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Assessing the Mechanical, Structural and Thermal Performance of Boehmeria Nivea and Agave Sisalana Fiber Reinforced Polymer Composite by using Seashell Powder as a Filler Material

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Abstract

Natural fiber composites have replaced plastics and have been used to the maximum extent. Hybridization of natural fibers with filler materials has achieved higher tensile, impact, and flexural strength compared to single fiber composites. In this research, the mechanical properties were investigated with the ramie and sisal hybrid fiber reinforced with seashell powder as filler material. Filler material can enhance the flexural property of the natural fiber. Hybrid composite plates were prepared by varying the weight percentage of fiber, and seashell filler material was varied by 5% and 7.5%. With the help of a high-pressure compression molding machine, the composite samples were prepared. Tensile, flexural, and impact behavior of the hybrid composite were evaluated as per the ASTM standards. As a result of hybridization of natural fibers, it shows excellent mechanical properties with 35% of fiber and 7.5% of seashell filler. Filler material enhanced the properties of tensile strength of 14.98 MPa to 28.44 MPa and flexural strength from 39.65 MPa to 76.52 MPa. Analysis of micro and nanoparticle imaging characterization of the hybrid composite was examined with the help of Scanning Electron Microscope (SEM), revealing the distribution and bonding between fibers and filler. Based on the experimental results, the ramie and sisal hybrid polymer composite with seashell filler material is highly recommended for the development of medium density fiberboard (MDF), lightweight materials.

Keywords: Ramie fibre, sisal fibre, seashell filler, mechanical properties, thermal characteristics

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INTRODUCTION

Natural fibers and their composites are emerging as an environmentally friendly substitute for conventional materials. Natural fibers such as jute, hemp, ramie, sisal, and flax are derived from plants and offer several advantages [1]. In contrast to synthetic fibers, they are biodegradable, renewable, and have a little environmental impact. Natural fiber composites are made by combining these fibers with a matrix material, typically a polymer. The resulting composites exhibit good mechanical properties, including tensile strength and modulus. The fibers can enhance the stiffness and strength of the composite while reducing its weight [2, 3]. These composites find applications in various industries, including automotive, construction, and packaging. In the automotive sector, they can be used for interior panels, door trims, and seat backs.

In construction, they can be used for insulation materials and lightweight structural components. In packaging, natural fiber composites can replace traditional plastics, reducing waste and environmental pollution. However, natural fiber composites also have some limitations [4]. They can be sensitive to moisture and have lower durability compared to synthetic fiber composites. Additionally, the properties of natural fibers can vary depending on factors such as fiber source, processing methods, and environmental conditions [5, 6].

Despite these limitations, natural fibers and their composites hold great promise for a more sustainable future. One of the group of crops known as the bast fiber crops is ramie (Boehmeria nivea), sometimes called China grass, white ramie, or rhea. [7]. It belongs to the nettle family or Urticaceae. Ramie is a natural fiber extracted from the stem of the ramie plant and it is also a cellulose fiber with good durability and strong in nature. It is one of the strongest natural fibers compared to flax, cotton or wool. The bark contains pectins and gums, this makes the fiber useable only after the chemical treatment [8, 9]. Ramie plant is believed to have originated in the Malay Peninsula. Ramie fiber has been cultivated for thousands of years, mainly in Asian countries and it is harvested 6 times a year. It has a long history of cultivation in china, where it was used for the textile applications. Cultivation of ramie plant has expanded globally. This fiber is widely known for its ability to reduce wrinkling and hold its shape. Comparing to cotton it exhibits eight times stronger when it is wet. It helps to reduce wrinkling and aids the ability of blends to hold shape when it is blended with other fibers, such as cotton or wool. The main advantage of the ramie fiber is their high resistance to bacteria, mold, mildew and rotting. Due to their high resistance to high levels of moisture or humidity, it is highly recommended in making of fabrics [10]. Ramie faced a decline in popularity due to the labor-intensive processing required to extract the fiber from the plant. However, with growing interest in sustainable and natural fibers, ramie has experienced a revival in recent years [11, 12]. Improved Cultivation Techniques: Future developments may focus on enhancing ramie cultivation techniques, including advancements in seed varieties, pest and disease resistance, and sustainable farming practices. Ramie fibers could be blended with other natural or synthetic fibers to create new fabrics with improved characteristics. For example, blending ramie with cotton can result in textiles that combine the strength of ramie with the softness of cotton [13].

Sisal is a natural fiber extracted from the leaves of the Agave Sisalana plant, primarily grown in tropical regions. Sisal cultivation can be traced back to ancient civilizations in the Yucatan Peninsula of Mexico [14]. Mayans and Aztecs used sisal fibers for making ropes, nets, and fabrics. Sisal cultivation expanded to other parts of the world, including East Africa, Brazil, and the Caribbean. It became a significant industry in these regions, particularly during the 19th and 20th centuries. Sisal found wide use in industrial applications due to its strength and durability [15]. It was commonly used for making ropes, twines, carpets, and other heavy-duty products. Future developments may focus on sustainable and environmentally friendly cultivation practices for sisal. This could involve improved water management, reduced chemical inputs, and more efficient harvesting techniques [16]. Sisal has potential beyond traditional uses. Research could explore new applications in fields such as biodegradable packaging, reinforcement materials for composites, and bio-based textiles. Advancements in fiber treatment and processing techniques may improve the softness and dye ability of sisal fibers, making them more suitable for a broader range of textile applications [17, 18].

Marine mollusks like snails, bivalves, and chitons have hard exoskeletons called seashells that support and shield their body. The mantle, a skin-like structure found in the mollusk's body wall, secretes calcium carbonate, which makes up the majority of its composition. Typically, seashells are composed of many layers of unique microstructures with varying mechanical characteristics. Different regions of the mantle secrete the shell layers, but only near the shell boundary does incremental growth occur [19]. Special cells at the edge of the mantle secrete a range of pigments that give many seashells their vibrant colors and intricate patterns. In certain situations, the camouflage function is evident, but in the majority of circumstances, the colors' meaning is not clear. Because of their countless varieties, exquisite shapes, and vibrant hues, seashells are collected all around the world. With 5% organic matter, the chemical makeup of the different seashells is found to be between 92 and 99%. [20, 21].

