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Development and Experimental Evaluation of *Aquillaria Agallocha* Filled Epoxy Composites

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Abstract

This study examined the effect of filler loading in Aquillaria Agallocha gum-reinforced epoxy composites made using the hand layup process. By systematically mixing Aquillaria Agallocha gum with an epoxy matrix in 5% increments, from 5% to 25% by volume, composite filaments were produced. The mechanical properties of the bio-composites were carefully analyzed to understand how their structure affects them. Tensile tests revealed that the improved composition has an elastic modulus of 1.7 GPa and a maximum strength of 20.2 MPa. The flexural strength was 34 MPa, with a modulus of 1700 MPa, indicating better volume retention. The Izod test results showed that the material could absorb more energy and had an impact resistance of 1.9 kJ/m². This composite opens the door for manufacturing sustainable engineering materials that could be used in biomedical devices, eco-friendly packaging, and consumer products that break down more efficiently in the environment.

Keywords: Aquillaria Agallocha Gum, Epoxy matrix, mechanical properties.

1.0 Introduction

The rapid depletion of fossil fuel resources and the environmental concerns associated with petroleum-based polymers have prompted significant research into sustainable material alternatives. Growing awareness of environmental issues, coupled with regulatory restrictions on single-use plastics in many regions, has further intensified interest in eco-friendly materials. In this context, biopolymers derived from renewable resources such as cellulose, proteins, polysaccharides, vegetable oils, and microbial sources have emerged as viable substitutes due to their biodegradability and reduced environmental impact. Recent studies have focused on enhancing epoxy composites through the incorporation of natural fillers. Nguyen and Nguyen [9] investigated epoxy composites reinforced with spent coffee grounds (SCG) at various weight fractions. Their results indicated that composites containing 30 wt% SCG exhibited excellent interfacial compatibility without phase separation, achieving flexural and tensile strengths of 80.07 MPa and 44.81 MPa, respectively. The study highlighted the potential of SCG to improve mechanical, thermal, and flame-retardant properties, making it a sustainable filler option. Nayak et al. [10] reported that the addition of BAR powder significantly improved the mechanical performance of epoxy composites. The optimum tensile and flexural strengths of 407.81 MPa and 339 MPa, respectively, were observed at 4 wt% filler content, while maximum impact strength (194.02 kJ/m²) was achieved at 6 wt%. These findings emphasise the critical influence of filler loading on composite properties. Similarly, Deepak et al. [11] examined epoxy composites reinforced with dry floral waste and found that a 12% volume fraction yielded optimal tensile and flexural performance. Sarki et al. also observed improvements in tensile strength and modulus with coconut shell powder,

although a slight reduction in impact strength was noted. In addition to natural fillers, Abdul-Hussein [12] explored the effect of industrial powders such as $CaCO_3$, K_2CO_3, and Na_2CO_3 in glass fiber-reinforced epoxy composites. The study reported enhancements in density, hardness, water absorption, flexural strength, and shear strength with increasing filler content, attributed to uniform particle dispersion and improved reinforcement efficiency. Koyuncu [13] investigated epoxy composites reinforced with pumice powder and maize shell, identifying 20 wt% and 15 wt% pumice content as optimal for tensile and flexural strength, respectively. Likewise, Lutfi and Jassim [14] demonstrated that cantaloupe peel powder improved hardness, compressive strength, flexural strength, and impact resistance across filler loadings ranging from 1% to 10%. Prasath et al. [15] reported significant improvements in tensile and flexural properties of epoxy composites reinforced with *Pterocarpus marsupium* resin powder, with optimal performance observed at 30% volume fraction. Furthermore, the incorporation of turtle shell powder (TSP) at 1–5 wt% enhanced tensile, flexural, impact, and hardness properties, with the B3 composite exhibiting superior overall performance. Shah et al. [16] also demonstrated that bamboo powder enhances composite stiffness, with an optimal filler content of 30% determined through dynamic mechanical analysis. Jenkins et al. [17] examined the influence of reduced graphene oxide (rGO) on epoxy/carbon fiber composites and reported improvements of up to 62% in flexural strength and 44% in modulus. However, these enhancements were found to diminish at elevated temperatures, highlighting the influence of thermal conditions on composite behavior. Sridevi et al. [18] studied the effects of casuarina leaf bio fibre on the mechanical and morphological properties of epoxy resin composites. Composites were made using the hand-layup method with different biofiber volume ratios (4%, 8%, 12%, 16%, 20%, and 24% v/v). Mechanical testing revealed that tensile strength peaked at a 12% biofiber volume, increasing by 29.2 MPa. The highest impact and flexural strengths were observed at 16% biofiber, measuring 2621 J/m² and 41. 1 MPa, respectively. Dynamic mechanical analysis showed improved viscoelastic properties due to biofiber presence, and scanning electron microscopy provided insights into filler dispersion and bonding.

Nalini et al. [19] studied how Moringa oleifera gum biofiller affects the mechanical, viscoelastic, and biodegradable properties of epoxy-based composites. Epoxy resin was mixed with different amounts of the biofiller (4, 8, 12, 16, and 20 v/v%). Composite samples were made using the hand-layup technique. Results showed that the composites improved in mechanical strength and viscoelastic properties, particularly at 12% v/v of biofiller. Thermal analysis indicated increased thermal stability, and SEM images showed a good distribution of the biofiller at this volume, enhancing overall composite performance. Jagadeesh et al. [18] studied hybrid composites reinforced with *Pongamia pinnata* shell powder and observed that 2 wt% filler provided superior interlaminar shear and flexural strength, while 6 wt% improved hardness and flexural modulus. Additionally, the incorporation of 2.5 wt% basalt powder enhanced rigidity and thermal stability. Comparable improvements have also been reported with coffee bean powder as a bio filler. Aa et al. [20] demonstrated that the addition of natural hydroxyapatite (nHAp) significantly enhances epoxy composite properties. A 10% filler loading increased flexural strength by 77% and tripled the impact strength. Microstructural analyses confirmed uniform dispersion of nHAp particles, while FTIR results indicated increased phosphate group intensity within the composite matrix. Sathish et al. [21] developed hybrid epoxy composites reinforced with cellulose-based fibers such as jute, coir, and bamboo. Among the tested compositions, the JC8 composite (21% jute, 1.5% coir, and 7.5% bamboo) exhibited superior tensile, flexural, and thermal properties, primarily due to the high cellulose content of the reinforcing fibers. Overall, the literature clearly indicates that the incorporation of bio-based fillers significantly enhances the mechanical and thermal performance of epoxy composites. However, the effectiveness of reinforcement is strongly dependent on filler type, content, and dispersion within the matrix. Based on these findings, the present study focuses on the utilization of ***Aquillaria Agallocha*** gum powder waste as a bio filler to evaluate its influence on the mechanical properties of epoxy composites.

