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Flexural and Thermo-Mechanical Properties Assessment of Nano-Silica BFRPC and GFRPC

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Abstract

Composite material is a high-performance material widely used in various applications, such as lorry boxes, due to their lightweight, high-strength properties, high chemical resistance and thermal stability. This study aims to evaluate the effect of Silane Treated Nano Silica (NS) inclusion on flexural behaviour and Dynamic Mechanical Analysis (DMA) properties of Glass/Basalt Fibre Reinforced Polymer (G/BFRP). Twelve composite systems were designed and fabricated using hand lay-up and vacuum silicon mould. Woven Basalt and Woven Glass Fibre were used as reinforcement materials. The polyester was modified with 1, 3, and 5 wt.% of Silane Treated Nano Silica (NS) using a mechanical stirrer before composites samples were fabricated. The samples size of 80 x 13 x 5 mm for the flexural test and 40 x 10 x 5 mm for DMA were prepared and tested according to ASTM D790 and ASTM D5023-15. The results showed that adding NS as a filler in BFRP and GFRP enhanced the flexural and DMA behaviour. The highest flexural strength was found in 1wt%NS-BFRPC, with a value of 286.86 MPa. The GFRPC system tends to have slightly higher damping factors than the BFRC system. This indicates that the GFRPC system has a slightly higher ability to absorb energy and damping behaviour. This information can be valuable for designing composite materials for high-stiffness and strength applications.

1. Introduction

Natural fibre composite (NFC) research and innovation have recently expanded quickly. The advantages of these materials over others, such as synthetic fibre composites, are low environmental impact, low cost, and support for their potential in a wide range of applications, which warrant investigation. It has taken significant effort to increase their mechanical performance to broaden the possible applications for this class of materials [1].

Furthermore, the popularity of natural fibre composites has grown across various industrial sectors due to technological advancements and greater environmental awareness. It is being promoted by using composite materials that maintain the environment's sustainability and replace synthetic materials that are becoming increasingly extinct. The number of publications connected to biocomposite research is increasing yearly, showing that many researchers are interested in this area [2]. For that reason, this study was carried out to identify exceptional properties, such as great mechanical strength, high chemical resistance, thermal stability, operating temperature range, non-flammable characteristics, good bonding with resin, and environmental friendliness, which will be compared by two fibre materials, namely Basalt fibre and Glass Fibre, which will be modified with Nano-silica to improve mechanical and thermal performance and Polyester resin.

The heavy reliance on synthetic materials in the industrial market poses a significant risk to future stability and the ability to meet human needs, leading to environmental degradation, supply chain vulnerabilities, and limited innovation [3]. Without diversifying materials and promoting sustainable alternatives, industries and medical sectors face the challenge of compromising long-term sustainability and resilience while potentially exposing human health to risks associated with the overuse of synthetic materials. Excess synthetic materials in production need fresh research in composite materials with natural elements[4]–[6]. Rapid technological advancement necessitates environmental preservation. Everyone is aware of natural disasters and climate change. Next, relying on a single material in manufacturing may result in shortages. This decline will significantly impact human civilisation and the biological environment unless substitute minerals are discovered.

Nanocomposites are materials that incorporate nanoparticles within a polymer, metal, or ceramic matrix. The presence of nanofiller in the composite has dramatically increased the material's properties, such as mechanical strength, toughness, and electrical or thermal conductivity. Adding a small amount of nanofiller, typically between 0.5 and 5% by weight, drastically alters the characteristics of the virgin material. Traditional micro-sized fillers can improve mechanical properties and wear resistance while minimising failure strain or plastic deformation in polymer composites. In contrast, nano-sized fillers can do the same without affecting other properties like toughness and strength [7].

Fibreglass is a lightweight, robust, and durable material that is employed in a variety of industries due to its remarkable features. Glass fibres are the most used reinforcing material for plastics due to their low cost (in comparison to aramid and carbon), and excellent mechanical properties [8]. Glass fibre has shown significant global expansion as the primary reinforcement in the market for fibre-reinforced polymer composites. Glass fibre materials are used in more than 95% of the fibre reinforcements used in the composites industry today, owing to their exceptionally favourable performance to price ratio. Glass fibres are created by combining extrusion and attenuation of molten glass [9].