In this research, the ramie and sisal fibres carried out for the reinforcement of epoxy resin with seashell powder as filler material. The objective of this research work is to study the mechanical properties of the hybrid composite by varying the weight % of the hybrid natural fibre and seashell filler material. The novel aspect of this research work is no existing research publications with this hybrid combination. As the existing studies examines only the single fiber investigation, but in this research, we are using the multi fiber combination and using seashell as the filler material. The hybrid fibre incorporation is more promising for the engineering field. In recent times the multi – fiber hybrid composite is widely known for the benefits of the enhanced tensile, flexural, chemical resistance and impact properties.

MATERIALS AND METHODS

Materials

Ramie and sisal fibers are collected from the neighboring regions of Chennai, Tamil Nadu, Chengalpattu, and India. The primary components, a high-grade epoxy resin (LY556) and hardener (HY951), were purchased from Coimbatore Seenu and Company in Tamil Nadu, India. Seashells are the most common sea products which is available in the nearby seas with different sizes, colors and shapes. They are easily accessible from the nearby seashore which has calcium carbonate and other rich minerals. They are collected from the nearby seashore or beach like Chennai, Pondicherry, Tamil Nadu, and India. The collected seashells are cleaned and crushed as powder for the filler materials, extracted ramie and sisal fibre are as shown in Figure 1.

Chemical Treatment

The ramie and sisal fibers are fed into the alkaline treatment which is otherwise called as chemical treatment. The natural fibers are submerged in a solution of sodium hydroxide (NaOH). A tiny quantity of the wax, lignin, and oils that cover the outer part of the fibers are eliminated from the natural fibers' surface after the alkaline treatment [22]. Following the chemical treatment, the fibers are left in the open sun for two days to dry.

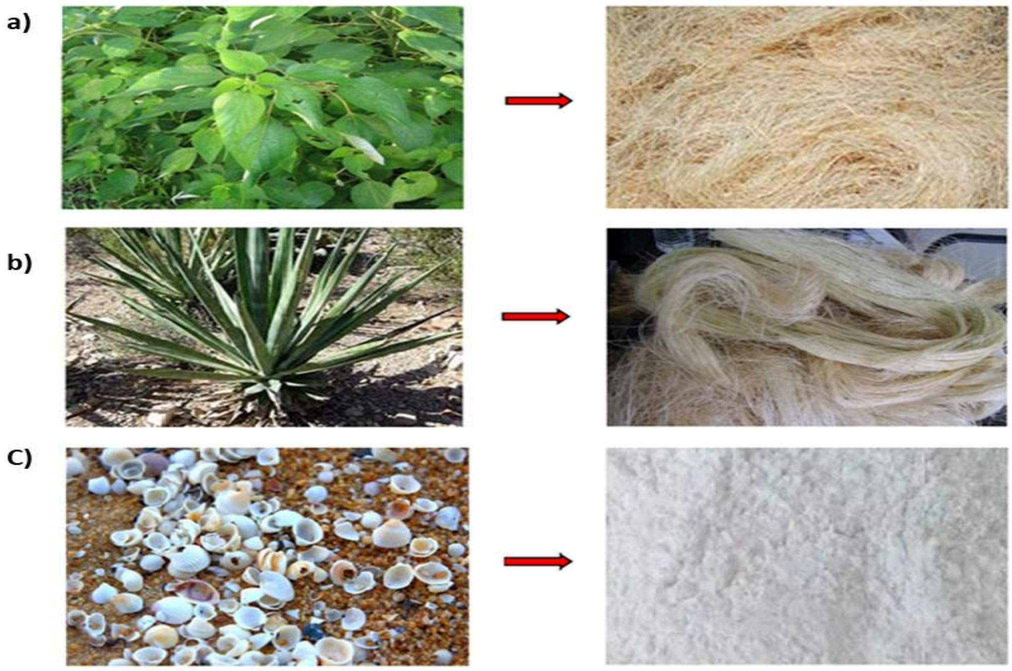


Figure 1. Ramie, Sisal Plant and Extracted Fibres with the Seashell Crushed as Powder.

Composite Preparation

The composite plate was made using the hand lay-up method. The mold size was kept as 200x200x3mmtopreparethespecimen.Ramiefibre,sisalfibre,seashellfillermaterialandepoxy resin were combined to produce the polymer composite plate and composition are shown in the Table 1. Fiber weight percentage was varied by 20%, 25%, 30% and 35 % and seashell filler material is varied by5% and 7.5% respectively. After the preparation of the composite plate it is kept for the 24 hour to 48 hour the curing period at the room temperature.

Mechanical Testing

The hybrid composite plate's tensile and flexural strengths were determined using the universal testing equipment. The samples varying percentage of natural hybrid fiber varying from 20%, 25%, 30% and 35% was prepared respectively. Thickness of the fibre composite was maintained at 3 mm. The specimens manufactured in accordance with ASTM standard D3039 were used to evaluate the tensile test. To evaluate the flexural strength, the bending tip was placed in the middle of a three-point bend test [23]. ASTM D 790 was followed in the preparation of the composite specimens. The four identical specimens were used to calculate an average value. Impact test was carried out using the miniature impact tester, which is used to identify the impact energy absorption of the hybrid fibre reinforced composite plate. The ASTM D 265 standard was followed in the preparation of the specimens to preserve the natural fiber's strength and stability.

Absorption Studies

The chemical and water absorption tests were conducted in accordance with ASTM C413-28 and ASTM D570, respectively. These studies were carried to identify the absorption stability of the composites. The four specimens' average value was determined. In order to dry, the composite specimens were left out in the sun for a whole day before being moved into an enclosed space to cool down. The composite specimen was fed into the distilled water at the room temperature that should not be excessive of 40 C for 10 days [24]. The absorption amount was measured every 24 hours. After 10 days the immersed fibers were removed from the distilled water. The surface of the fibre was cleaned for weighing.

The water absorption test is calculated using the formula

$$\Delta W = \frac{Wt-Wd}{Wd} X\ 100 \qquad (1)$$

ΔW= Weight percentage, W_t is the weight of the sample at time t during the immersion and W_d is the dry sample weight at initial time. After removing the composite samples, this process can take up to 10 hours, and they are weighed every hour.

RESULT AND DISCUSSION

Mechanical properties

The experimental results of tensile, flexural & impact strength are shown in the Table 2.

Table 1. Hybrid fibre,Resinand Cellulosefiller Composition.

