ISSN 2228-9860 eISSN 1906-9642 CODEN: ITJEA8

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International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

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Dynamic Mechanical Analysis of Al Mesh and Granite Dust-filled Polyester Basalt/Glass Hybrid Laminates

Muhammad Aizuddin Mohamad[1], Aidah Jumahat[1,2*], Nor Hayati Abdul Hamid[2], Napisah Sapiai[1], Mochamad Chalid[3]

[1] Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, MALAYSIA.

[2] Institute for Infrastructure Engineering Sustainable and Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA.

[3] Department of Metallurgical and Material Engineering, Faculty of Engineering, Universitas Indonesia (UI), INDONESIA.

**Corresponding Author (Tel: +60-122290890, Email: aidahjumahat@uitm.edu.my)*

Paper ID: 12A9T

Volume 12 Issue 9

Received 29 April 2021
Received in revised form 01 July 2021
Accepted 09 July 2021
Available online 15 July 2021

Keywords:

Polymer Composites; Aluminium mesh; DMA properties; Glass fiber; Basalt fibre; Granite dust; Woven Basalt (WB), Glass Chopped Strand Mat (GCSM); Composites laminates; DMA test; Fabricate glass fibre (GF) laminates; Basalt fibre (BF) laminates; Hybrid aluminium mesh basalt fibre metal laminates.

Abstract

The influence of granite dust and aluminium mesh on the dynamic mechanical properties of hybrid basalt/glass fibre reinforced polymer composite laminates has been investigated. The composites specimens were produced using hand lay-up technique involving modified polyester (PE) resin with 1wt%, 3wt%% and 5wt% of granite dust. Twelve systems of the hybrid composite laminates were prepared and subjected to dynamic mechanical analysis (DMA) test under three-point bending mode according to ASTM D5023-15. In general, the results showed that the addition of granite dust (GD) and the presence of aluminium mesh improved the dynamic-mechanical properties of the basalt composite laminates. Using Woven Basalt (WB), Glass Chopped Strand Mat (GCSM) and Aluminium (Al) mesh, the WB/GCSM-PE and WB/GCSM/Al-PE laminate systems showed the highest improvement in storage modulus (E') properties with the presence of the GD. This suggests that the presence of GD restricts the mobility chain movement of the polyester matrix and toughens the fibre-matrix bonding, hence the hybrid basalt/glass composites tend to store more strain energy.

Disciplinary: Engineering Mechanics, Materials Engineering, Mechanical Engineering, Polymer Composites.

Cite This Article:

Mohamad, M.A., Jumahat, A., Hamid, N. H. A., Sapiai, N., Chalid, M. (2021). Dynamic Mechanical Analysis of Al Mesh and Granite Dust-filled Polyester Basalt/Glass Hybrid Laminates. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 12*(9), 12A9T, 1-12. http://TUENGR.COM/V12/12A9T.pdf DOI: 10.14456/ITJEMAST.2021.188

1 Introduction

Composite materials have been used in large quantities in recent decades due to their ease of fabrication and high strength-lightweight properties. In recent years, composite materials have surpassed traditional materials in terms of chemical, physical, and mechanical properties, as well as thermal properties [1]. Composites made of fibre reinforced polymer (FRP) have a wide range of applications and outstanding physico-mechanical properties. FRP composites hold extra credit because of their lightweight, excellent specific stiffness and strength, and liberty in design [2]. They are commonly used in a variety of applications, including furniture, construction materials, the automobile industry, civil and military engineering, biomedical engineering, and many others.

Glass fibre is a remarkable material due to its high strength-to-weight ratio, high corrosion and chemical resistance, wide availability, and lower cost than other fibres. In general, there are different types of glass fibres used based on the usage such as E-glass, E-CR glass, S-glass and AR-glass [3]. Glass fibre has the properties of being lightweight as a quarter of steel and has high compressive strength because it is widely used as a supporting structure. Even so, the depletion of petroleum resources and the concern on the environment have compelled industries to reduce their reliance on petroleum-based glass fibre. As a result, the focus has shifted to the fabrication of natural fibre reinforced polymer composites, which are more sustainable and environmentally friendly.

Due to environmental concerns and the benefits of natural fibres over conventional synthetic fibres used in composites, basalt fibres have been identified as an appealing option among the wide variety of natural fibres available to replace glass fibres. As mineral-based fibres, basalt fibre has a better strength characteristic compared to glass fibre. Basalt fibre is also a good candidate for concrete and shoreline structures compared to glass fibre because it has low resistance towards alkaline, acidic, and salt attack. It has attracted attention due to its good physics-chemical properties, eco-compatibility, and recyclability [4].

Thermoset polymers are highly cross-linked polymers that cure through the use of heat, heat and pressure, and/or light irradiation. This structure has desirable properties such as high flexibility for tailoring desired ultimate properties, high strength, and modulus of elasticity [5]. Nevertheless, brittleness and low strength are the significant and obvious drawbacks with respect to this kind of polymers. Due to these limitations, modifying the polymer resin with the addition of filler material is one approach to overcome the issue. Many researchers stated that adding fillers to the matrix improved the stiffness, strength, and toughness of composite material [6-–10].