Natural basalt is a material that is good for the environment. Basalt rock is used in the production of basalt fibres (BFs). Basalt was spontaneously transformed into high-performance inorganic fibres of one type, known as BF. BF is a "green industrial material" in this context. BF is dubbed the "green, non-polluting substance of the twenty-first century." Basalt rock is abundantly available and well-known for its strength, durability, and safety. Because recycling is much more effective with BFs than glass fibres [10], so they are more environmentally friendly.

This research aims to compare the performance of BFRP and GFRP with the presence of Silane Treated Nano Silica (NS). The samples for these two systems were prepared by stacking 14 plies fibres using hand layup method. The samples were fabricated using polyester resin as the polymer matrix. In addition, three different weight percent, i.e., 1, 3, and 5, were used to evaluate the optimum NS content in the composite samples. Next, the mechanical and physical testing were conducted in accordance to ASTM Standards, i.e., Flexural test based on ASTM D790 and Dynamic Mechanical Analysis using ASTM D7028.

2. Material and Methodology

Carbon Tech Global Sdn supplied polyester resin and Hardener M60 Butanox. Meanwhile, woven glass fibre and basalt fibre were supplied by Innovative Poltrusion Sdn Bhd. Nano silica was extracted using the sol-gel process from granite dust supplied by JKR Malaysia. Each fibre requires 14 plies for four systems or plates of nano silica-modified BFRP composites and four systems or plates of nano silica-modified GFRP composites. A 300mm x 300mm fibre laminate was fabricated in the first place and cut to the required dimension, according to the related testing. Each plate comprised 14 layers of either glass or basalt fibres, resulting in an average thickness of 5 mm. FRP (GFRP and BFRP) plies were prepared using woven fabric with 300mm x 300mm dimensions. Nano silica and Polyester Resin (PE) were combined in a plastic cup. Then, the mixture was stirred for up to 120 minutes in a vacuum chamber to achieve a more even consistency. The hardener was weighed according to the weight ratio of the FRP and mixture, 100:2. After stirring, the hardener was incorporated into the mixture. The FRP ply was laid on the laminated plastic, and the liquid was poured. Alternately, laying up and pouring were performed for 14 plies for a whole plate. The vacuum silicone mould was turned on to remove bubbles from the plates. The plates were left for approximately 40 to 60 minutes. The sample plates were removed from the vacuum silicone mould, placed in a safe location, and left to cure.

2.1 Flexural Test

Flexural testing, one of the oldest and most widely used methods for assessing the strength of brittle materials, was traditionally a low-cost, simple, and versatile approach for determining a material's quality and strength. Most flexure testing was performed by materials scientists and processors interested in characterisation issues [10]. This study performed the flexural test following the ASTMD790 (Third Point Loading) standard. The flexural test aimed to establish the material's resistance to flexing or stiffness by measuring the force required to bend a material beam.

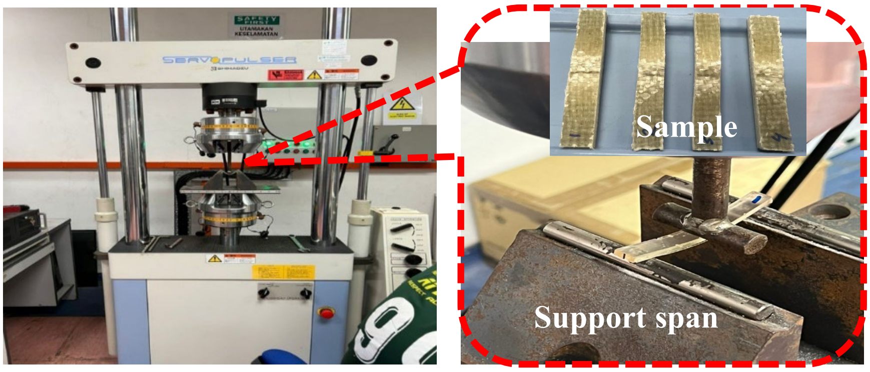


Fig. 1 *Flexural testing*

2.2 Dynamic Mechanical Analysis (DMA)

DMA (Dynamic Mechanical Analysis) was a versatile approach that augmented the data offered by more traditional thermal analysis techniques. Temperature-dependent dynamic characteristics, such as storage modulus (E'), loss modulus (E''), and damping factor (Tan δ), provided information on the interfacial bonding between the reinforced fibre and the polymer matrix of the composite material. The ASTM D7028 Dynamic Mechanical Analysis (DMA) test was performed in this study. Dynamic mechanical analysis improved the detection of phase transitions and relaxation processes in various materials. It was a technique used to calculate the solid-state rheological properties of viscoelastic materials as a function of frequency and temperature [11].