2.0 Materials And Methods

2.1 Materials

Epoxy resin (LY556) and a polyamine-based hardener (HY951) were utilized as the matrix system in this study. Aquillaria Agallocha powder, obtained from local traders in Kanchipuram, India, was used as the bio filler. Prior to fabrication, the powder was thoroughly dried and subjected to ball milling to achieve a particle size in the range of 10–25 μm. The density

of the processed Aquillaria Agallocha powder was determined to be 1.05 g/cm³. Composite specimens were fabricated using a hand layup technique followed by compression moulding. To evaluate the effect of bio filler loading on the mechanical, thermal, and biodegradable properties, composites were prepared with varying ***Aquillaria Agallocha*** gum powder content ranging from 5% to 25% by volume. Prior to layup, a releasing agent was applied to the inner surfaces of the mould to facilitate easy removal of the cured composites. The epoxy resin and hardener were mixed in a weight ratio of 10:1, and the required proportions of coffee bean powder and ***Aquillaria Agallocha*** gum were subsequently incorporated into the matrix. The mixture was manually stirred for approximately 15 minutes to ensure uniform dispersion of the fillers. The prepared mixture was then poured into a wooden mould and evenly spread using a brush to minimize void formation and ensure proper surface finish. The mould was subjected to compression and allowed to cure under ambient conditions. After complete curing, the composite laminates were removed from the mould and cut into standard test specimens in accordance with ASTM specifications to ensure uniformity during mechanical testing.

2.2 Testing Methods

The mechanical properties of the epoxy composite specimens were evaluated through tensile, flexural, and impact tests in accordance with ASTM standards. Tensile testing was carried out in accordance with ASTM D638 at a crosshead speed of 5 mm/min. Flexural properties were determined using a three-point bending test in accordance with ASTM D790, with a testing speed of 1.5 mm/min. Impact strength was measured using an Izod impact tester following ASTM D256 standards. For each test, five specimens were analyzed, and the average values were reported to ensure accuracy and reliability of the results.

Fractography Study

The morphological characteristics of the composite specimens were analyzed using scanning electron microscopy (SEM). The fractured surfaces were examined to evaluate the interfacial bonding between the bio filler and the epoxy matrix. SEM micrographs were obtained using a Hitachi S-3400N scanning electron microscope. Prior to analysis, the specimens were sectioned into thin slices and coated with a conductive carbon layer to enhance image quality. The observations were carried out at an accelerating voltage of 20 kV.

Viscoelastic behavioural study

Polymers act as solids at lower temperatures, with the elastic characteristics taking precedence, and they behave as liquids at higher temperatures, with the inner friction being the major force in absorbing the energy. Therefore, it is important to analyze the composite sample's rheological characteristics. Visco-elastic properties of the epoxy-Sal tree (*Shorea Robusta*) gum composite specimens were estimated by using Dynamic Mechanical Analysis (DMA), and it was carried out on SEIKO DMAI - DMSC 6100 equipment as per ASTM-D7028

Aquillaria Agallocha **gum-based epoxy composition**

Table 1. Composition of composite

Specimen ID	***Aquillaria Agallocha gum***	**Epoxy resin**
AA 05	5 % AA	+ 95% Epoxy
AA 10	10 % AA	+ 90% Epoxy
AA 15	15 % AA	+ 85% Epoxy
AA 20	20 % AA	+ 80% Epoxy
AA 25	25 % AA	+ 75% Epoxy

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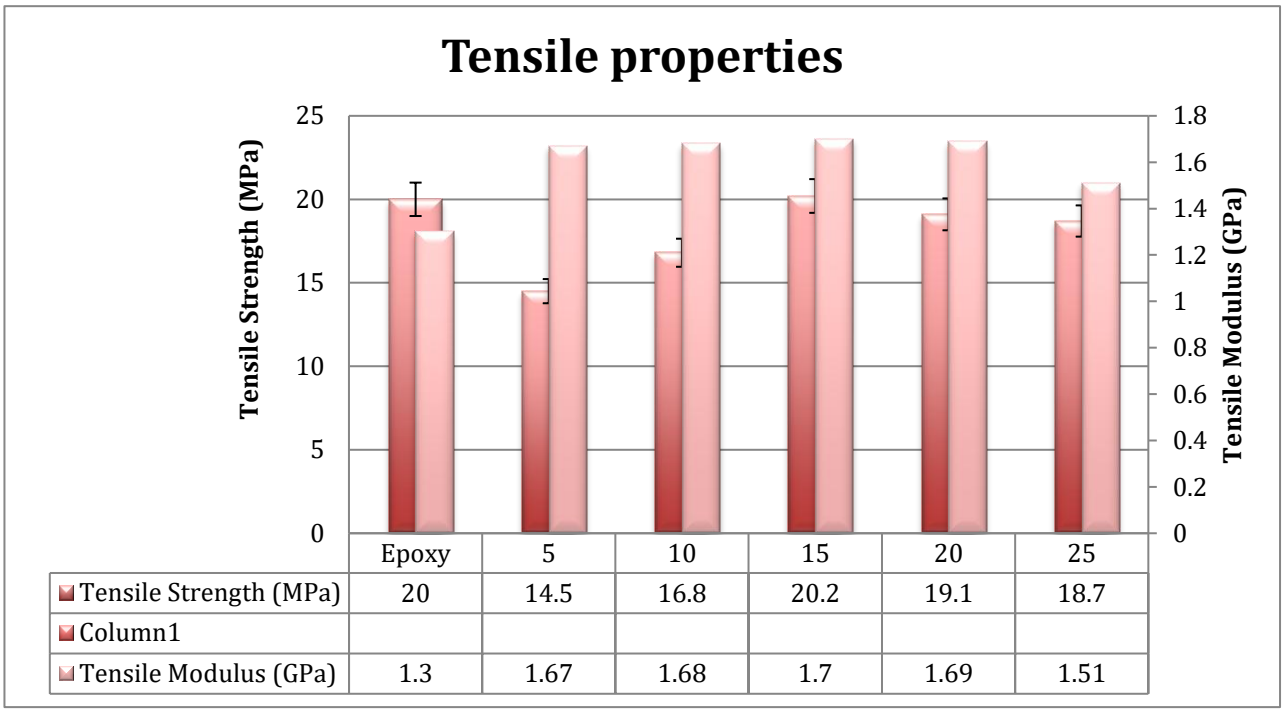
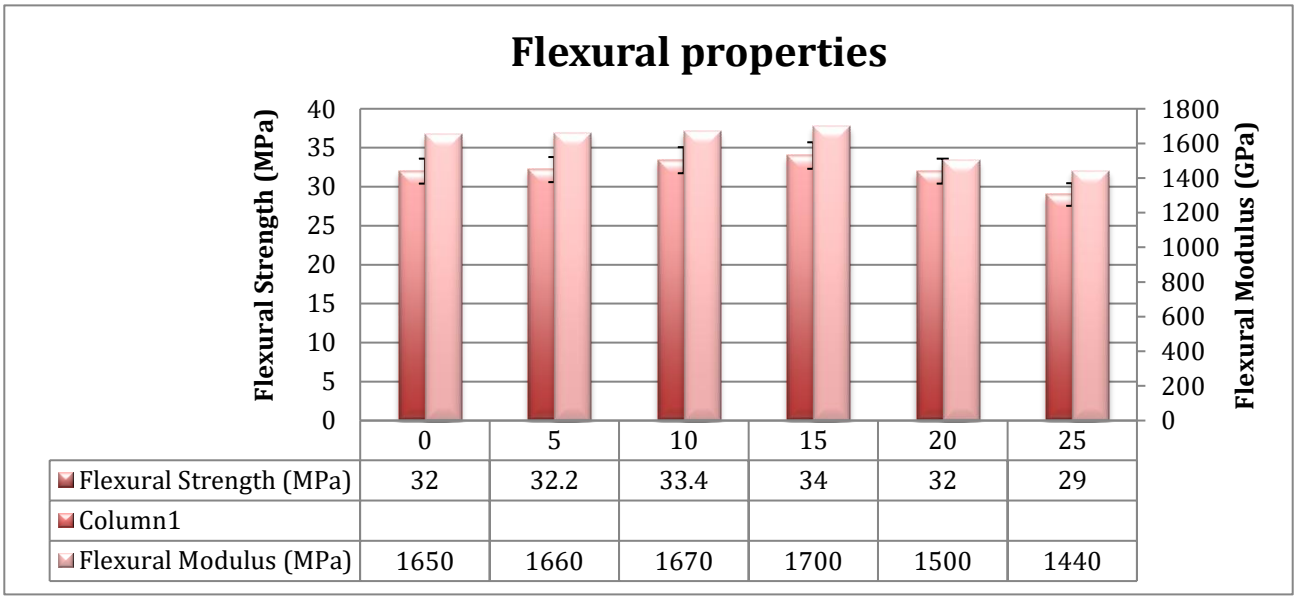
3.0 Results and Discussion