In this research, embedding granite dust into the polymer resin is a method used to toughen the matrix of the composites. Granite dust is primarily composed of silica predominantly, alumina and potassium with small amounts of calcium and magnesium [11]. This dust is white in colour [12]. Granite dust is a natural resource with a lot of potential for use as a filler because of its excellent properties including high modulus of elasticity and strength. Granite dust is a form of industrial waste that poses a risk to the environment. Many other researchers have used these quarry dust as an ingredient in concrete replacement [13] to prepare hot asphalt mixture, ceramics, and bricks [14]; used by artists to create stoneware clay bodies for ceramic artwork, and as a filler or hardener in pastel sketches [15]. However, there is little to no existing comprehensive set of data for filler embedded by granite dust for the polymer matrix of FRP composites.

In addition, the other toughening approach on the composites is through the inclusion of Aluminium (Al) mesh into the laminate. Al mesh, as opposed to a sheet, expands the possibility of production methods used with fibre reinforced polymer composites i.e. Fibre Metal Laminates (FMLs). [16]. Al mesh is extremely light in weight, has low density, high strength, excellent corrosion resistance, and is relatively inexpensive [17]. Arun and Julyes [18] proposed inserting Al wire mesh between the layers of fibre to overcome the low adhesion or bonding of fibre-matrix. This procedure allows a greater contact area between the Al mesh and the matrix which makes it compact, thus increasing the toughness of the interface and requires more energy to debond the matrix. Some researchers reported that the inclusion of Al mesh layers between the fiber-matrix improved the mechanical properties, resulting in higher flexibility, ductility, and toughness [17, 19].

Therefore, in this study, the combination of reinforcing fibre i.e. glass and basalt, polyester (PE) resin, granite dust and Al wire mesh into FRP composites would perhaps offer broader insight into the possibilities of improving the performance of composite in DMA properties. The new systems of GFRP laminates, BFRP laminates and BFRP-Al mesh laminates are developed with the presence of granite dust as filler material.

2 Method

2.1 Materials

The hybrid composites were produced using woven and chopped-strand mat (CSM) types of glass fibre and woven basalt fibre as reinforcement material and the polyester (PE) resin as the matrix. The woven and CSM glass fibre was supplied by Trelleborg Pipe Seals Duisburg GmbH, while the basalt fibre was supplied by Zhejiang GBF Basalt Fibre Co. Ltd. The ISO PE resin was supplied by Carbon Tech Global Sdn. Bhd. Granite dust used as filler was supplied by Jabatan Kerja Raya (JKR), Kelantan, Malaysia. The 0.5 mm thickness of aluminium wire mesh was used as the toughening material.

2.2 Specimen Fabrication

The fabrication of composites started with the preparation of modified polyester resin with granite dust. The 63µm of granite dust was prepared with three (3) different weight percentages (1wt%, 3wt% and 5 wt%) before mixing it with polyester resin. The resin was mixed using the ratio of 100(resin):2(hardener). To reach good dispersity of granite dust in polyester resin, the stirring process was performed for about 1 hour. The mixture of modified resin was applied by hand lay-up process for impregnation of basalt/glass fibres according to the stacking sequence as shown in Table 1. The stacked composites laminates experienced a vacuum-bagged process for an hour to remove entrapped air before they were left for the curing process. After cured, the composite specimens were cut into the size of 40mm x 10mm for DMA using a vertical bandsaw machine.

Table 1: Designation of Hybrid Basalt/Glass Fiber Reinforced Polymer Composites

Specimen Acronym	Stacking Sequence	Description
WG/GCSM-PE Laminates WG/GCSM/N-PE WG/GCSM/1GD-PE WG/GCSM/3GD-PE WG/GCSM/5GD-PE	[GCSM/WG$_2$/GCSM$_2$/WG]	Neat and modified PE resin by 1wt%, 3wt% and 5wt% of granite dust with woven GF and CSM-GF laminates
WB/GCSM-PE Laminates WB/GCSM/N-PE WB/GCSM/1GD-PE WB/GCSM/3GD-PE WB/GCSM/5GD-PE	[GCSM/WB$_2$/GCSM$_2$/WB]	Neat and modified PE resin by 1wt%, 3wt% and 5wt% of granite dust with woven BF and CSM-GF laminates
WB/GCSM/Al-PE Laminates WB/GCSM/Al/N-PE WB/GCSM/Al/1GD-PE WB/GCSM/Al/3GD-PE WB/GCSM/Al/5GD-PE	[GCSM/Al/WB$_2$/Al/GCSM$_2$/Al/WB]	Neat and modified PE resin by 1wt%, 3wt% and 5wt% of granite dust with woven BF, CSM-GF and Al mesh laminates

2.3 Dynamic Mechanical Analysis (DMA) Test

The DMA test was conducted according to ASTM D5023-15 standard using A “Mettler Toledo DMA1 Star System” machine as shown in Figure 1. The three-point bending mode was used with a temperature range set up at 30°C to 150°C, with a heating rate of 3°C/min and a displacement amplitude of 20 m at a single frequency of 1 Hz. A minimum of three identical specimens for each composite system was tested to obtain the important properties of storage modulus (E’) and damping factor (tan δ).