S. No	Composite Designation	Epoxy Resin (Volume%)	Ramie&Sisal Fibre(Volume%)	Seashell Filler (Volume%)
1	A20	75	20	5
2	A25	70	25	5
3	A30	65	30	5
4	A35	60	35	5
5	B20	73.5	20	7.5
6	B25	67.5	25	7.5
7	B30	62.5	30	7.5
8	B35	57.5	35	7.5

Table 2: Composite plate results for the tensile, flexural and impact tests.

S. No	Samples	TensileTest (MPa)	FlexuralTest (MPa)	ImpactTest(J)
1	A20	18.56	75.74	2.5
2	A25	17.12	42.42	2.7
3	A30	14.98	76.48	2.8
4	A35	14.75	39.65	3
5	B20	10.79	62.57	2.6
6	B25	22.71	61.8	2.9
7	B30	16.07	52.84	3.5
8	B35	28.44	76.52	3.7

Tensile Test

The tensile strength of the composite samples was measured in order to evaluate the impact of different levels of fiber and seashell filler content and the following are the values achieved during the testing. Tensile strength of 18.56 MPa, 17.12 MPa, 14.98 MPa and 14.75 MPa are achieved for 20, 25, 30 and 35 % of ramie-sisal fibre in the 5% of the filler sample. For 7.5% of filler sample 10.79 MPa, 22.71 MPa, 16.07 MPa and 28.44 MPa was attained for 20, 25, 30 and 35 % of ramie- sisal fibre. The maximum of 28.44 MPa was recorded in the 7.5% of filler sample (B35) with fiber weight of 35%. High tensile can improve the load bearing capacity provided by the fibers as shown in the Figure 2 (a). The seashell filler presence improves the stress distribution throughout the polymer matrix [25, 26]. Boehmeria Nivea fiber-reinforced composites exhibited an initial tensile strength improvement compared to the neat polymer. The fibers, with their inherent strength and aspect ratio, effectively transferred the load, leading to a more ductile behavior. The addition of seashell powder as a filler had a dual effect. The fine particles of the seashell powder filled the voids between the fibers and the polymer, enhancing the packing density. This led to a more efficient stress transfer mechanism, resulting in an additional increase in tensile strength. The combination of Boehmeria Nivea and Agave Sisalana fibers with seashell powder fillers exhibited complex interactions. This synergistic effect was observed when the filler and fiber loadings were optimized, leading to a maximum tensile strength. [27].

Flexural Test

The flexural strength was evaluated and the following are the findings of the test. Flexural strength of 75.74 MPa, 42.42 MPa, 76.48 MPa and 39.65 MPa was attained for 20, 25, 30 and 35 % of ramie-sisal fibre in the 5% of the filler sample and 62.57 MPa, 61.8 MPa, 52.84 MPa and 76.52 MPa was achieved for 20, 25, 30 and 35 % of ramie-sisal fibre in the 7.5% of the filler sample. Boehmeria Nivea fiber-reinforced composites demonstrated enhanced flexural strength compared to the unfilled polymer. This was due to the fiber's ability to carry a significant portion of the load and prevent premature failure. The surface-treated Boehmeria Nivea fibers showed even better performance as the treatment improved the fiber-matrix interfacial bonding, allowing for more efficient stress transfer. The seashell powder also acted as a secondary reinforcement, providing resistance to the compressive stresses that develop during bending on the inner surface of the specimen. The maximum of 76.52 MPa was attained with the 35% of ramie-sisal fiber with 7.5% of seashell filler. As shown in Figure 2(b), a high flexural strength will enhance the interfacial bonding between the fiber and matrix, whereas a low flexural strength will cause the fiber to pull out under flexural stress. [28]. Agglomeration of the filler particles occurred, creating stress concentrations that weakened the composite structure. These agglomerates acted as defect sites, reducing the material's ability to effectively resist bending. Additionally, the excessive filler disrupted the fiber-matrix interface, impeding the smooth transfer of stress and leading to premature failure under bending loads. The flexural strength of Boehmeria Nivea and Agave Sisalana fiber-reinforced polymer composites with seashell powder fillers is influenced by multiple factors, including fiber type, filler loading, and their mutual interactions. By precisely controlling these parameters, it is possible to engineer composites with enhanced flexural properties suitable for a wide range of structural applications.