	Epoxy	5	10	15	20	25
Tensile Strength (MPa)	20	14.5	16.8	20.2	19.1	18.7
Column1						
Tensile Modulus (GPa)	1.3	1.67	1.68	1.7	1.69	1.51

Fig. 1: Effect of *Aquillaria agallocha* (AA) gum v/v% on the tensile strength of AA-Epoxy

3.1 Mechanical Properties



	0	5	10	15	20	25
Flexural Strength (MPa)	32	32.2	33.4	34	32	29
Column1						
Flexural Modulus (MPa)	1650	1660	1670	1700	1500	1440

Fig. 2: Effect of *Aquillaria agallocha* (AA) gum v/v% on the Flexural strength of AA-Epoxy composite.

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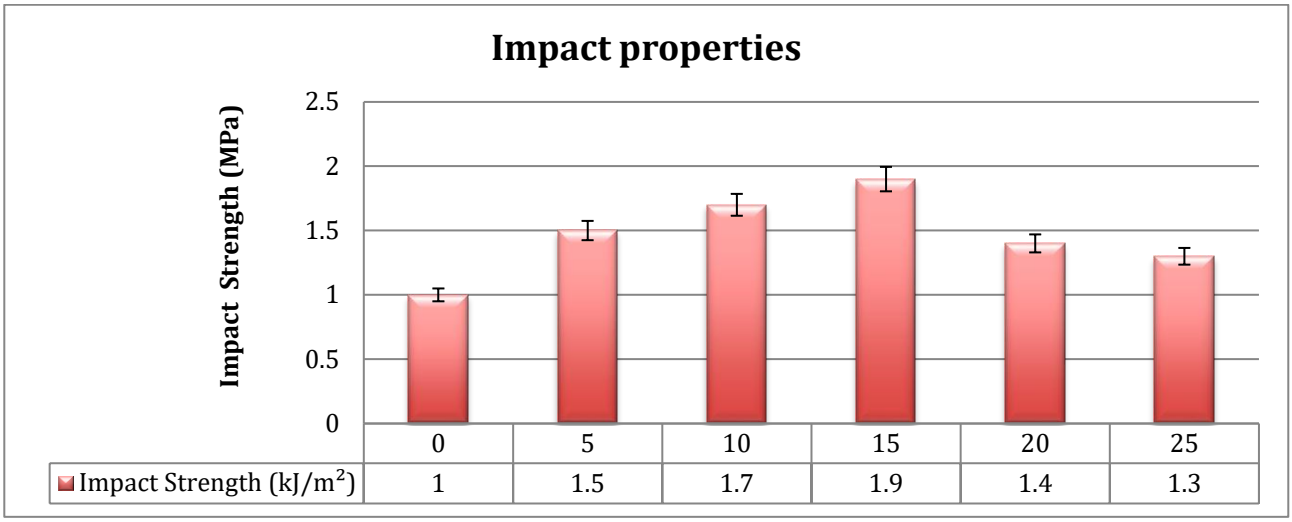

Fig.3: Effect of *Aquillaria agallocha (AA)* gum **v/v% on the Impact strength of AA-Epoxy composite.**

Figures 1–3 show the results of tensile, flexural, and impact tests on the epoxy composites. The stress–strain behavior clearly shows that the mechanical performance of the composites is strongly affected by the volume fraction of the bio filler. Figure 1 illustrates how tensile strength varies with the addition of Aquillaria agallocha (AA) gum bio filler. It is observed that tensile strength increases as the filler content rises, reaching a maximum of 20 MPa at 15% (v/v) loading. A similar pattern appears in the flexural and impact properties, where the composite with 15% (v/v) filler demonstrates better performance, with a flexural strength of 34 MPa and an impact strength of 1.7 J/m².

The tensile strength of pure epoxy is 20 MPa, and its tensile modulus is 1.3 GPa. The tensile strength decreases to 14.5 MPa with the addition of filler particles AA, possibly due to changes in interaction since the filler is hydrophilic and epoxy is hydrophobic. Consequently, the interfacial dispersion is poor, leading to inadequate interfacial bonding and interaction. Due to the low filler content in the matrix, localized agglomeration may occasionally occur, acting as stress concentrators and limiting load transfer. However, as the v/v% of filler in the epoxy matrix increases, the surface area also increases, enhancing the connection between the matrix and the filler and promoting interfacial attraction and adhesion. When the optimal concentration of 15 v/v% is reached, the composite achieves a maximum tensile strength of 20.2 MPa.

The ratio of tensile stress to tensile strain is the tensile modulus. The tensile modulus increases with the addition of 5 v/v % of filler because it only measures relative deformation within the material's elastic limit. Adding AA particles to the epoxy matrix boosts the modulus because it makes the material harder and less prone to deformation than epoxy alone, owing to the rigid nature of the AA filler. Thus, the tensile modulus increased from 1.3 GPa for pure epoxy to 1.67 GPa for epoxy reinforced with 5% v/v AA.

The amount of stress a substance can withstand before tearing, rupturing, breaking, or irreversibly bending is measured by its flexural strength. The composite's top surface experiences compression, while its bottom surface experiences tension. The flexural strength of pure epoxy increases from 32 MPa to 32.2 MPa, and the modulus increases from 1650 MPa to 1660 MPa when 5 v/v% of AA is added to the epoxy matrix. This occurs because flexural strength depends on the thickness of the material and the size of the sample, not on the effectiveness of the interfacial bonding. Due to the rigid nature of AA particles, the composite resists deformation, supports tensile tension, and withstands bending. Additionally, the AA particles act as barriers, preventing cracks from spreading, which enhances flexural strength. At an optimum 15 v/v %, the flexural strength and modulus reach 34 MPa and 1700 MPa. Impact strength measures a material's ability to resist cracking, breaking, or plastic deformation when faced with unexpected and severe impacts or shock loads. This key property affects how well the material withstands impulsive forces. Knowing these values is vital for designing parts exposed to high impact or shock loads and for predicting potential failures. Pure epoxy has an impact strength of 1.0 KJ/m²; adding 5 v/v% of filler increases this to 1.5 KJ/m² and reaches an optimum at 15 v/v% 1.9 KJ/ m² because impact resistance

depends on the energy absorbed during cracking, bending, or deformation and not on the nature of epoxy matrix interaction and adhesion. The observed trend is because even though pure epoxy is strong, cracks can propagate rapidly once developed, leading to sudden deformation. When filler is added, its rigid nature and interactions between the epoxy matrix and filler delay crack development, as the initial amount of filler fills voids and cracks, resulting in slower crack propagation. As cracks propagate under sudden stress, debonding occurs between the filler and matrix, followed by filler pullout. These multiple mechanisms—crack propagation, debonding, and pullout— increases the amount of energy absorbed ultimately leading to increased impact strength.