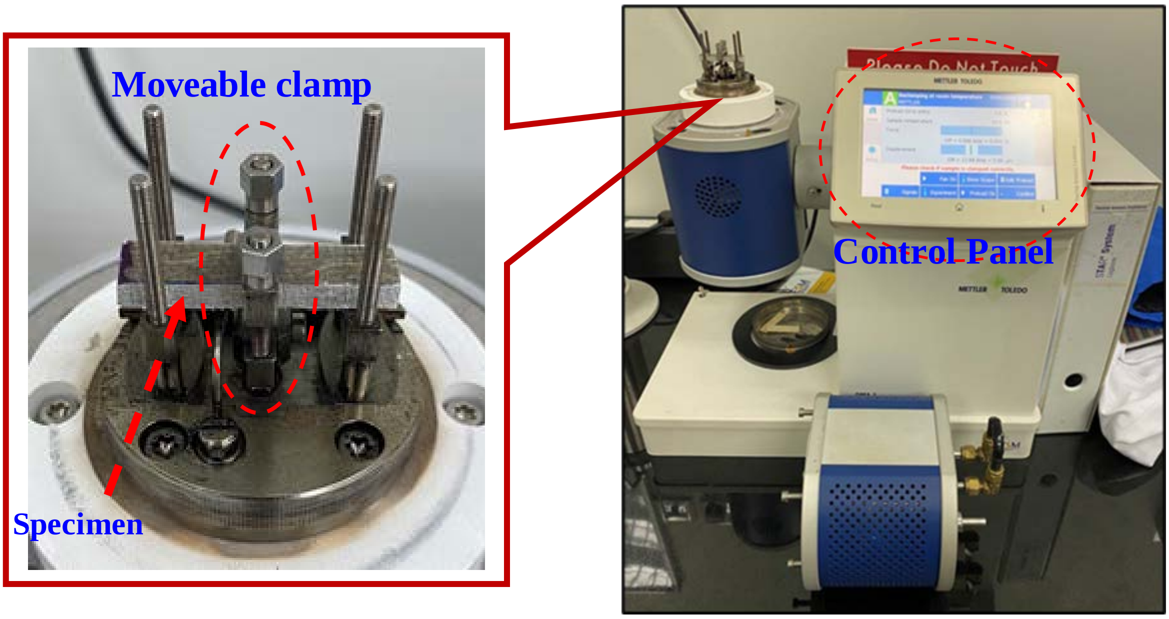

Figure 1: “Mettler Toledo DMA1 Star System” Machine with 3-Point Bending Mode Setup.

3 Result and Discussion

The effects of granite dust (GD) on the DMA properties of WG/GCSM-PE laminates, WB/GCSM-PE laminates and WB/GCSM/Al-PE were studied and compared. The DMA properties i.e. modulus and damping factor are summarized in Tables 2, 3 and 4 for WG/GCSM-PE laminates, WB/GCSM-PE laminates and WB/GCSM/Al-PE laminates composites, respectively. Storage modulus, E’ was evaluated to measure the elastic response of the composites on their ability to store energy by referring to the E'- temperature curve. Damping factor was measured for loss factor of composites damping with the use of temperature sweep method to characterize the glass transition temperature that was obtained on the prominent peak of the tan δ-temperature curve. The lower the damping factor values, the better the fibre-matrix bonding of the composites, which resulted in good DMA properties [20].

3.1 WG/GCSM-PE Laminates Composites

Figure 2 depicts the storage modulus, E' with respect to temperature for WG/GCSM-PE laminate composites. From approximately 40 to 120°C, the E' curves showed a steady decreasing pattern, suggesting a glass/rubbery state change. It is obvious that the components of composites reduce molecular mobility or viscosity [21]. In WG/GCSM-PE composites system, WG/GCSM/N-PE composite, which was without GD, had the highest peak storage modulus of 6272.88MPa at the glassy state of 40^{o}C. The addition of GD into resin reduced the storage modulus for WG/GCSM/1GD-PE, WG/GCSM/3GD-PE, WG/GCSM/5GD-PE with about 11%, 27% and 29%, respectively. At the glass state, the WG/GCSM/5GD-PE composites exhibited the lowest storage modulus but had a temperature limit almost similar to that of WG/GCSM/3GD-PE composites. This indicates that even with a small or large amount of GD within resin, it does interfere with the crosslink within the matrix element. The inclusion of GD in glass fibre reinforced composites reduced the elasticity of WG/GCSM-PE laminates composites. The presence of granite dust disrupted the matrix element's cross-over, thus reduced the E' of modified WG/GCSM-PE laminates composites. The DMA properties of WG/GCSM-PE laminates composites are listed in Table 2.

