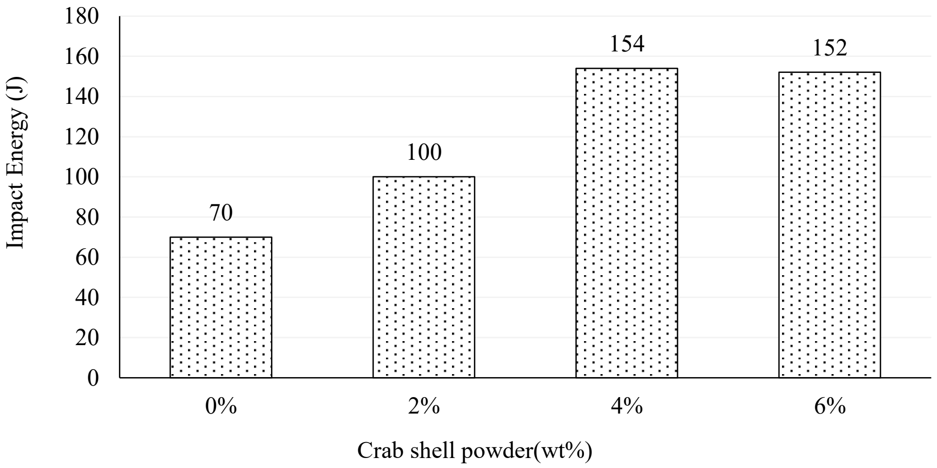

Figure 5. Impact energy absorbed with variation in brachyuran shell particle infused S-glass fibre epoxy composites.

These results highlight the importance of controlling the concentration and dispersion of fillers for improved impact performance, since they show that adding crab shell powder significantly increases the composites' toughness up to an optimal loading, after which the mechanical benefits fade.

Limitations of the Present Research

This study acknowledges several inherent limitations pertaining to the material processing and mechanical characterisation of brachyuran powder-infused polymer composites. The mechanical response is profoundly influenced by particle attributes—including shape, aspect ratio, size distribution, and the degree of dispersion within the matrix. Specifically, coarse particles function as stress concentrators, while the inclusion of ultra-fine particles increases resin viscosity, complicating procedural steps such as degassing and mould filling, especially at filler loadings exceeding 8 wt%. These phenomena pose significant challenges in the consistent fabrication of glass-epoxy composites intended for performance evaluation. Furthermore, non-uniform particle dispersion and elevated filler concentrations facilitate the development of microvoids, resulting in diminished flexural and impact strength. The sensitivity of test results to these variables often manifests as batch-to-batch variability, thereby limiting the broader generalisability and statistical robustness of mechanical data across different sample groups.

Although rigorous sample preparation protocols were adopted—ensuring all specimens originated from the same batch and employing controlled hand layup techniques—absolute reproducibility remains elusive due to the inherent heterogeneity of the composite system. The research observed a noticeable decrease in mechanical properties at higher filler loadings, reflecting both the complex interactions among multiple processing parameters and the limitations in achieving repeatable, reliable mechanical characterisation. It is important to note that, while efforts to minimise variability were substantial, factors such as manual fabrication procedures, uncertainties in filler distribution, and unavoidable lot-to-lot differences restricted the broader applicability of the findings and their statistical reproducibility.

Future scope of work: Although the present work centres on the mechanical performance of the material, future investigations should extend to its tribological, thermal, rheological, acoustic, and damping responses. Exploring these additional properties will offer a more holistic understanding of the material's behaviour and further support its application in developing eco-friendly, biodegradable, and sustainable components for 3Dprinting technologies.

CONCLUSION

A filler content of about 4% is usually optimal for the mechanical characteristics of composites supplemented with brachyuran shell particles or comparable bio-fillers. Reduced hardness, tensile, and flexural strengths are the result of particle agglomeration, poor matrix-filler adhesion, and internal flaws as the material passes this threshold. To achieve balanced and increased mechanical performance in biofill-reinforced composites, it is necessary to optimise the filler concentration and dispersion.

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