The improvement in mechanical properties at optimal filler loading can be attributed to effective stress transfer between the epoxy matrix and the dispersed biofiller particles. The presence of well-distributed filler enhances load-bearing capacity and restricts polymer chain mobility, thereby increasing stiffness and rigidity. This is further supported by the observed rise in tensile and flexural moduli, indicating improved resistance to deformation. However, beyond the optimal filler content (15% v/v), a decline in mechanical properties occurs. This decrease can be explained by poor interfacial bonding and agglomeration of filler particles at higher loadings. Excessive filler content results in insufficient wetting of the particles by the epoxy matrix, leading to weak interfacial adhesion and the formation of voids or defects. These imperfections act as stress concentration points, reducing the overall mechanical strength of the composite. Therefore, while adding AA bio filler enhances stiffness and mechanical performance up to a certain point, excessive filler leads to adverse effects due to inadequate matrix–filler interaction. These findings align with the study reported by Vieira et al. [22], where incorporating bio-based fillers like eggshell powder into green polyethylene composites improved mechanical, thermal, and rheological properties up to an optimal filler level. The chemical composition of the gum also plays a crucial role in enhancing the biocomposite's mechanical properties. Specifically, gum from Aquillaria agallocha contains chromones, sesquiterpenoids, fatty acids, and phenolic compounds. The phenolic -OH groups of Aquilaria agallocha can form hydrogen bonds with the epoxy groups in the resin and the gum, potentially increasing the crosslinking density between the two substances. Fatty acids in the AA gum can interact with the hardener's amino groups to create cross-linking structures, which may benefit thermal stability and mechanical strength. Due to its highly branched structure, AA gum may distribute more uniformly throughout the epoxy matrix, further improving overall properties. This study's conclusions support those previously published by Sridevi et al. (2024), who demonstrated that the best mechanical properties in an epoxy matrix were achieved when a supplementary bio-filler such as moringa gum was used because of the filler's chemical constituents a

3.2 Morphological analysis

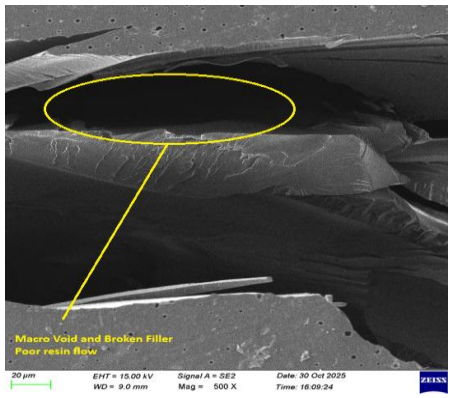

Fig.4: 20 % (AA) Weak interfacial interaction between the filler and matrix

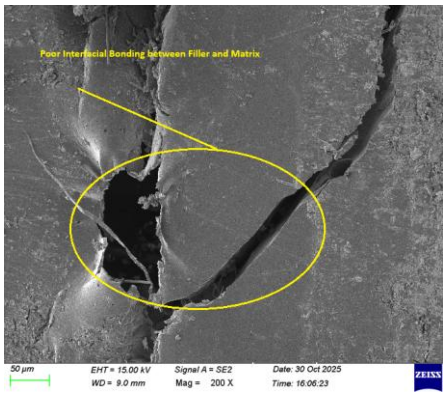

Fig.5: 25 % (AA) Poor adhesion at the filler–matrix interface results in ineffective stress transfer

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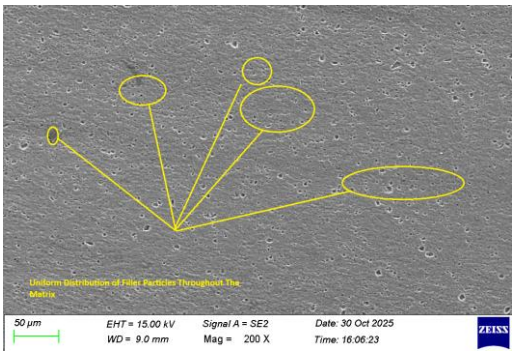

Fig.6: 15 % *Aquillaria Agallocha* (AA) gum **v/v% with Epoxy Strong interfacial bonding between the filler and matrix.**

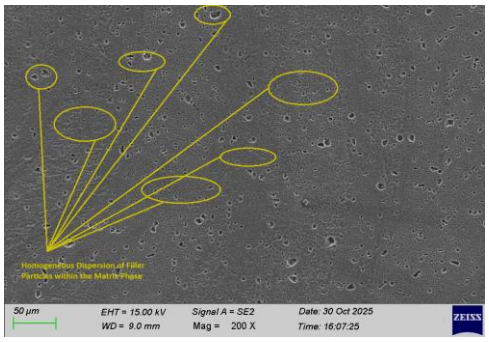

Fig.7: Enhanced interfacial bonding between filler and matrix minimises debonding and improves mechanical performance through efficient stress distribution

Fractographic analysis was conducted on typical fractured samples of AA-reinforced biocomposites to comprehend the failure mechanisms at the microstructural level. The distinct fracture patterns affected by varying filler compositions and interfacial bonding characteristics are displayed in the SEM images. The fractographic analysis of tensile fracture surfaces (Figures 4, 5, 6, 7) offered an important understanding of filler–matrix interfacial interactions and failure mechanisms across different filler loadings. With reduced filler content (approximately 15% v/v AA), the fracture surface looked relatively smooth and clean, suggesting weak interfacial adhesion between the hydrophilic AA particles and the hydrophobic epoxy matrix. The existence of significant voids and interfacial spaces indicates inadequate adhesion, resulting in ineffective stress transmission and subpar mechanical performance. Weak interactions between the filler and matrix lead to early debonding when loads are applied.At the optimal filler loading, the fracture morphology showed significantly improved interfacial characteristics. The surfaces displayed rough and irregular textures with shallow pull-out cavities and minimal gaps between filler and matrix. The presence of matrix residues adhering to filler particles indicates strong interfacial bonding. These features confirm effective mechanical interlocking and enhanced stress transfer across the interface. The rigid AA particles can sustain and transfer loads from the ductile epoxy matrix through mechanisms such as hydrogen bonding and mechanical anchoring, thereby enhancing the composite's overall mechanical properties. However, at higher filler loadings (above 25% v/v), the fracture surfaces revealed significant agglomeration of AA particles. Filler clusters created non-uniform regions with insufficient matrix coverage, leading to micro voids, interfacial gaps, and microcracks due to inadequate wetting of the filler by the epoxy matrix. These defects serve as stress concentration sites, ultimately causing crack initiation and rapid propagation, which result in premature and catastrophic failure of the composite. The findings are consistent with those of Hariram, S., Shankar et al., 2024, who reported that epoxy reinforced with Acacia catechu gum showed better uniform dispersion of filler particles at optimal loading, whereas voids, agglomeration, and poor interfacial interactions occurred at higher filler loadings.

