UNIVERSITI MALAYSIA PERLIS
International Journal of Nanoelectronics and Materials
IJNeaM
ISSN 1985-5761 | E-ISSN 2232-1535

Transforming textile waste: Enhancing thermal and water uptake properties of hybrid composites with multi-walled carbon nanotubes

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Received 23 March 2025, Revised 1 August 2025, Accepted 11 September 2025

ABSTRACT

Underestimating the requirement to recycle and use textile waste has caused environmental difficulties. Researchers have discovered several techniques to reuse and recycle textile waste. This has offered a huge possibility for designing composite materials with different reinforcements. This research investigated how multi-walled carbon nanotubes (MWCNT) change the thermal and water-absorbing properties of a material made from textile waste and basalt fibres. Six different composite systems were fabricated in this study using the moulding technique. Fabricated specimens were analysed using thermogravimetric analysis (TGA) (ASTM E1131), dynamic mechanical analysis (DMA) (ASTM D7028), and a water uptake test (ASTM D5229). TGA results reveal that hybridisation and MWCNT improve the degradation temperature by 8.2% and 8.7%, respectively. The DMA test shows an 8.3% and 8.8% increase in the storage modulus due to fibre hybridisation and MWCNT addition. Furthermore, hybridisation and MWCNT improve water absorption by 36.2% and 46.2%, respectively. In conclusion, incorporating MWCNT strengthens the hybrid composite's thermal and moisture absorption properties.

Keywords: *Textile waste, Basalt fibre, MWCNT, Thermal properties*

1. INTRODUCTION

More than half a million metric tonnes of microfibre contamination from the textile industry annually finds its way into the world's oceans. The amount of microfibre created annually is enough to fill 50 billion water bottles [1-2]. The main factor contributing to textile waste pollution is post-consumer textile waste, which is defined as any garment or household product discarded by consumers. Poor fit, low quality, wear and tear, boredom, and the influence of the fast fashion industry on consumers can all contribute to garment disposal [3]. The reclamation of textile wastes as raw materials for novel applications is presently irrelevant considering the cost effectiveness and current technology gap. On the bright side, these textile wastes can be reused instead of recycled by utilising them as fibre reinforcements in fibre reinforced polymer (FRP) composites.

Generally, textile waste can be classed as either natural or synthetic. Unfortunately, using textile wastes as fibre reinforcements comes with a caveat: they are anisotropic, consisting of various types of fibres with different configurations, not to mention the differences in surface morphology between them. As a result, these differences will form porosity, which consists of air gaps and interstitial voids between the fibres. So, the uneven distribution of the polymer matrix in the liquid phase would cause tiny cracks and other flaws that would make it harder for mechanical stress to move to the solid phase [4].

Fibre hybridisation is a potential method of enhancing composites' physical properties. Hybridisation involves combining two or more different types of reinforcing fibres within a single material matrix to create a composite with a better balance in mechanical properties. This is because hybridised fibres interact synergistically to maintain the advantages while alleviating some disadvantages for each of the individual fibres [5]. However, the dispersion of the two reinforcing fibres plays a crucial role in fabricating hybrid composites. It measures how the two fibre types are mixed in the matrix efficiently. The lowest degree of dispersion is when both fibres form two distinct layers, while the excellent dispersion is when the two fibres are fully distributed randomly [5][6].

Basalt has been widely used as reinforcing fibre in composites due to its combination of excellent characteristics, low cost, and basalt fibre's higher qualities compared to textile fibre [7]. Its hybridisation with textile waste is predicted to enhance the composite's mechanical capabilities [8]. The use of basalt fibres in composites has led to a material that is both more robust and more rigid, with improved resistance to heat and corrosion. As a result, basalt fibre is commonly employed in automotive construction [9]. However, carbon nanotubes' unique mechanical properties have prompted significant interest in using them in composite reinforcement. It was therefore postulated that fibre hybridisation would cause a cascade of benefits [10].

Since the revolutionary breakthrough of fullerenes and carbon nanotubes three decades prior, the concept of incorporating nanoparticles into various polymer matrices has opened a new research platform in the field of composite materials [11][12][13]. Research has well documented the higher specific surface area, surface energy, and density of nanoparticles compared to microparticles. On top of that, nanofiller incorporation performs comparably, if not superior, to microfillers, with a lesser amount required while simplifying the processing and reducing composite weight. Furthermore, the fabrication of nanoparticle-modified polymers results in a variety of morphologies that have a significant impact on the material's final properties [14]. A nanoparticle 100 nm in size is reinforced into a polymer matrix to improve mechanical properties in consequence of its significantly high aspect ratio. Ideally, a properly formed nanocomposite material will have nanoparticles distributed evenly throughout the polymer. Hence, this allows the filler to appropriately bind to the surrounding matrix, distributing stresses more uniformly throughout its length [15].