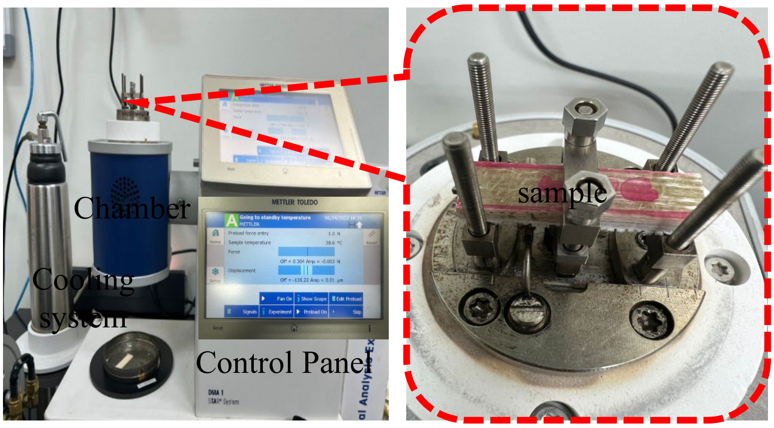


Fig. 2 *Dynamic mechanical analysis testing*

3. Results and Discussions

The outcomes represent the average measurements from five tested samples for each category of composite laminate. The variation in these samples lies in the proportion of nano silica incorporated into the resin before the pouring phase in the hand lay-up fabrication procedure. The investigation focused on assessing the flexural strength and dynamic mechanical analysis characteristics of BFRC and GFRC.

3.1 Effect of Nano-Silica on Flexural Properties of Basalt Fibre Reinforced Polymer Composites (BFRPC) and Glass Fibre Reinforced Polymer Composites (GFRPC)

Figures 3 and 4 show the resulting stress (MPa) and strain (MPa) from 2 systems: basalt fibre-reinforced polymer composite, BFRPC and glass fibre-reinforced polymer composite and GFRPC. As we can see, the highest strength at 286.86 MPa with 1wt%NS-BFRPC. Starting at 0wt%NS-BFRPC with a value of 244.20 MPa, then increasing by 17.46% percentage to 1wt%NS-BFRPC with a value of 286.86 MPa. Then, the value decreases to 268.79MPa and decreases again to 258.07 MPa. Meanwhile, for GFRPC, the highest flexural strength we found from Figure 3 in 1wt%NS-BFRPC with a value of 249. 19MPa.The value starts at 223.64 MPa with 0wt% of nano silica and then increases to 249.19MPa with an increment of 11.42%. then it decreases to 238.03MPa then to 224.03MPa.

The data indicates that adding nano silica generally improves the stiffness (Young's modulus) and strength (ultimate flexural strength) of the BFRC and GFRC. The consistent strain at fracture across different nano silica content levels suggests that while adding nano silica enhances stiffness and strength, it doesn't compromise the material's ability to undergo deformation before fracturing. The observed trends align with the expected effects of reinforcing materials with nano silica, which can enhance the composite's mechanical properties due to the reinforcing effects of the nanoparticles [11].

As the weight percentage of nano silica increases in BFRPC, the modulus of elasticity (E) tends to increase. This indicates that higher nano silica content leads to stiffer composite materials. The ultimate flexural strength (UFS) also tends to increase with higher weight percentages of nano silica [12]. This suggests that incorporating nano silica enhances the strength of BFRPC. The strain at fracture remains relatively constant across different weight percentages of nano silica in BFRPC. This implies that adding nano silica doesn't significantly affect the material's ductility or ability to deform before fracturing [13].

Like BFRPC, the modulus of elasticity (E) tends to increase as the weight percentage of nano silica increases in GFRPC. This indicates that higher nano silica content leads to stiffer composite materials [14]. The ultimate flexural strength (UFS) shows a slight increase with higher weight percentages of nano silica in GFRPC. This suggests that nano silica incorporation enhances the strength of GFRPC. Interestingly, the strain at fracture increases with higher nano silica content in GFRPC. Adding nano silica can lead to a slightly more ductile behaviour in GFRPC [15].