3.4 Biodegradability Evaluation.

In a simulated soil environment at room temperature, specimens of the epoxy/AA composite were exposed for 120 days to evaluate its biodegradability. It should be noted that there was a significant increase in weight after 20 days; the 15%(v/v) epoxy/AA showed a weight gain of 5.2%, while the 25%(v/v) epoxy/AA showed a 2.8% weight gain. The initial weight increase is attributed to water absorption through diffusion, which penetrates the polymer matrix. AA gum has hydrophilic properties because it is composed of phenolic compounds like tannin and sesquiterpenoids, making it easier for moisture to penetrate the composite. Water molecules tend to accumulate at the filler-matrix interface by moving through micro gaps and interfacial spaces. This creates moisture content gradients influenced by hydrophilic AA particles. However, after 40

days, there was a steady decrease in the weight of the samples: the 15% (v/v) epoxy/AA exhibited a weight loss from -3.5% to -18.0%, and the 25% (v/v) epoxy/AA showed a decrease from -0.2% to -19.5% over 120 days. This weight reduction results from hydrolysis of bonds between the coating and filler surface, leading to degradation of the filler/matrix adhesion and a decline in the composite's mechanical properties. The findings are consistent with those of (Saba et al, 2016,Polymers), who reported a two-stage soil degradation behavior of epoxy filler composites. Thus, in 15%(v/v) epoxy/AA, the onset of degradation is faster, but in 25%(v/v) epoxy/AA, it is delayed yet more intense. Overall, both exhibit favourable degradation behaviour.

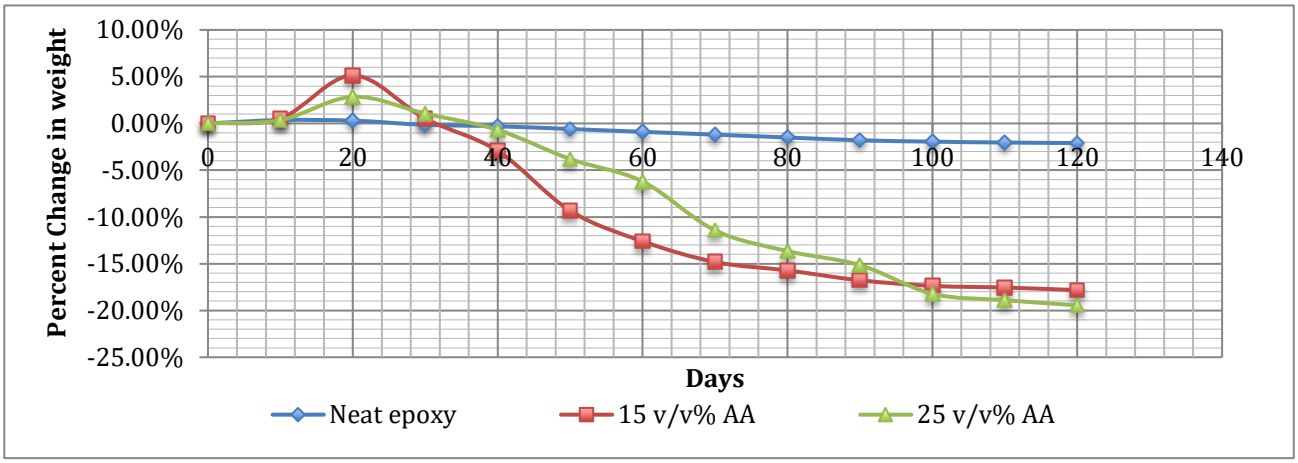

Fig.8: Biodegradability Evaluation *Aquillaria agallocha (AA)gum* v/v% -Epoxy composite.

After 120 days, the visual inspection showed that the surface was deteriorating, changing colour, and cracking. The results align with various degradation mechanisms, indicating that surface erosion is more common than bulk hydrolysis in typical soil conditions. The improved biodegradability of AA-reinforced epoxy composites demonstrates that they are more environmentally friendly because they can be broken down in a controlled way at the end of their lifespan.

3.5 Water Absorption Behaviour

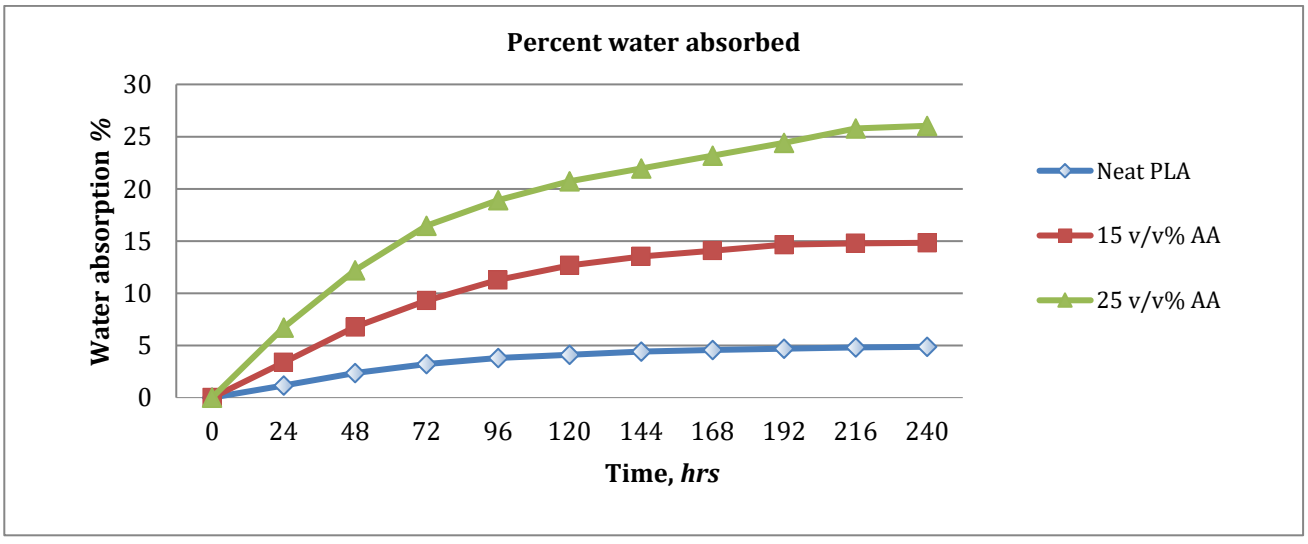

Fig: 9 water absorption Evaluation *Aquillaria agallocha (AA)* v/v% -Epoxy composite

The moisture absorption behavior of natural filler composites needs to be studied to understand their durability based on usage. Water molecules typically enter natural filler composites through three different mechanisms: diffusion of moisture within micro-gaps between polymer chains; capillary transport into these micro-gaps; and flaws at the interfaces between the fibers and the matrix. The filler absorbs most of the moisture through hydrogen bonding, and the interface between the filler and the matrix also takes up a significant amount of moisture.As shown in Fig. 9, the graph uses time (hours) as the independent variable to show the percentage of water absorption. The results confirm that a composite's water absorption rate increases with higher natural filler content. The percentage of water absorbed rises with immersion time and stabilizes after ten days.