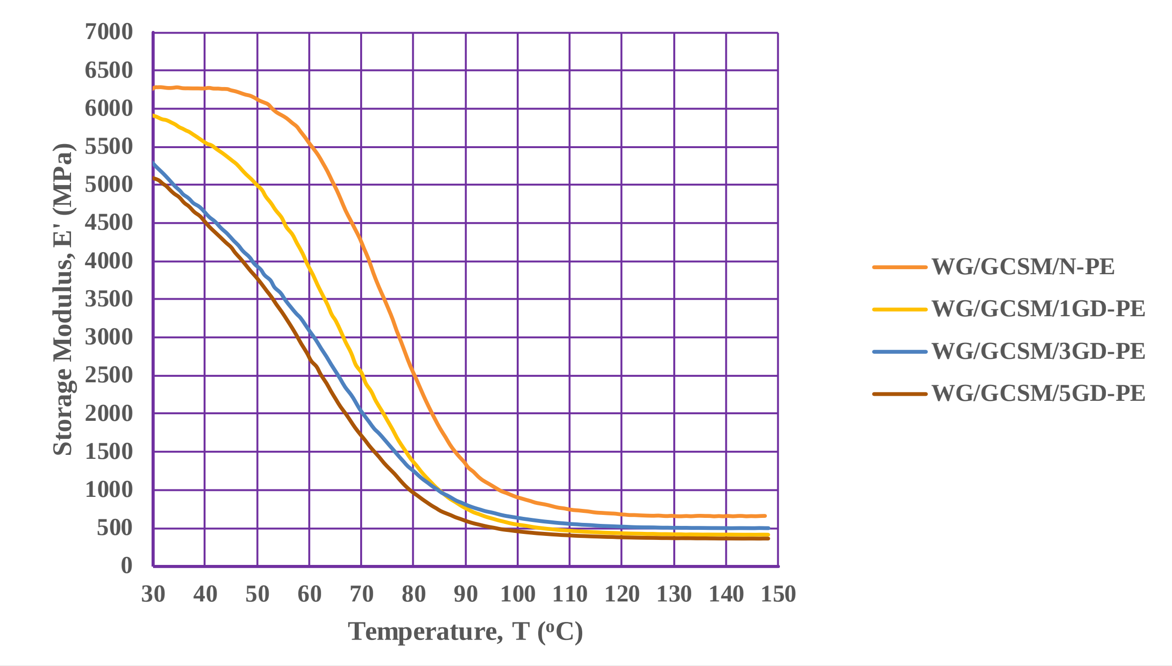

Figure 2: Storage Modulus of WG/GCSM-PE Laminates Composites

Figure 3 presents the damping factor (tan δ) shown by the WG/GCSM-PE laminates composites as a function of temperature. The WG/GCSM/N-PE composites exhibited the highest damping factor which indicated the least brittle behaviour. The tan δ shifted to the right side, with the glass/rubbery state changed, whereby the WG/GCSM/N-PE was the last composite that reached the peak of the glass transition temperature, T_g. Nonetheless, the WG/GCSM/N-PE had a nearly identical peak with WG/GCSM//1GD-PE composites. The presence of 1% wt of GD in glass fibre laminates caused no significant changes for tan δ in terms of loss factor, which had similar damping values. The peak of T_g for WG/GCSM/1GD changed from 88.89 to 83.45°C. WG/GCSM/3GD-PE composites exhibited the lowest damping factors among WG/GCSM-PE laminates composites. The limited mobility of the matrix molecules' segments happened as the inclusion of 3wt% GD reduced their mobility and friction. The tan δ peak limit decreased by 16% as compared to WG/GCSM/N-PE composites. For WG/GCSM/5GD-PE composites, it was observed to be the first composite that reached T_g peaks among the WG/GCSM-PE laminates composites. This indicated that when 5wt% of GD contents were embedded into resin, it was considered as the strongest composites as the glassy/rubbery state changed earlier compared to other WG/GCSM-PE laminates composites.