BFRPC and GFRPC show similar trends in response to the addition of nano silica. Higher weight percentages of nano silica generally lead to increased stiffness (modulus of elasticity) and enhanced strength (ultimate flexural strength) in both systems. The strain at fracture remains relatively consistent or slightly increases with higher nano silica content in both systems, suggesting that ductility is not significantly compromised [16]. The exact effects of nano silica on the mechanical properties can vary slightly between the two polymer composites, likely due to the unique properties of basalt and glass fibres and the interactions between nano silica and the polymer matrices [17]. Incorporating nano silica into BFRPC and GFRPC generally improves their stiffness and strength without significantly compromising ductility. These findings can help design composite materials with enhanced mechanical properties for various engineering applications [18].

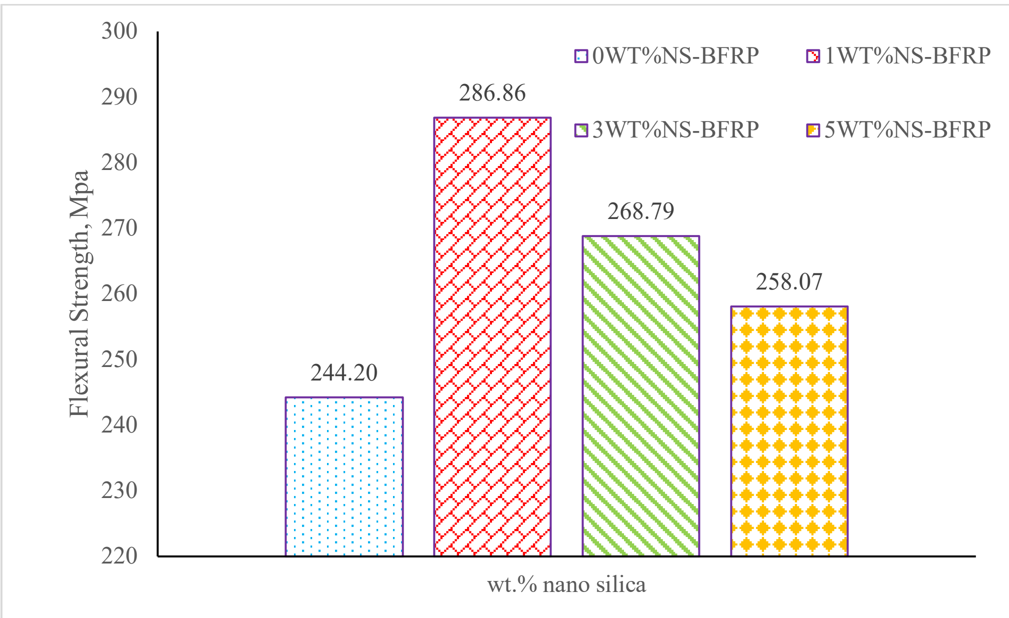


Fig. 3 *Flexural strength of BFRPC*

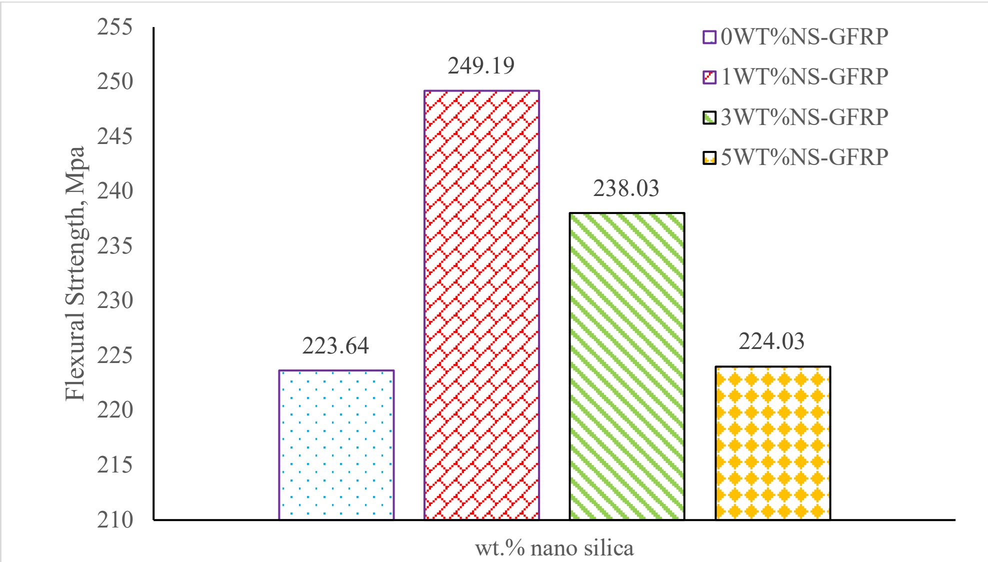


Fig. 4 *Flexural strength of GFRPC*

3.2 Effect of Nano-Silica on Viscoelastic Properties of Basalt Fibre Reinforced Polymer Composites (BFRPC) and Glass Fibre Reinforced Polymer Composites (GFRPC) Through Dynamic Mechanical Analysis (DMA)