The water absorption behavior of *Aquillaria agallocha* (AA) gum reinforced epoxy composites is heavily influenced by the natural hydrophilicity of the filler. A strong correlation was observed between filler loading and moisture uptake. The composite containing 15% (v/v) AA showed a moisture absorption of 3. 3.3% after 24 hours of immersion, which is significantly higher than that of neat epoxy (less than 1. 17%). Over time, the absorption increased and reached a saturation level of 14. 7% after roughly 216 hours. For 25% (v/v) AA reinforced epoxy resin, moisture absorption was 6. 7% after 24 hours of immersion, still notably higher than neat epoxy and 15% (v/v) AA. With prolonged exposure, the absorption rose, reaching a maximum of 25. 14.7% after approximately 216 hours. Since the matrix content is higher at lower filler volume percentages, composites with 15%(v/v) AA exhibited less water absorption. This is because the hydrophobic nature of the matrix prevents water molecules from interacting with the fiber component. As the filler content increases, hygroscopicity also increases. This strong hygroscopic behavior largely results from hydroxyl (–OH) functional groups present in AA. These polar groups easily form hydrogen bonds with water molecules, enhancing moisture uptake. Water enters the composite through multiple transport mechanisms, including (i) diffusion through micro voids in the polymer matrix, (ii) capillary action via interfacial gaps and microcracks, and (iii) penetration through existing structural defects. Moisture exists in two forms: bound water and free water. Bound water is linked through hydrogen bonds between water molecules and the polar functional groups of the AA filler and epoxy matrix, whereas free water accumulates in voids, microcracks, and interfacial regions. Water absorption by hydrophilic AA particles causes swelling, which induces internal stresses at the filler–matrix interface. These approaches improve interfacial bonding and reduce moisture sensitivity, increasing the suitability of the composites for use in humid or aqueous environments.The results align with the moisture absorption behavior observed in woven hybrid composites, where a similar trend was noted. The findings also agree with Abdul Khalil, H. P. S., Jawaid, M., and Abu Bakar, A. (2011), who reported that woven hybrid composites absorb water through these three mechanisms, with water absorption increasing as filler content rises up to an optimal level.

3.6 Dynamic Mechanical Analysis

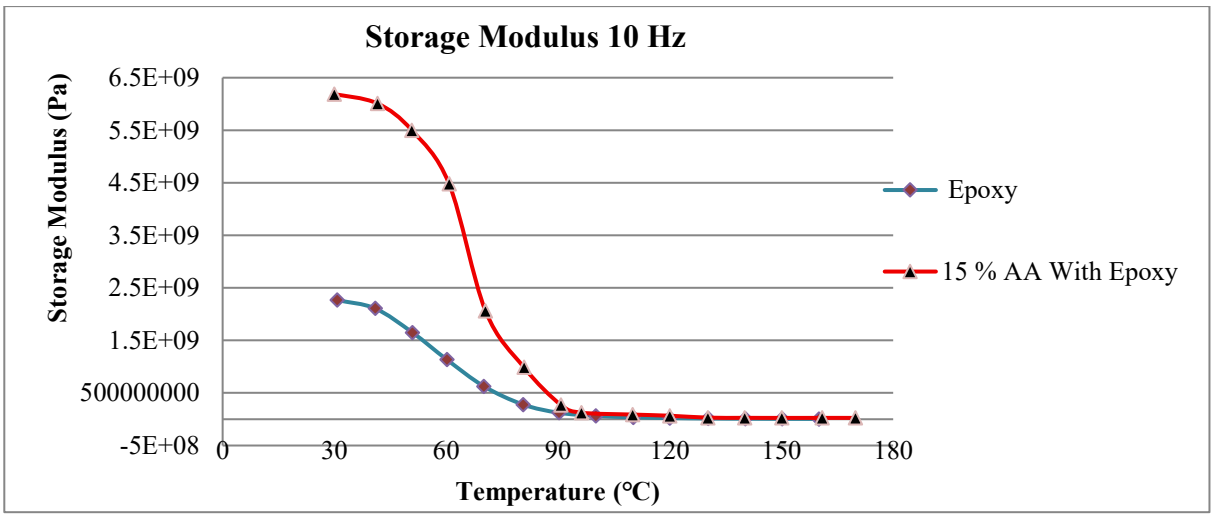

Fig.10: DMA analysis of Evaluation the *Aquillaria agallocha (AA)* v/v% -Epoxycomposite

It is widely employed to characterize the viscoelastic behaviour of composite materials through key parameters such as storage modulus (E′), loss modulus (E″), damping factor (tan δ), and glass transition temperature (Tg). The plots showed that adding 15 v/v % of AA gum increased the storage modulus of the composite to 6.18 $\times 10^9$, compared to 2.2 $\times$ 10^9 for the neat resin. This improvement is because the filler enhances stiffness and rigidity through better adhesion between the matrix and filler, which is due to the hydrophilic and hydrophobic properties of the filler and epoxy. When the temperature rises from 30°C to 60°C (in the glassy region), the storage modulus decreases to 4.4 $\times$ 10^9 for the composite and 1.13 $\times$ 10^9 for the neat epoxy. This occurs because increasing temperature boosts kinetic energy, leading to the breaking of weak forces like hydrogen bonds and Van der Waals forces, which causes the C-C bonds in epoxy to move. Consequently, the stiffness and rigidity lessen, resulting in the observed decline in storage modulus.

As the temperature rises from 50°C to 80°C, the epoxy exhibits a sharp decrease in storage modulus from 1.65 x 10^9 to 2.80 x 10^8, and the composite's storage modulus drops from 4.47 x 10^9 to 2.7 x 10^8. This is known as the transition region Tg, which indicates the viscoelastic behaviour of the system. In the composite, the Tg shifts to a higher temperature, implying improved matrix-filler adhesion that enhances the stiffness of the composite material. The results also conflict with the SEM observations showing a uniform, homogeneous distribution of filler particles in the epoxy matrix, resulting in good interfacial bonding, strong adhesion, and increased stiffness within both the matrix and the filler. As the temperature rises above 100°C, the kinetic energy increases, leading to the breaking of weak bonds and causing flexibility in the polymer chains. Even then, the storage modulus remains consistent and within acceptable ranges, indicating a good crosslinking density between the epoxy and the matrix.