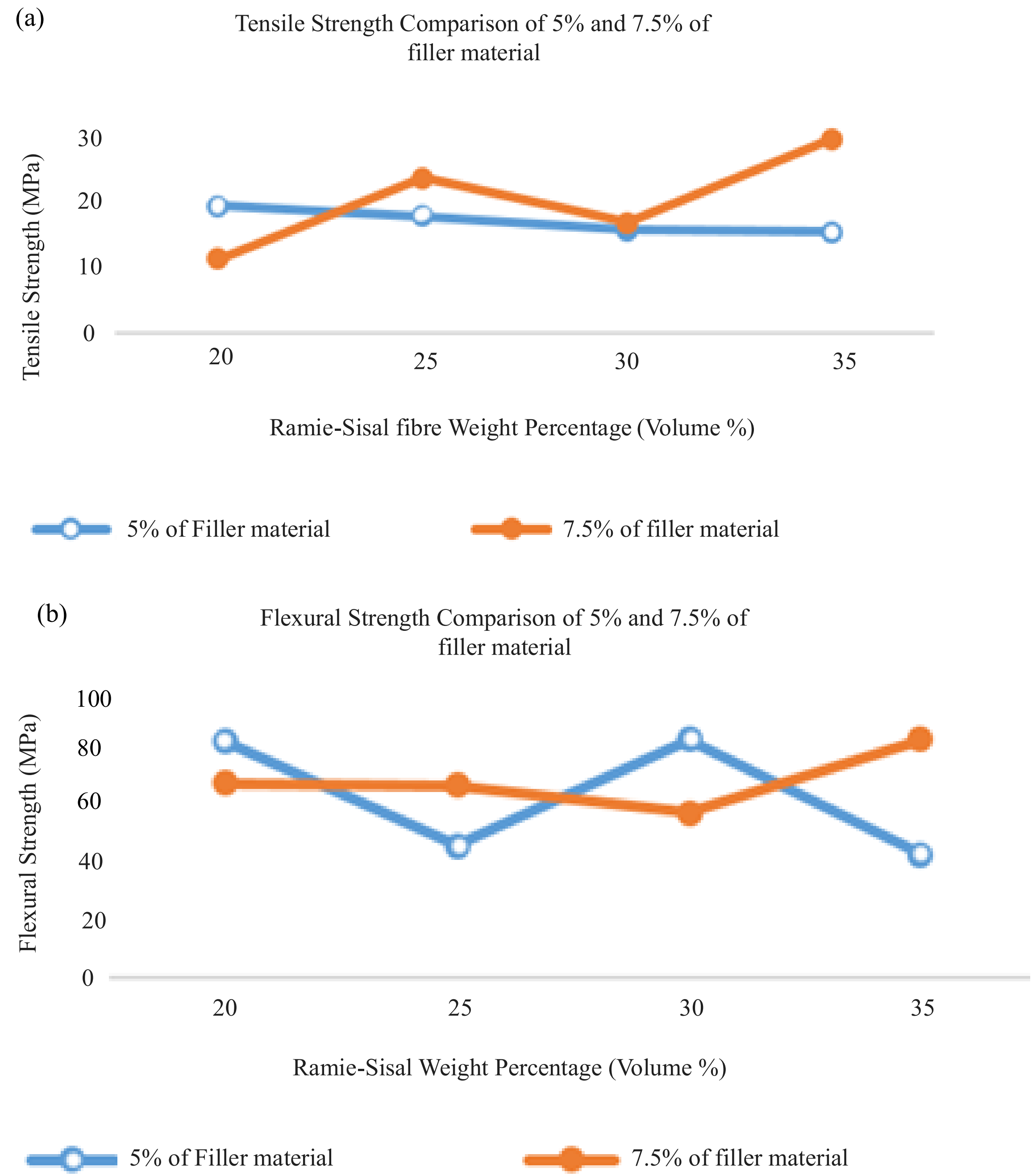


Figure 2. a) Tensile Strength and b) Flexural Strength.

Impact Test

Impact strength of the composite samples was tested and the findings are 2.5 J, 2.7 J, 2.8 J and 3.0 J for the fiber weight percentage of 20%, 25%, 30% and 35% with the seashell filler content of 5% and 2.6 J, 2.9 J, 3.5 J and 3.7 J was attained for th 7.5% of seashell filler with respect to the fiber weight percentage of 20%, 25%, 30% and 35% respectively. Maximum of 3.7 J impact strength was achieved in the 35% of ramie-sisal fibre with 7.5% of seashell filler content as shown in the Figure 3. High impact strength can absorb a greater amount of energy before fracturing and exhibits greater resistance to sudden impacts [29, 30]. Boehmeria Nivea fiber-reinforced composites exhibited a significant improvement in impact strength compared to the unfilled polymer. The fibers, with their inherent toughness and ability to deform plastically under load, effectively absorbed and dissipated the impact energy. The fibrillar structure of Boehmeria Nivea fibers provided multiple channels for energy dissipation, preventing the rapid propagation of cracks during impact. The impact strength of Boehmeria Nivea and Agave Sisalana fiber-reinforced polymer composites with seashell powder fillers is a complex function of fiber type, filler content, and their mutual interactions. Future research could focus on further refining the composite formulations and exploring new manufacturing techniques to maximize the potential of these sustainable materials in terms of impact performance.

Absorption Studies

The water and chemical absorption studies was carried out for 10 hours and 50 hours analysis with ramie-sisal hybrid composites of A20, A25, A30 and A35 for the 5% filler content and B20, B25, B30 and B35 for 7.5% of filler content. Fibers, being hydrophilic in nature, have hydroxyl groups on their surfaces that attract water molecules. Water absorption reduced the modulus of elasticity and tensile strength of the composites. Chemical absorption, especially in aggressive chemical environments, could lead to degradation of the fiber-matrix interface, causing a significant drop in the overall mechanical performance of the composite.

From the 10 hour water and chemical analysis the maximum of 7.67 % and 7.59 % of weight gain was recorded from the A30 sample as shown in Figure 4 (a) and (b) and minimal amount of water and chemical was absorbed in the B35 sample as shown in Figure 5 (a) and (b) with 5.71 % and 5.79% of weight gained then the composite slowed down of absorbing water and chemical [31]. %0 hour water and chemical analysis was also evaluated as shown in Figure 6 (a) and (b). From the 50 hour water and chemical analysis the B35 sample as gained less amount of water and chemical as shown in Figure 7 (a) and (b). After the saturation level there is no significant gain in weight percentage of the ramie-sisal composite remained constant absorbing of water and chemical. The water and chemical absorption behaviour was analysed for all the sample composites. The absorption was linear in the starting stage, then it slows down and reached the saturation level [32]. Composites with 35% of ramie-sisal fibre exhibited the less amount of water and chemical. Ramie-sisal combination as attained minimal amount of water and chemical compared to the previous studies [33–35]. All the composite samples were inspected after the water and chemical immersion test.

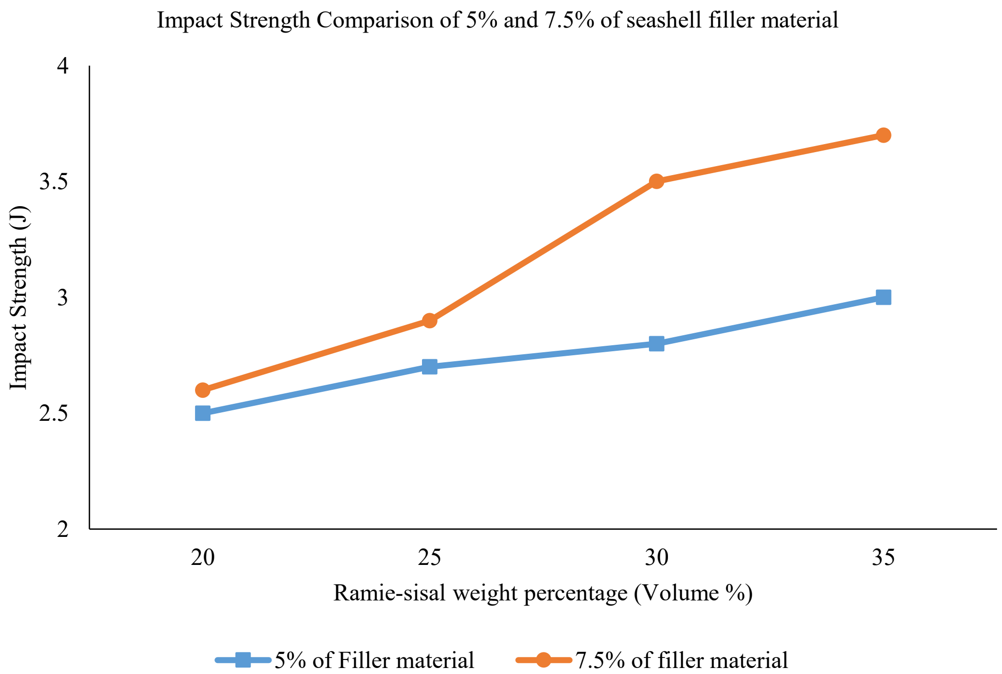


Figure 3. Impact strength analysis.