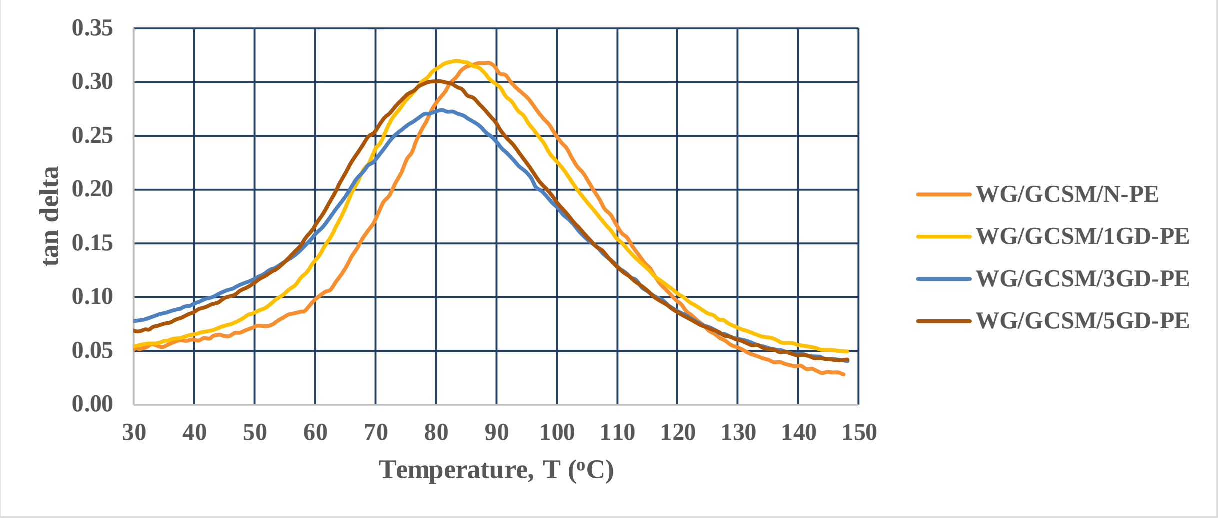

Figure 3: Damping Factor of WG/GCSM-PE Laminates Composites

Table 2: DMA Parameter of WG/GCSM-PE Laminates Composites

System	Mean Storage Modulus, E' (MPa)		Mean T_g (°C) at tan δ Peak
	Glassy state (at 40°C)	Rubbery state (at 120°C)	
WG/GCSM/N-PE	6272.88	677.036	88.89 (tan δ = 0.317)
WG/GCSM/1GD-PE	5541.66	432.266	83.45 (tan δ = 0.319)
WG/GCSM/3GD-PE	4578.88	518.837	81.02 (tan δ = 0.274)
WG/GCSM/5GD-PE	4454.77	379.353	80.79 (tan δ = 0.300)

3.2 WB/GCSM-PE Laminates Composites

Figure 4 depicts the effect of GD in WB/GCSM-PE laminate composites on storage modulus over a temperature range of 30°C to 150°C. The WB/GCSM-PE composites with the addition of GD clearly showed that E' at glassy state increased as compared to WB/GCSM-PE without GD. WB/GCSM/5GD-PE composites had the highest storage modulus with about 875.168MPa of storage modulus at a rubbery state. It is concluded that the addition of GD clearly restricted the movement of the polyester matrix and toughened the fibre-matrix bonding, which made the composites store more energy under the function of temperature. Furthermore, the steady decrease in E' as temperature increased showed that the composites strongly crosslinked density, which meant a stronger network structure and higher stiffness [22]. Regardless, the findings showed that the presence of 1wt% GD in the WB/GCSM/1GD-PE composites at the rubbery state increased the storage modulus with about 9.3% increment, as compared to the unmodified resin of composites (WB/GCSM/N-PE). However, the storage modulus of WB/GCSM/1GD-PE was lower than the WB/GCSM/5GD-PE. It implies that higher storage modulus values for some filler contents of the composites represented their relatively high mechanical properties as the effectiveness of GD as the filler material for WB/GCSM-PE laminates composites was compared to those of the neat resin used for laminates composite. Overall, the 5wt% of GD embedded into WB/GCSM-PE laminates composites resulted in increasing the E', thus increased the ability to store more energy.

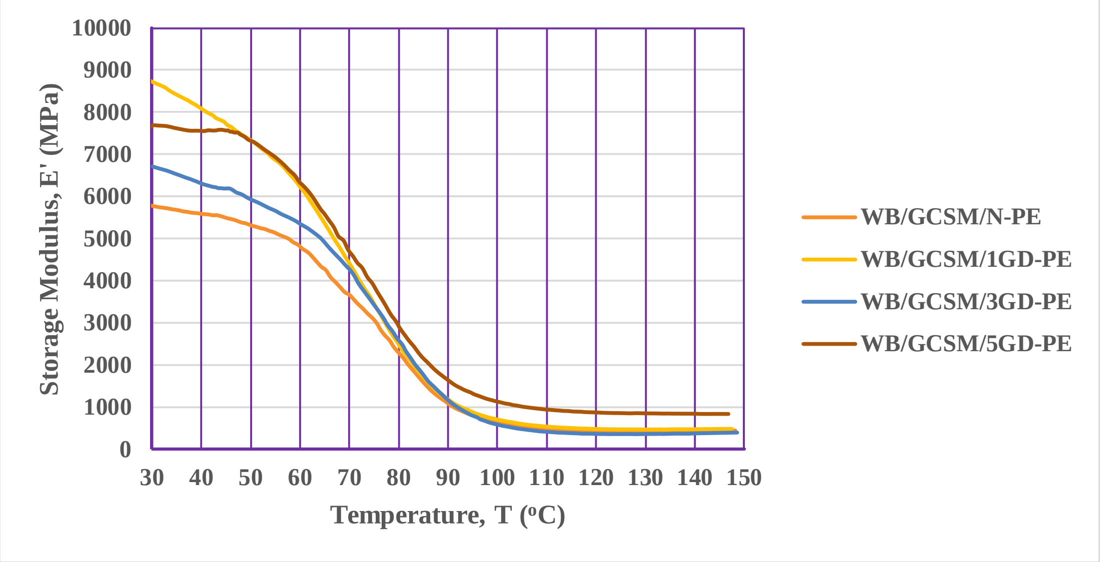

Figure 4: Storage Modulus of WB/GCSM-PE Laminates Composites.

Figure 5 illustrates the effect of GD on the damping factor of WB/GCSM-PE laminates composites. The damping factor increased as the temperature was increased for all WB/GCSM-PE laminate composites prior to each glass transition temperature, T_g at the peak point. The T_g for WB/GCSM-PE laminates composites was observed to have a damping factor (tan δ) of more than 0.350 except for WB/GCSM/5GD-PE composites which had the damping factor, tan δ of 0.305. The incorporation of 3wt% GD in the polymer matrix restrained the segment mobility of the matrix molecules, resulting in the highest damping factor of 0.363 at 89.85°C of T_g. The composites with WB/GCSM/5GD-PE had the lowest damping factor, indicating that incorporating 5wt% GD into the polyester resin of composites greatly improved the interfacial adhesion of the fibre-matrix and acted as a barrier that limited the mobility of the chain segments and resulted in strong fibre-matrix interlocking bonding [23]. Consequently, the strong interfacial bonding between the fibres and the matrix resulted in a lower tan δ. The DMA properties of WB/GCSM-PE laminates composites are summarised in Table 3.