Loss Modulas (E'')

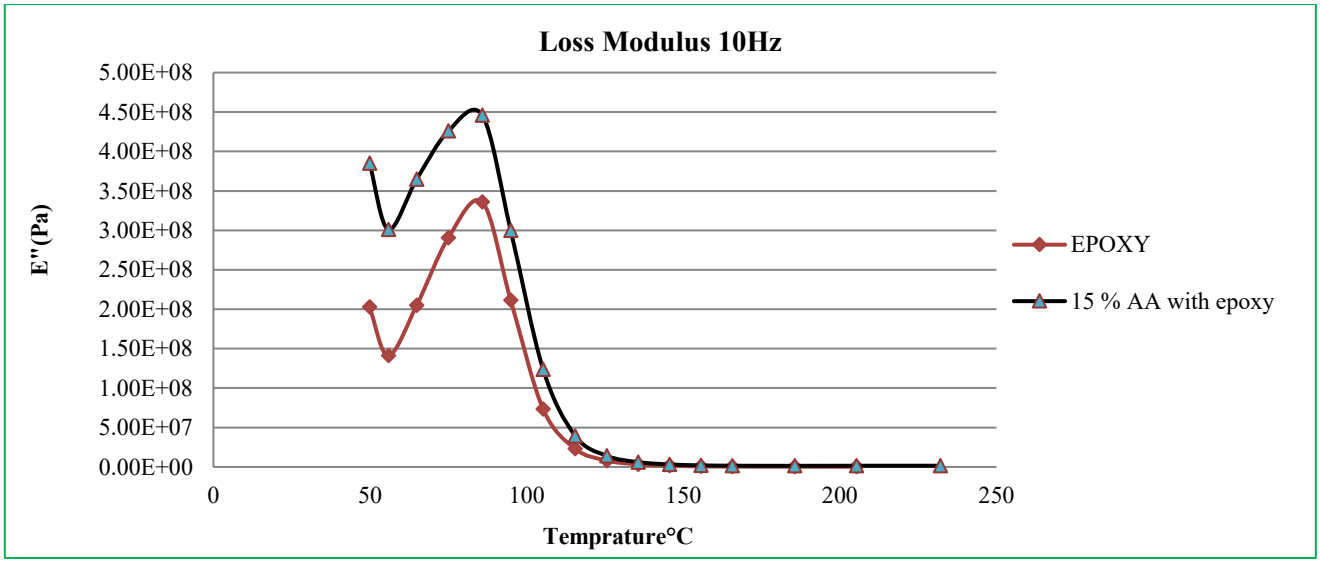

Fig.11: Loss modulus analysis of Evaluation the *Aquillaria agallocha (AA)* v/v% -Epoxy composite

The DMA curves of Loss modulus E" against temperature for neat epoxy and epoxy reinforced with AA gum are shown in Figure 11. The loss modulus graph follows a similar trend to the E' plot, indicating that the addition of AA particles in bio-epoxy/AA enhances the loss modulus. Figure 12 shows a decrease in the height of the "E" peak for neat epoxy but an increase in the amount of AA in the epoxy matrix. The E" peak values increase. From the graph, it is clear that at all temperatures, the E' value is higher for the composite than for neat epoxy. For both neat epoxy (E" - 3.35 x 10^8) and the composite (4.45 x 10^8), the E" peaks around 85°C-90°C, indicating the glass transition region, which is broader for the composite than for the epoxy. After 100°C, both show a decrease in E" values: 2.29 x 10^7 for the epoxy and 3.57 x 10^7 for the composite, indicating the transition from the glass transition state to the rubbery state. Interestingly, higher E" peak heights were observed for epoxy/AA, because as the filler is introduced into the epoxy matrix, interfaces develop, suggesting greater diffusion and no obvious agglomeration in the bio-epoxy matrix. During deformation, friction occurs,

and more energy is dissipated. Similar trends and findings have been reported by other researchers (Khan et al. 2022; Uppin et al. 2022).

The ratio of the loss modulus (E″) to the storage modulus (E′) is known as the damping factor, which is represented by the symbol tan δ. The link between temperature and damping coefficients is shown in Figures 11 and 12. As the temperature approaches the glass transition temperature (Tg), the damping factor increases from approximately 0.08 at 40°C to a maximum of about 0.75 at ~80°C for neat epoxy, and from 0.07 at 40°C to around 0.52 at ~85–90°C for the 15% AA composite, reaching a higher value at Tg. After that, it reduces in the viscous area, where the tan δ value decreases sharply for epoxy from 0.75 to nearly 0.02 beyond 120°C, whereas for the composite it decreases more gradually from 0.52 to about 0.08 up to 160°C. This is because the static molecules and tiny groups within the epoxy structure become more mobile as the temperature increases.

The damping factor value for clean epoxy was the highest (peak ≈ 0.75), suggesting greater molecular mobility. Furthermore, the inclusion of the filler material caused a reduction in the peak value of the tan δ (reduced to ≈ 0.52), as seen in Figs. 10 and 11. This could be because the filler material and epoxy matrix have better interfacial adhesion. It was also found that the composite material's glass transition temperature rose upon the inclusion of gum from AA, shifting from approximately 80°C (epoxy) to around 85–90°C (composite).

The width of the tan δ peak for neat epoxy is relatively sharp and narrow (approximately 70–95°C range), indicating a uniform and homogeneous polymer structure with rapid transition. In contrast, the composite exhibits a broader peak (about

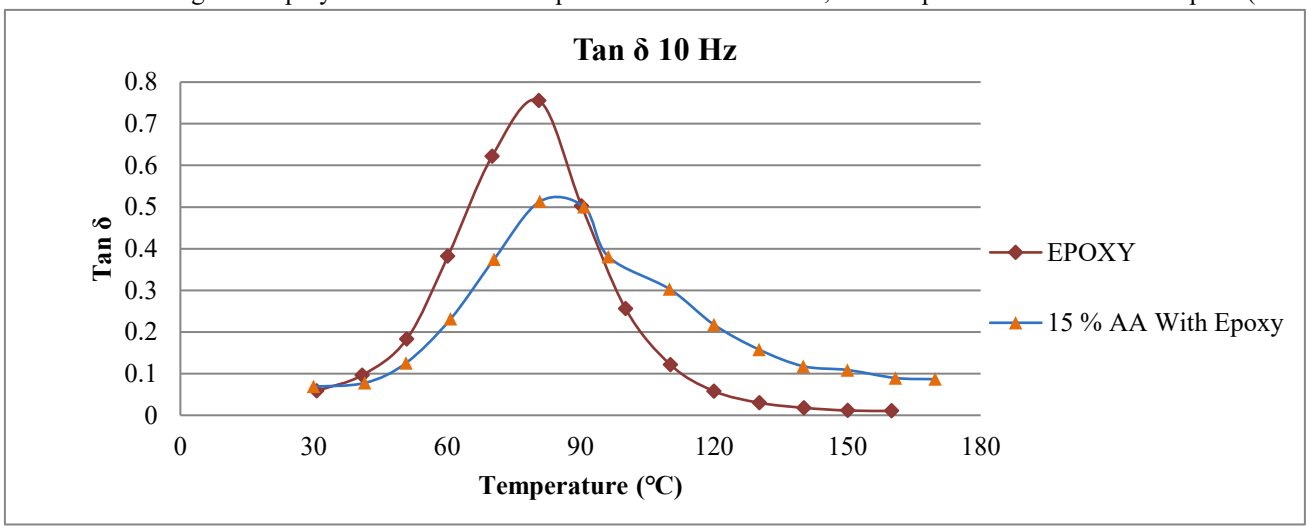

Fig:12 Tan δ analysis of Evaluation the *Aquillaria agallocha (AA)* v/v% -Epoxy composite

65–120°C range), which reflects a wider relaxation time distribution due to the presence of filler particles and interfacial regions. This broader peak indicates increased damping over a wider temperature range and suggests a heterogeneous microstructure with multiple relaxation mechanisms.

Thus, in the AA–epoxy system, the addition of Aquillaria agallocha (AA) particles into the epoxy matrix leads to a moderate enhancement in stiffness, as evidenced by a slight increase in the storage modulus. However, the presence of weak interfacial bonding and possible filler agglomeration results in elevated loss modulus and a broader tan δ peak, indicating increased energy dissipation and damping characteristics over a wider temperature range. The improvement in glass transition temperature is also relatively limited.