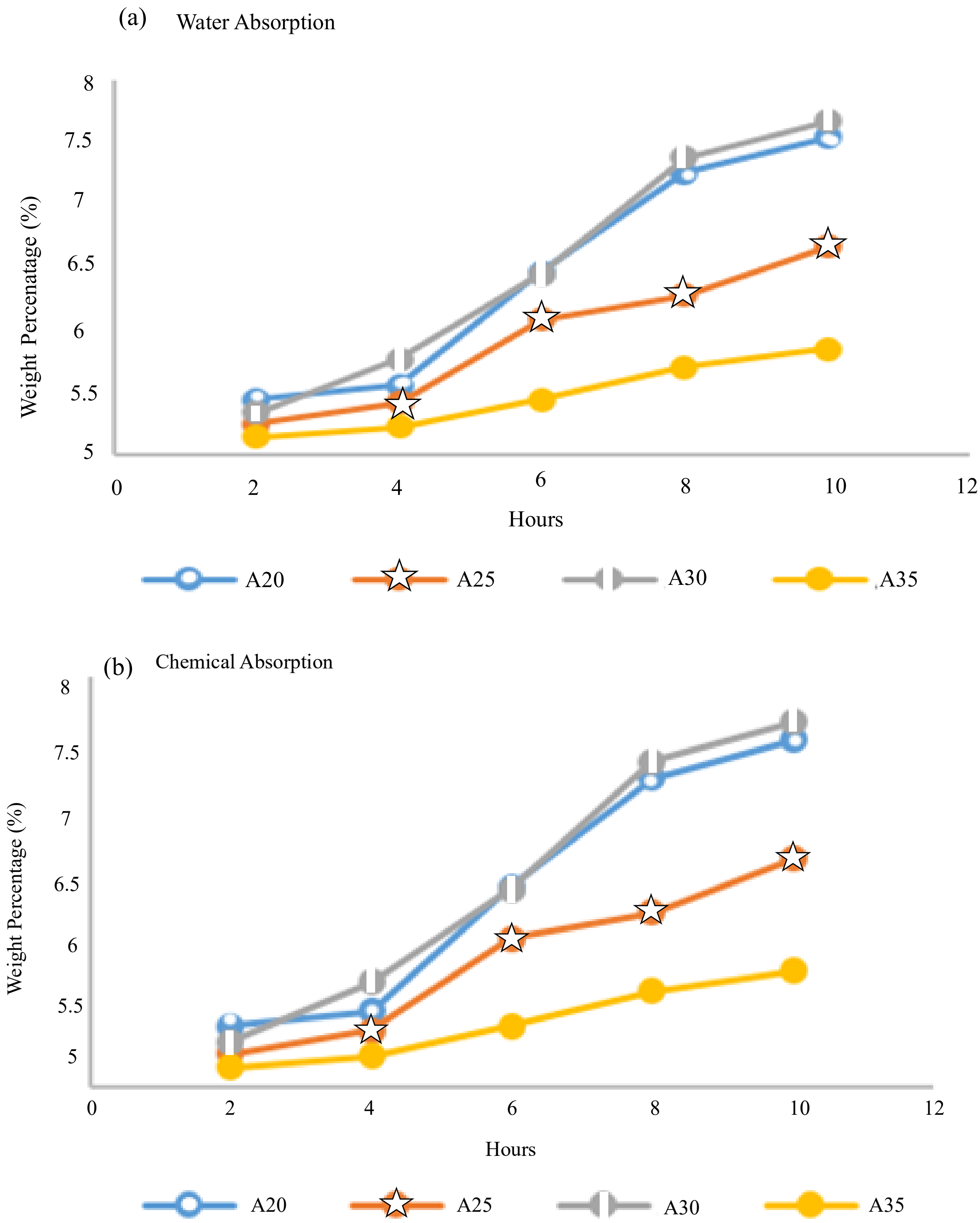


Figure 4. a)10 hour water absorption and b) 10 hours chemical absorption for ramie-sisal hybrid composites for 5% seashell filler material.

Scanning Electron Microscopy Analysis

The scanning electron microscopy (SEM) images demonstrate the presence of a fibrous structure within the potato filler, which suggests its potential as a reinforcement material in epoxy polymer composites[36–38]. The fibrous nature of the filler, in conjunction with the surface modifications resulting from sodium hydroxide (NaOH) treatment, has the potential to significantly enhance the filler-matrix interaction. It might show the alignment and dispersion of ramie fibers within the composite as shown in the Figure 8.