Based on Figure 5, we can see BFRPC; across all weight percentages of nano silica, the storage modulus (E') generally decreases with increasing temperature. This is a common trend indicating reduced stiffness at higher temperatures. 0wt%NS-BFRC: Storage Modulus (E') values are relatively high at all temperatures (50°C, 100°C, and 140°C), indicating good stiffness and energy storage capacity. At 1wt%NS-BFRC, Storage Modulus (E') values are lower than 0wt%NS-BFRC, showing reduced stiffness with adding 1% nano silica. While, at 3wt%NS-BFRC, Storage Modulus (E') values are intermediate between 0wt%NS-BFRC and 1wt.%NS-BFRC, suggesting the effect of nano silica on stiffness is not linear. Meanwhile, at 5wt%NS-BFRC, Storage Modulus (E') values are relatively lower than 0wt%NS-BFRC, indicating a further reduction in stiffness with higher nano silica content.

In the meantime, as on Figure 6 for GFRPC, As the weight percentage of nano silica increases in the composite material, the storage modulus (E') generally tends to decrease. This suggests that the stiffness of the composite decreases with higher amounts of nano silica. 0wt%NS-GFRPC: Storage Modulus (E') values are relatively high at all temperatures, similar to the 0wt%NS-BFRC, indicating good stiffness. While at 1wt%NS-GFRPC, Storage Modulus (E') values are lower than 0wt%NS-GFRPC, showing reduced stiffness with adding 1wt.% nano silica. In the meantime, at 3wt%NS-GFRPC, Storage Modulus (E') values are the highest among all systems at all temperatures, indicating the highest stiffness in this composition. While at 5wt%NS-GFRPC, Storage Modulus (E') values are relatively lower than 3wt%NS-GFRPC, showing a reduction in stiffness but still higher than the other systems.