Compared to other variants, the optimized AA composite, especially at 15% filler loading, shows significantly better DMA performance. An important rise in storage modulus from 2.2×10^9 Pa (neat epoxy) to 6.18×10^9 Pa (15% AA composite) in the glassy region (~30°C) indicates increased stiffness and load-bearing ability. The loss modulus is better controlled, with

peak values of 3.35 × 10^8 Pa for epoxy and 4.45 × 10^8 Pa for the composite around 85–90°C, and the lower tan δ peak (reduced from ~0.75 for epoxy to ~0.52 for the composite) suggests decreased damping and a stronger elastic response. Additionally, the shift of the glass transition temperature to higher values, from approximately 80°C for neat epoxy to about 85–90°C for the 15% AA composite, indicates improved thermal stability.

The improved performance of the 15% AA composite results from uniform filler dispersion, strong interfacial bonding, reduced void content, and effective stress transfer between the filler and matrix, as also evidenced by the higher storage modulus retention (4.47 × 10^9 Pa for composite vs 1.65 × 10^9 Pa for epoxy near Tg region). The results align well with the findings of R. Senthilkumar, M.P. Natarajan et al. (2021), who reported that adding sal tree gum to the epoxy matrix enhanced the viscoelastic behavior of the biocomposite at optimal filler loading. In general, the enhanced AA-epoxy composite has a lot of promise for use in sustainable engineering

Cole -Cole plot:

The Cole–Cole plot, also known as a complex plane or Nyquist plot, offers insight into the viscoelastic and relaxation behaviour of composite materials by illustrating the relationship between the storage modulus (E′) and loss modulus (E″). In the AA–epoxy system, the Cole–Cole plot usually shows a broader and more irregular semicircular arc, indicating non-uniform relaxation behavior, with storage modulus (E′) ranging approximately from 0 to 2.2 × 10^9 Pa and loss modulus (E″) increasing up to around 3.5 × 10^8 Pa for neat epoxy. This variation is linked to weak interfacial bonding and potential agglomeration of *Aquillaria agallocha* (AA) gum particles within the epoxy matrix. The larger spread in the plot corresponds to higher energy dissipation, consistent with the increased loss modulus (~3.35 × 10^8 Pa) and higher tan δ (~0.75) seen in DMA results. Such behavior reflects poor stress transfer and a heterogeneous microstructure. Additionally, the irregular arc shape indicates multiple relaxation times due to non-uniform filler dispersion and interfacial defects.

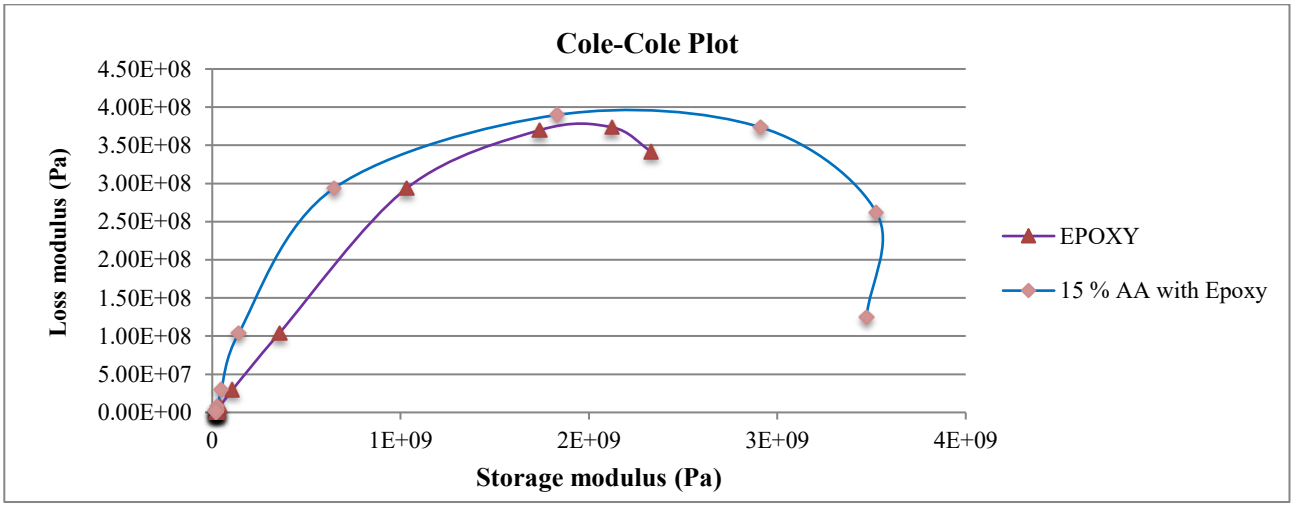

Fig.13:Cole-Cole plot in Evaluation the *Aquillaria agallocha (AA)* v/v% -Epoxy composite

In contrast, the optimized AA composite, especially at 15% filler loading, exhibits a more defined and nearly ideal semi-circular Cole–Cole plot, with storage modulus extending up to ~3.8 × 10^9 Pa and loss modulus reaching approximately 4.0 × 10^8 Pa. This reflects a more uniform and homogeneous structure with consistent relaxation behavior. The smaller arc radius and better symmetry indicate lower damping (tan δ reduced to ~0.52) and less energy loss, as seen in DMA analysis. These improved plot features confirm stronger interfacial bonding, even filler distribution, and fewer voids, resulting in better stress transfer and mechanical performance. The smoother semicircular arc also suggests a single dominant relaxation mechanism, indicating improved compatibility between filler and matrix. Therefore, the Cole–Cole plot supports the DMA results by showing improved viscoelastic behavior in the optimized AA composite.

Conclusion

The current study shows that the mechanical, viscoelastic, biological, and environmental behavior of epoxy composites are greatly influenced by the incorporation of Aquillaria agallocha (AA) bio filler to the epoxy matrix. According to the findings, the ideal filler loading is 15 v/v% AA, which offers the greatest balance of mechanical characteristics. Compared to 20 MPa and 1.3 GPa for pure epoxy, the composite displayed a tensile strength of 20.2 MPa and a tensile modulus of 1.7 GPa at this composition. Similarly, the flexural strength increased to 34 MPa, with a modulus of 1700 MPa, suggesting greater stiffness and load-bearing capacity. The impact strength increased by almost twofold, from 1.0 to 1.9 kJ/m^2, demonstrating improved toughness as a result of multiple mechanisms operating, like late crack propagation, debonding of the filler from the epoxy matrix, followed by filler pull-out. As the concentration of AA increased above the optimal 15 v/v%, there is a reduction in mechanical properties. SEM analysis also revealed a decline in mechanical performance due to filler agglomeration, inadequate wetting, and poor interfacial adhesion as the filler concentration increased beyond the optimum. These results were further supported by dynamic mechanical analysis, which revealed a change in the glass transition temperature and an increase in the storage modulus from 2.2×10^9 to 6.18×10^9 Pa, suggesting enhanced thermal stability and rigidity at the ideal load. Furthermore, the composites exhibited high moisture absorption (up to 26%) and considerable biodegradability (about 17.8% weight loss), indicating their hydrophilic nature.

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