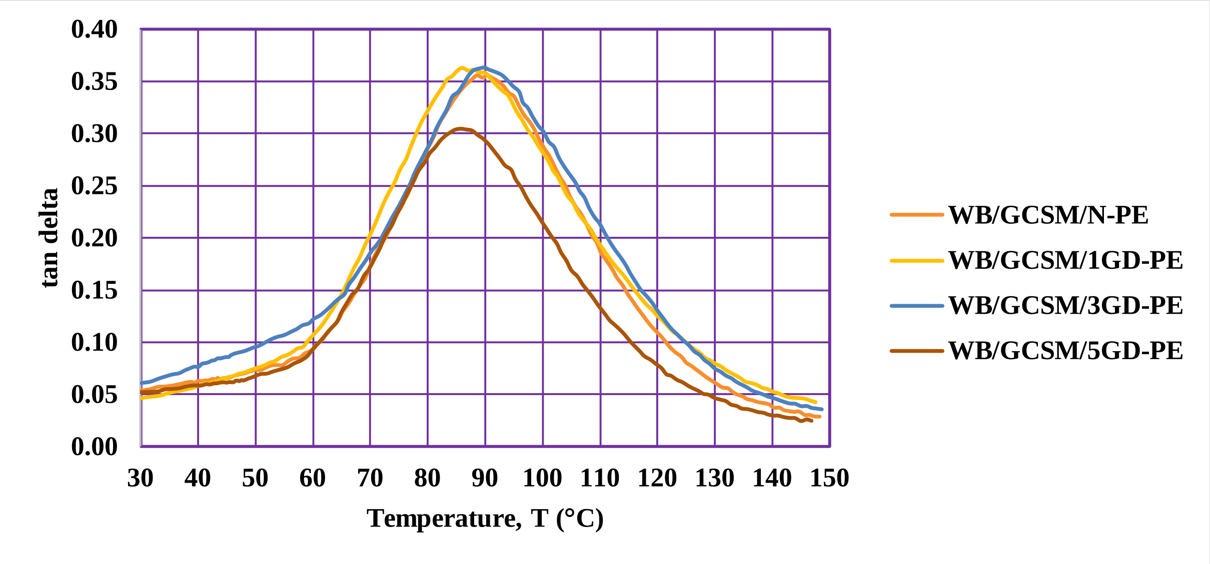

Figure 5: Damping Factor of WB/GCSM-PE Laminates Composites

Table 3: DMA Parameter of WB/GCSM-PE Laminates Composites

System	Mean Storage Modulus, E' (MPa)		Mean T_g (°C) at tan δ Peak
	Glassy state (at 40°C)	Rubbery state (at 120°C)	
WB/GCSM/N-PE	5581.43	442.915	90.30 ((tan δ = 0.356)
WB/GCSM/1GD-PE	8057.52	484.146	87.99 (tan δ = 0.361)
WB/GCSM/3GD-PE	6306.74	366.013	89.85 (tan δ = 0.363)
WB/GCSM/5GD-PE	7551.58	875.168	85.73 (tan δ = 0.305)

3.3 WB/GCSM/Al-PE Laminates Composites

Figure 6 shows the storage modulus with respect to temperature for WB/GCSM/Al-PE laminate composites. The WB/GCSM/Al/5GD-PE composites indicated the highest storage modulus of about 292.35MPa at the rubbery state. It also observed about 78.2% changes of storage modulus from glassy to rubbery state. This might be due to the higher restriction of interference Al mesh in WB/GCSM/AL-PE composites as the Al mesh has the ability to plastically deform, thus increases the stiffness of composites [16]. Despite that, better bonding of fibre-matrix was established when 5wt% GD was added in the fibre metal laminate system when compared to those of 1wt% or 3wt% of GD. Nevertheless, in WB/GCSM/Al-PE laminates composites, E' decreased at a higher temperature, which was clearly observed in WB/GCSM/Al/1GD-PE composites when 1wt% GD content was introduced. The storage modulus of WB/GCSM/Al/3GD-PE reduced about 90% from glass/ to rubbery state. The 5wt% of GD in WB/GCSM/Al-PE laminates composites produced an optimum value and increased the E' of the hybrid basalt fibre with Al mesh laminates composites. The fibre metal laminate that has 5wt% of GD in glass-basalt-Al mesh composites showed the highest stored energy. Thus, the presence of Al mesh toughened the fibre laminates.