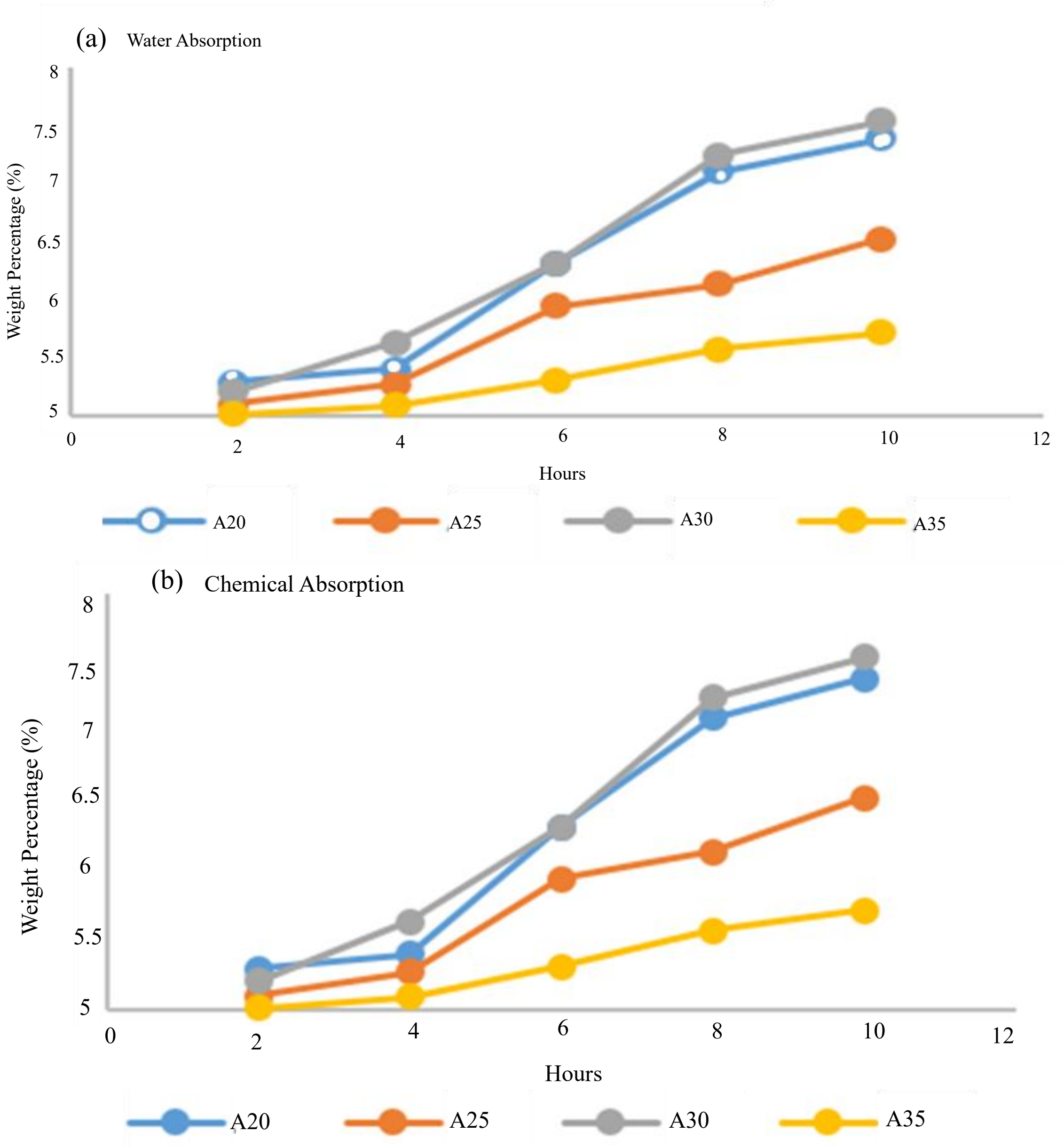


Figure 5. a) 10 hour water absorption and b) 10 hours chemical absorption for ramie-sisal hybrid composites for 7.5% seashell filler material.

This can help in analyzing the mechanical properties and potential applications. The fiber distribution, matrix-fiber adhesion, and the presence of voids or defects within the composite were analyzed using scanning electron microscopy (SEM) images. The SEM images revealed that samples with higher tensile and flexural strength exhibited excellent fiber dispersion, while samples with lower mechanical properties displayed indications of fiber pull-out and inadequate matrix-fiber bonding. Additionally, no instances of fiber debonding, fiber exposure, or fiber fracture were observed in the case of dry samples.In general, the introduction of a larger amount of fibers produces a marked difference in the modes of fracture of the composites[39, 40]. The abrasion behavior of epoxy resin results in the formation of pits and dimples due to resin adhesion to the tool. This phenomenon is a significant contributor to weight loss. The performance of fiber-reinforced composites depends on their microstructure and fiber-matrix bonding. From the SEM analysis the fiber distribution, orientation and interfacial bonding and that play a key role in mechanical properties. If the fibers do not bond well, the composite can easily break through and if the fiber bonding with the matrix are well distributed, then the material performs better with good durability and resistance of the polymer composite. The addition of seashell powder as a filler material helped to improve the composite structure by reducing porosity and reinforcing the material. The filler particles filled gaps between fibers and that is helpful in better load distribution and stress transfer. The combination of ramie and sisal fibers in the composite results in a unique microstructure[41–42]. The long, slender ramie fibers provide high tensile strength and stiffness, while the sisal fibers contribute to toughness and impact resistance. Under SEM examination, the fibers are often interwoven and randomly oriented, creating a complex network within the matrix. This network can enhance the mechanical properties of the composite by distributing loads more effectively. The presence of natural fibers also gives the composite a distinct texture and appearance[43–44].