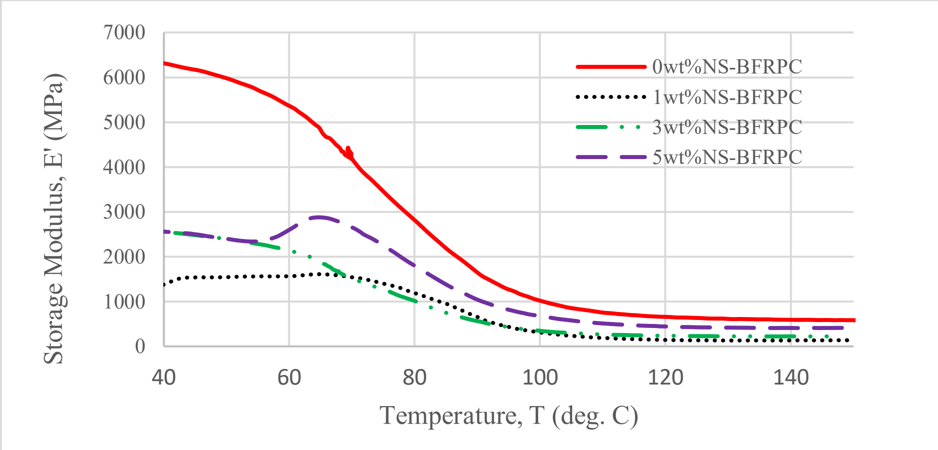


Fig. 5 *Figure: Storage modulus for BFRPC and GFRPC*

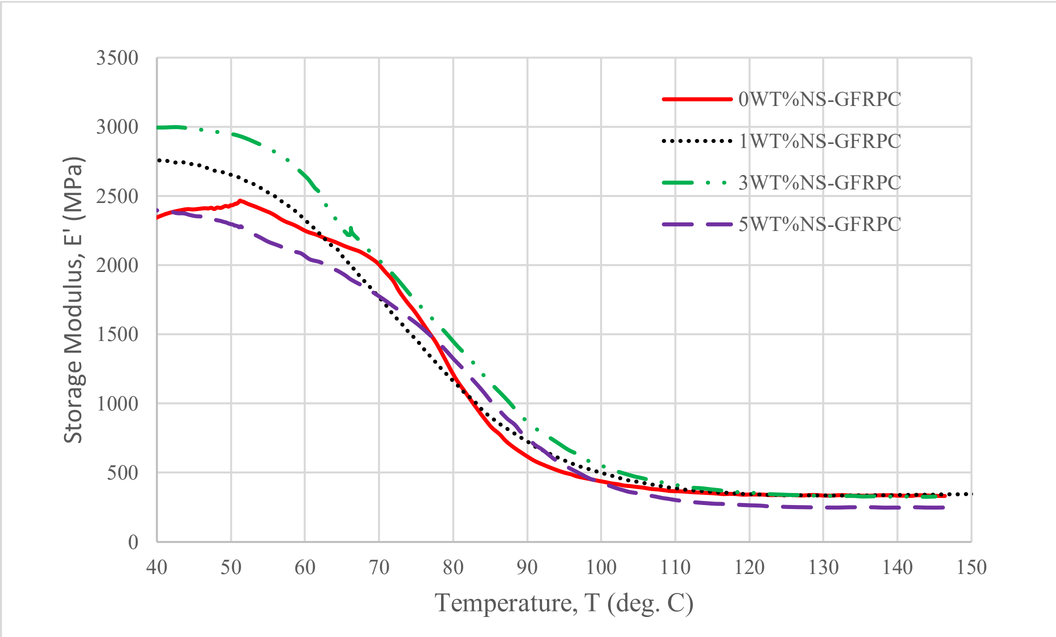


Fig. 6 *Figure: Storage modulus for GFRPC*

Generally, the storage modulus (E') values for both BFRC and GFRPC systems decrease as the temperature increases. This is expected behaviour for most materials. Among the same weight percentage of nano silica, the GFRPC system tends to have higher storage modulus values than the BFRC system. This suggests that adding nano silica has a more pronounced effect on stiffness in the GFRPC system. For both systems, the addition of higher percentages of nano silica (3wt% and 5wt%) tends to decrease the storage modulus (E') and stiffness, indicating that there might be a limit to how much nano silica can be added before stiffness starts to decrease significantly.

The loss modulus (E'') also decreases with increasing temperature, indicating that energy dissipation decreases as the temperature rises. At 0wt%NS-BFRC, Loss Modulus (E'') values are relatively high at all temperatures, indicating significant energy dissipation and damping behaviour. While at 1wt%NS-BFRC, Loss Modulus (E'') values are lower than 0wt%NS-BFRC, showing reduced energy dissipation with adding 1% nano silica. Meanwhile, at 3wt%NS-BFRC Loss Modulus (E''), values are intermediate between 0wt%NS-BFRC and 1wt%NS-BFRC, indicating that adding nano silica affects energy dissipation non-linearly. In the meantime, 5wt%NS-BFRC, Loss Modulus (E'') values are relatively higher than 1wt%NS-BFRC and 3wt%NS-BFRC, suggesting that higher nano silica content can enhance energy dissipation.

Meanwhile, at 0wt%NS-GFRPC, Loss Modulus (E'') values are relatively high at all temperatures, similar to the behaviour observed in 0wt%NS-BFRC, indicating significant energy dissipation. At 1wt%NS-GFRPC, Loss Modulus (E'') values are relatively lower at 0wt%NS-GFRPC, showing reduced energy dissipation by adding 1% nano silica. While, at 3wt%NS-GFRPC, Loss Modulus (E'') values are higher compared to 1wt%NS-GFRPC but lower compared to 0wt%NS-BFRC, suggesting that the addition of nano silica enhances energy dissipation but not to the same extent as in the BFRC system. although at 5wt%NS-GFRPC: Loss Modulus (E'') values are relatively lower than 3wt%NS-GFRPC, indicating reduced energy dissipation at higher nano silica content.

The BFRC and GFRPC systems generally show similar trends in energy dissipation, as evidenced by the loss modulus (E'') values. In both systems, adding nano silica reduces the loss modulus (E'') values, indicating a decrease in energy dissipation. For the same weight percentage of nano silica, the BFRC system exhibits higher energy dissipation than the GFRPC system. This suggests that nano silica substantially affects energy dissipation in the BFRC system [19]. Higher nano silica content generally enhances energy dissipation in both systems, but the extent of enhancement varies. BFRC tends to have a more pronounced effect with higher nano silica content.