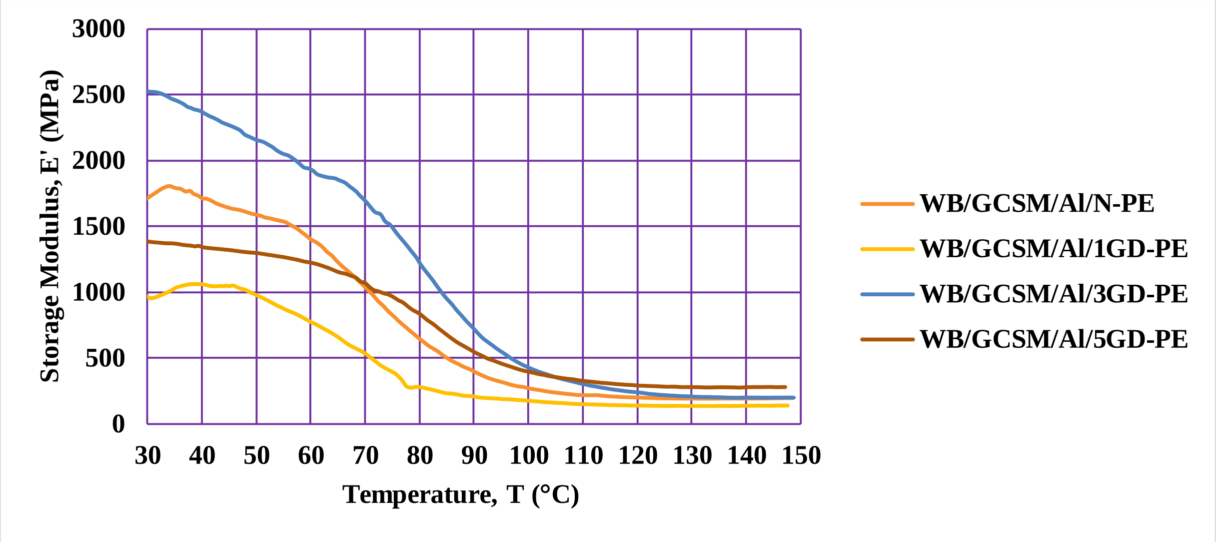

Figure 6: Storage Modulus of WB/GCSM/Al-PE Laminates Composites

Figure 7 shows the effect of granite dust on the damping factor of WB/GCSM/Al-PE laminates composites. The inclusion of 5wt% GD caused more restrictions of chain movement; hence, the WB/GCSM/Al/5GD-PE composite showed a very high T_g value. The increase in GD contents lowered the peak of tan delta due to a greater restriction in the polymer molecules [24]. This happened due to the presence of Al mesh which caused the resin to penetrate and bind the GDs particles. Meanwhile, the WB/GCSM/Al/1GD-PE composite was noticed to have higher tan δ compared to WB/GCSM/Al/3GD-PE and WB/GCSM/Al/5GD-PE composites. By having 0.470 damping factor, the WB/GCSM/1GD-PE composites exhibited the least brittle composites of WB/GCSM/Al-PE. In WB/GCSM/Al/3GD composites, the damping factor, as observed, was lower than WB/GCSM/Al/N-PE composites. This means that it has better elasticity property when compared to WB/GCSM/1GD-PE composites. Nevertheless, the attribution of Al mesh along with 5wt% GD contributed the highest damping factor at 91.55°C T_g, presenting that WB/GCSM/Al/5GD-PE had the strongest fibre-matrix bonding. The summary of DMA properties of WB/GCSM/Al-PE laminates composites is given in Table 4.