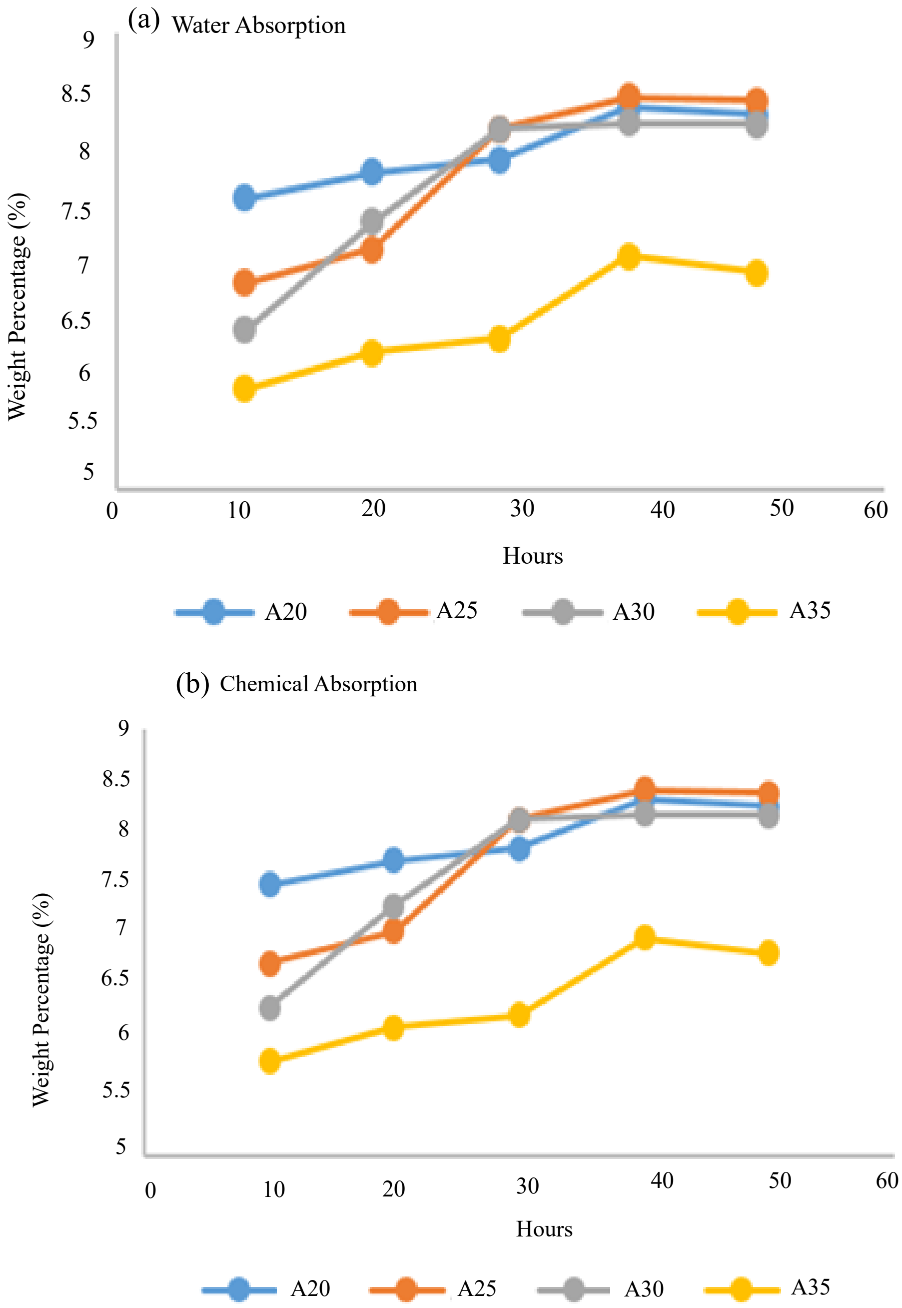
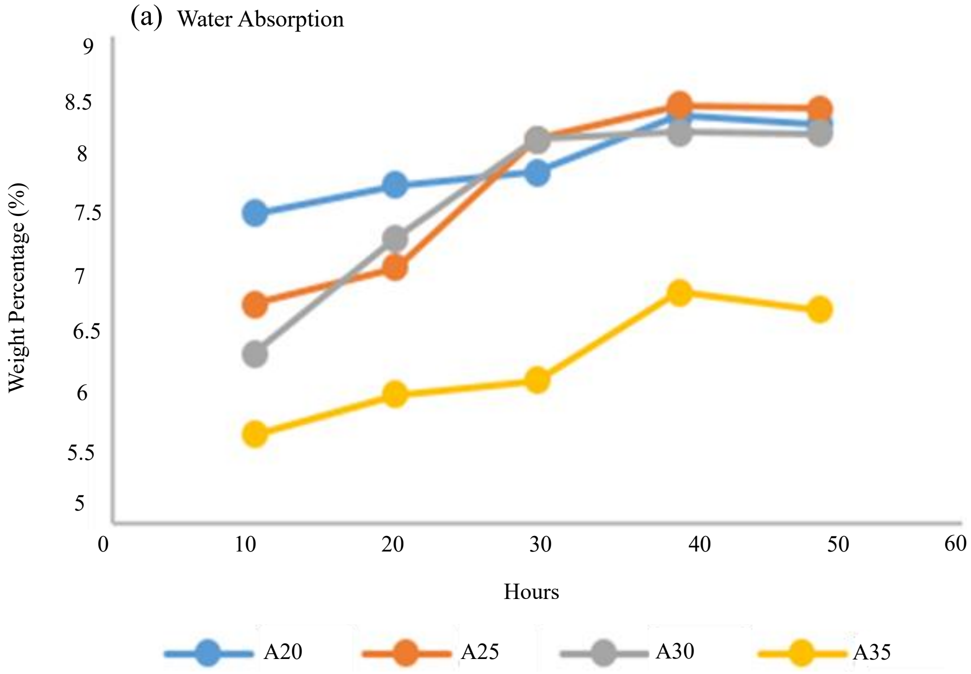


Figure 6. a) 50 hour water absorption and b) 50 hours chemical absorption for ramie-sisal hybrid composites for 5% seashell filler material.



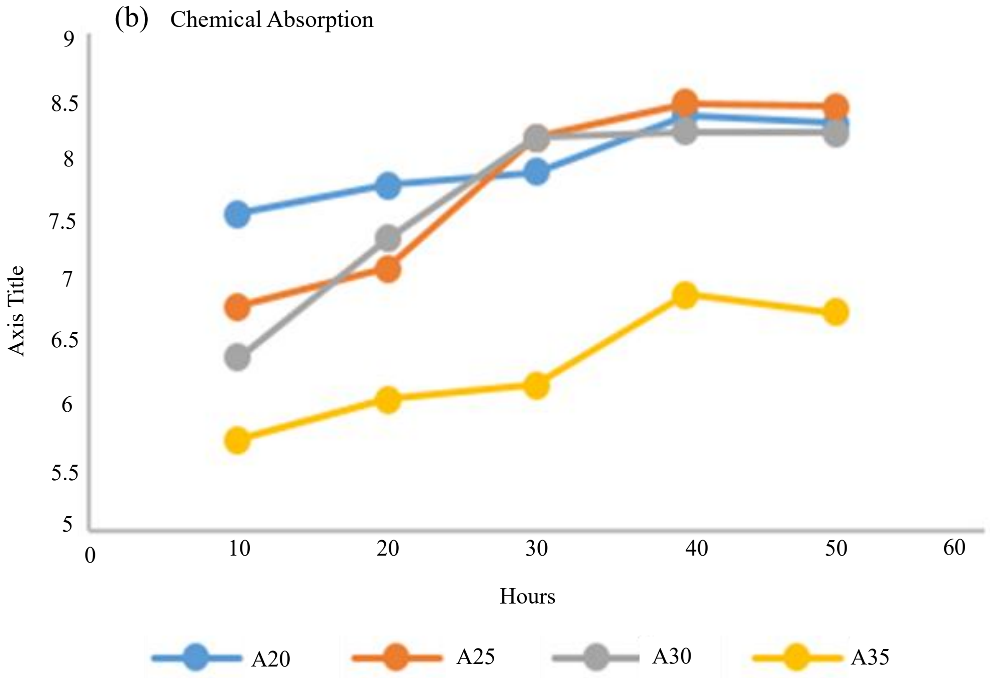


Figure 7. a) 50 hour water absorption and b) 50 hours chemical absorption for ramie-sisal hybrid composites for 7.5% seashell filler material.