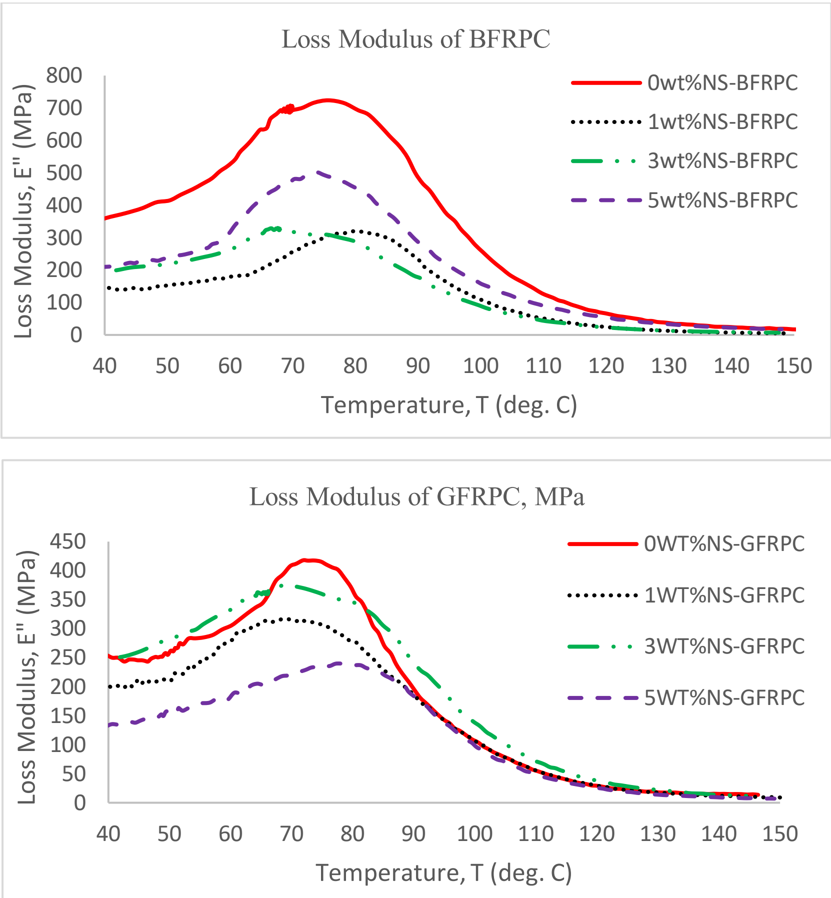
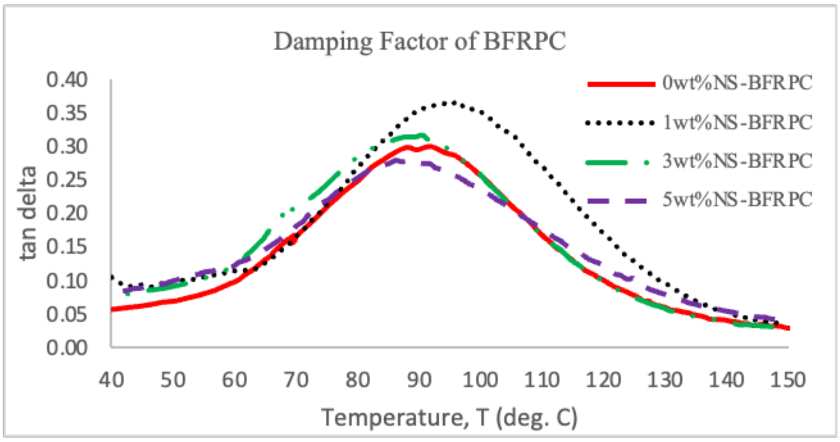


Fig. 6 *Loss modulus for BFRPC and GFRPC*

The glass transition temperature (Tg) values show a slight variation with the addition of nano silica, but there isn't a clear trend. The composition of the material influences the Tg values. The damping factor (tan delta) values vary with the weight percentage of nano silica. This suggests that the addition of nano silica can influence the energy dissipation characteristics of the composite material. The glass transition temperature (Tg) is the temperature at which a material transitions from a glassy, rigid state to a more rubbery, flexible state. It represents a change in the material's molecular arrangement and mechanical properties [20]. The damping factor (tan delta) is a measure of how much energy is absorbed by a material during a deformation cycle. It indicates the material's energy dissipation and damping level [21].