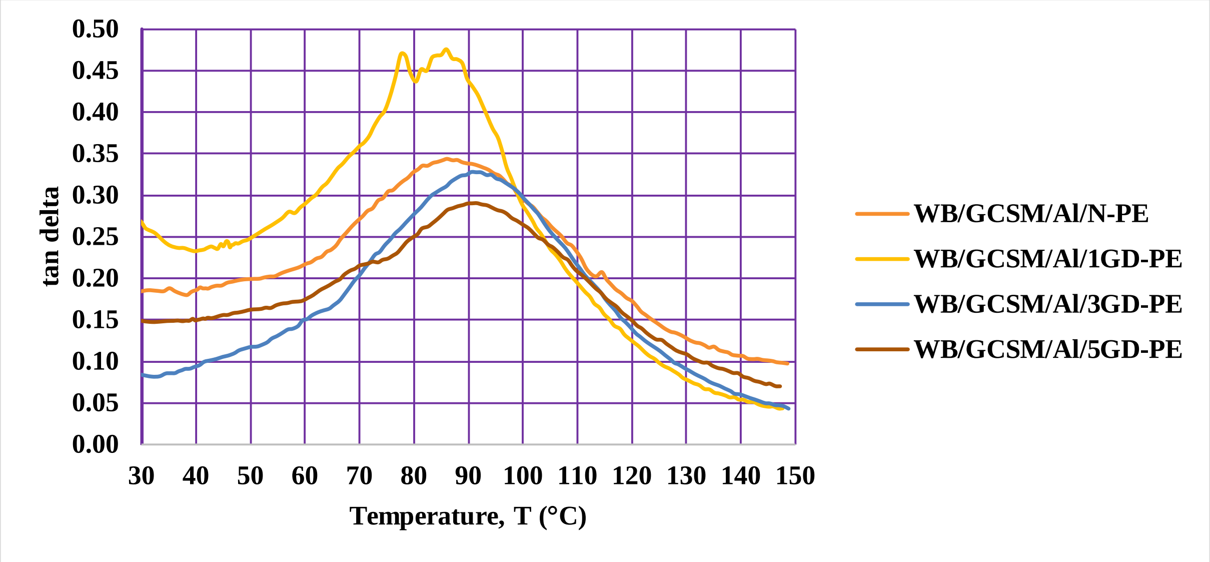

Figure 7: Damping Factor of WB/GCSM/Al-PE Laminates Composites

Table 4: DMA Parameter of WB/GCSM/Al-PE Laminates Composites

System	Mean Storage Modulus, E' (MPa)		Mean T_g (°C) at tan δ Peak
	Glassy state (at 40^{o}C)	Rubbery state (at 120^{o}C)	
WB/GCSM/Al/N-PE	1709.65	200.430	86.07 (tan δ = 0.344)
WB/GCSM/Al/1GD-PE	1057.19	140.889	77.57 (tan δ = 0.470)
WB/GCSM/Al.3GD-PE	2353.46	237.661	90.51 (tan δ = 0.329)
WB/GCSM/Al/5GD-PE	1341.18	292.352	91.55 (tan δ = 0.290)

4 Conclusion

The effect of granite dust on the DMA properties of three different hybrid composite systems was successfully evaluated. In this study, three granite dust loadings of 1wt%, 3wt% and 5wt% were used to fabricate glass fibre (GF) laminates, basalt fibre (BF) laminates and hybrid Aluminium mesh basalt fibre metal laminates. From the analysis of the DMA results, it can be concluded that:

- The presence of granite dust as a filler in the polymer matrix for WG/GCSM-PE laminates composites causes a reduction in the ability of energy stored or elasticity of the composites.
- However, contrast results were obtained for WB/GCSM-PE and WB/GCSM/Al-PE laminates composites. The addition of 5 wt% increased the E' at rubbery states for both hybrid basalt/glass composite systems. The addition of GD was found to be the most effective for the storage modulus and T_g enhancement as the presence of GD restricted the mobility chain movement of the polyester matrix and toughened the fibre-matrix bonding. Hence, the composites tend to store more energy when the temperature increases.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

6 Acknowledgement

The authors gratefully appreciate the financial support from Universiti Teknologi MARA (UiTM), Ministry of Education Malaysia and Institute of Graduate Studies (IPSIS). The research is performed at Faculty of Mechanical Engineering, UiTM Malaysia under the support of LESTARI Grant no: 600-RMC/MyRA 5/3/LESTARI (054/2020).

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Muhammad Aizuddin bin Mohamad has completed his Bachelor Degree (Hons) in Mechanical Engineering from Universiti Teknologi MARA (UiTM). His main research of interest is fibre reinforced polymer (FRP) composites. His final year project involved an investigation on impact buckling strength measurement of aluminium mesh glass and basalt fiber metal laminates under axial impact loading. Currently, he is doing research for MSc on natural fibre composites which involves Microfillers of Fibre-matrix Toughening.

Assoc. Prof. Dr.Aidah Jumahat is an Associate Professor at the Faculty of Mechanical Engineering Universiti Teknologi MARA (UiTM). She got a PhD degree in Mechanical Engineering from the University of Sheffield United Kingdom, an MSc (Mechanical Engineering) degree and a B.Eng. (Hons.) Mechanical and Materials Engineering degree from the Universiti Kebangsaan Malaysia. Her research interest focusses on the Properties of various types of Fibre Reinforced Polymer Composites Materials and Structures.

Professor Dr. Nor Hayati binti Abdul Hamid is a Professor at Institute for Infrastructure Engineering and Sustainable Management (IIESM) UiTM has a PhD in Civil Engineering from the University of Canterbury, New Zealand, an MSc in Civil Engineering from the University of New Castle, United Kingdom and a BSc in Civil Engineering from the University of Pittsburgh, USA. She is a Technical Committee for SIRIM Berhad. Her research encompasses Structural Dynamics, Earthquake Engineering, Beam-column joint with corbel, Tunnel Form Buildings, Precast Hollow Core Wall and Slab, Damage Avoidance Design of Rocking Wall, Precast Shear-key Wall Panel, Insulated Sandwich Panel, Wall-slab Connection for Industrialized Building System (IBS), Moment-resisting Frame using Eurocode 8 and Base Isolation System (High Damping Rubber Bearing).

Dr. Napisah binti Sapiai is a Post-Doctoral at Faculty Mechanical Engineering, Universiti Teknologi MARA, (UiTM), Shah Alam, Malaysia. She obtained a Bachelor of Material Engineering and a Master of Science in Materials Engineering from the School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Pulau Pinang. She got a PhD degree in Mechanical Engineering from Universiti Teknologi MARA, Shah Alam, Selangor. Her research involved Nanofillers, Carbon Nanotubes, Nanosilica, Nanoclay, Surface Modification of Nanofillers, Polymer Composites, Natural Fibres and synthetic Fibres Composites.

Dr. Mochamad Chalid is an Associate Professor of the Department of Metallurgical and Material Engineering, Faculty of Engineering, Universitas Indonesia. He got a PhD in Polymer Product Technology, Chemical Engineering from Rijk Universiteit Groningen, The Netherlands. His areas of research interest are Polymers, Materials and Chemistry.