The interaction between the fibers and the matrix plays a crucial role in determining the overall performance of the composite. Surface treatments and proper processing can improve the adhesion between the fibers and matrix, leading to better morphological stability and enhanced mechanical properties. To improve the bonding between fibers, filler and polymer matrix the compression molding under high pressure was used to enhance fiber dispersion and reduce void formation within the matrix. Proper fiber orientation was ensured to create better mechanical interlocking and for strong polymer chain bonding. The seashell filler materials strengthened the overall composite by providing additional bonding by filling the gaps between the fibers and the matrix. The interfacial bonding performance based on the matrix, reinforcement, and filler materials [45, 46].

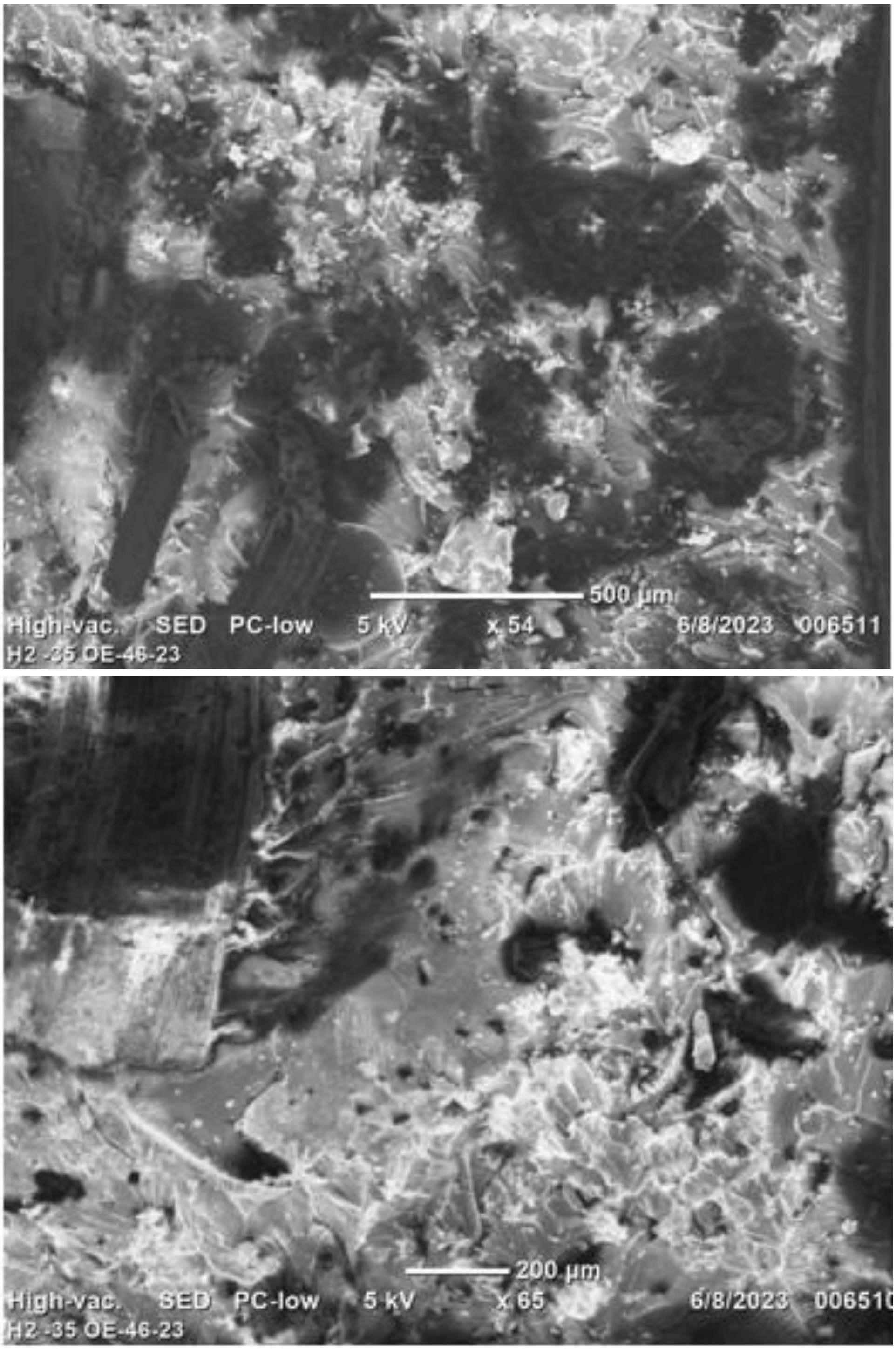


Figure 8. SEM image of ramie-sisal hybrid fibre composite.

CONCLUSION

The investigation of ramie and sisal fiber reinforcement of epoxy resin with seashell powder filler material has yielded significant insights. The combination of these natural fibers and filler has shown great potential in enhancing the properties of epoxy resin composites.The ramie and sisal fibers contribute to increased mechanical strength, while the seashell powder filler offers additional benefits such as improved thermal stability and reduced weight. The composite material exhibits a unique morphological behavior, with the fibers and filler interacting within the epoxy matrix to form a complex and robust structure. In this research, the ramie-sisal hybrid composite were developed by varying the weight of 5% and 7.5% of seashell filler content. The result of the experiment indicated the weight percentage of 35% fiber with 7.5% of seashell filler material has achieved best mechanical properties compared to the other compositions. Composite sample of B35 exhibited the tensile strength of 28.44 MPa, flexural strength of 76.52 MPa and impact strength of 3.7 J. This study found that the composite samples with higher seashell filler material has exhibited the higher mechanical properties compared to the 5% of the seashell filler sample. This indicates that the amount of fiber and filler present in the composites are critical factor in enhancing the materials structural integrity. The surface properties are not significantly influenced by the content of reinforcement materials from the analysis of consistent hardness of the hybrid composites.

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Not applicable

ConflictofInterest Statement

The authors declare no conflict of interest in this manuscript.

CreditAuthor Statement

Hariharan contributed to manuscript preparation. Parthiban is responsible for the conception and validation processes, Ajithram for data support, and Ranjan for language correction.

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