Among the BFRC samples, the Tg values are generally higher than the GFRPC samples. This suggests that the BFRC system tends to exhibit a higher glass transition temperature with the addition of nano silica. Adding nano silica tends to increase the Tg values in both systems slightly. This could be due to the interaction between nano silica and the polymer matrix, which affects the polymer's molecular mobility and glass transition behaviour [22].

The damping factor (tan delta) values vary across different weight percentages of nano silica and between the two systems. The GFRPC system tends to have slightly higher damping factors than the BFRC system. This indicates that the GFRPC system has a slightly higher ability to absorb energy and exhibit damping behaviour [23]. Higher weight percentages of nano silica generally lead to lower damping factors in both systems. This suggests that the addition of nano silica can influence the damping behaviour of the materials, possibly by affecting the interaction between the nano silica particles and the polymer matrix [24].



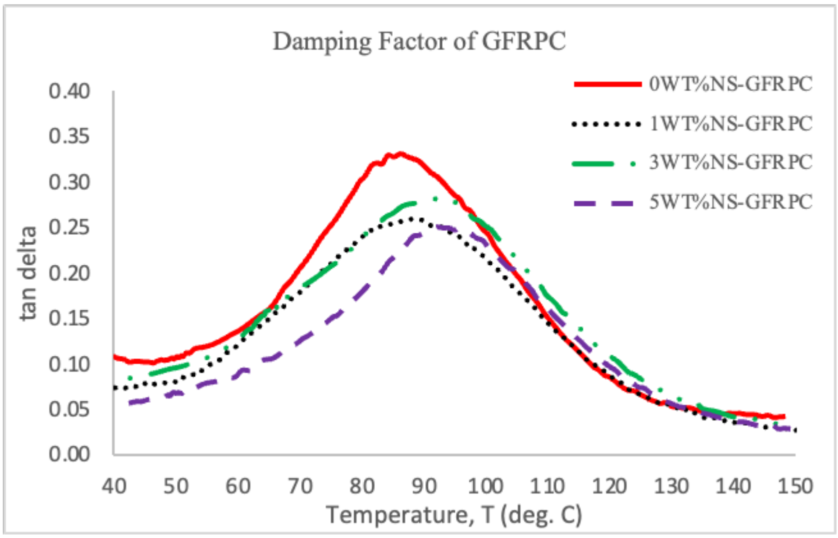


Fig. 7 *Damping factor of BFRPC and GFRPC*

4. Conclusion

In conclusion, adding NS as a filler in glass/basalt fibre-reinforced polymer (FRP) composites positively impacted their flexural behaviour and Dynamic Mechanical Analysis (DMA) properties. Three different NS contents (1wt%, 3wt%, and 5wt%) were used, and twelve composite systems were fabricated and tested. Woven basalt and glass fibres were employed as reinforcement materials, while polyester was modified with varying NS percentages.

The results of the flexural tests showed that the inclusion of NS enhanced the flexural strength of both Basalt Reinforced Polymer (BFRP) and Glass Reinforced Polymer (GFRP) composites. Among all the systems tested, the composite material with 1wt% NS content exhibited the highest flexural strength. This indicates that incorporating NS as a filler improved the composite's ability to resist bending and increased its overall strength. The characteristic of nano silica is that it tends to agglomerate at a certain level; in this experiment, it was at 1 wt%.

The storage modulus (E') and damping factor were evaluated regarding the DMA properties. The composite system with 1wt% had the highest damping factor for both composite systems. However, the addition of NS still positively influenced the DMA properties, resulting in increased storage and loss modulus compared to the systems without NS.

The study concluded that BFRP outperformed GFRP, and the composite system with 1wt% NS content showed the optimum balance between flexural strength and DMA properties. Therefore, it can be concluded that 1wt% NS was the optimum usage as the filler in the composite material. These findings highlight the potential of NS to enhance the mechanical and viscoelastic properties of composite materials, making them more suitable for specific applications. Further research can explore additional NS contents and investigate factors such as long-term durability and cost-effectiveness to optimise the use of NS in composite manufacturing and promote environmental sustainability in the industry.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm the equal contribution in each part of this work: Mohamad Asrofi Muslim, Aidah Jumahat, Shahrul Azam Abdullah, F. Kamaruzzaman, N. A. Haris, Mohd Azrul Jaafar, Raymond Siew Teng Loy. All authors reviewed the results and approved the final version of the manuscript.

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