In this research, epoxy resin was used as the matrix material, and basalt fibres and textile waste were used as reinforcing materials. The mechanical properties of the specimens were greatly improved as a result of the insertion of MWCNT as a filler material into the hybrid composite material. The fabricated specimens were tested to study and comprehend the thermal and absorption properties of the composite materials. This study is a continuation of the study previously conducted in [1], which evaluated the mechanical properties. While, in the current study, the thermal and absorption properties were investigated through the dynamic mechanical analysis (DMA), thermogravimetric analysis (TGA) and water uptake test.

One of the main issues with textile composites is their unpredictability due to fibres having a different range of contents. It is possible that post-consumer textile waste will contain a variety of fibre types and orientations, both of which have the possibility to substantially affect the service dependability of the composite material. The findings that were gleaned from the investigation into the manufacturing of textile waste composites can prove to be quite useful in further stages of development. In recent times, little to no study has been carried out to elucidate the influence of hybridising textile waste and basalt, let alone embedding MWCNT into the hybrid. Thus, this research can be considered a novelty. On hybridisation composites, thermal, flexural, and water absorption tests were not routinely compared in research comparing mechanical tests. This study's findings might help in understanding how to improve the characteristics of composite materials through hybridisation of fibres and nanofiller modification. The obtained observations and data may be valuable for future study and development of filler-modified fibre textile waste which later can be used in various applications.

This textile waste composites have potential applications in various industries such as building applications (non-structural elements, such as insulation, partition boards, and composite panels) [4], automotive components (interior parts e.g., door panels, dashboards, seat backing) [9], furniture manufacturing (chair shells, table tops, and other non-load-bearing furniture components) [16], and geotextiles for civil engineering applications (can be used for soil stabilization, drainage, and erosion control) [17][18].

2. METHODOLOGY

2.1. Materials

Materials for fabrication include finely crushed post-consumer textile waste, basalt fibre outsourced from Zhejiang GBF Basalt Fibre Co. Ltd., Dongyang, China, and MWCNT from CNano Technology in Beijing, China. For the matrix material, epoxy resins, Miracast 1517, were used using a ratio of 100 (resin) to 30 (hardener).

2.2. Preparation of MWCNT modified epoxy resin

MWCNTs were weighed with a specific amount each as required for the preparation of 3 modified specimens (0.5 wt.%, 0.75 wt.%, and 1.0 wt.%), which would then be added with an appropriate amount of acetone, ensuring even dispersion before blending with epoxy resin. The prepared MWCNT was stirred gently with the epoxy after considering the appropriate placement level of the mixer blade propellers in the solution. The rotating mixer blade propeller was gradually adjusted to 700 rpm and allowed to be continuously stirred for 2 hours. Figure 1 shows the detailed preparation steps of MWCNT's modified epoxy resin. The prepared mixtures later be used in fabricating the modified composite specimens.

2.3. Specimen's Fabrication

In general, the specimens were classified into two categories: unmodified matrix composites (without MWCNT) and modified matrix composites (with MWCNT) as in Table 1. All composite specimens would comprise 90 wt.% unmodified epoxy resins or MWCNT-modified epoxy resins, while the remaining consisted of fibres (textile waste and basalt fibres). Only 10 wt.% of fibres were used in this study to prevent agglomeration and ensure proper resin coverage. This is because fibre content in composites is a critical parameter. High fibre content can lead to difficulties in processing and increased viscosity, which can result in poor wetting and agglomeration. For the modified matrix, 0.5, 0.75, and 1 wt.% of MWCNT were integrated into the matrix system (epoxy). MWCNT concentration is also crucial. While MWCNTs can enhance composite properties, high concentrations can lead to agglomeration, which can reduce their effectiveness and create defects. The chosen concentrations likely represent a balance between property enhancement and processability.

The mixture of fibre and epoxy would be moulded by evenly spreading the prepared mixture. After that, a plastic laminate was applied to the filled mould, and the mixture was compressed by placing weights on top of the mould. This is done on purpose to control and reduce the porosity and void that are created during the mixing process. After the epoxy had cured, it was removed from the mould and given final touches like smoothing and trimming. The detailed preparation steps are demonstrated in Figure 2.

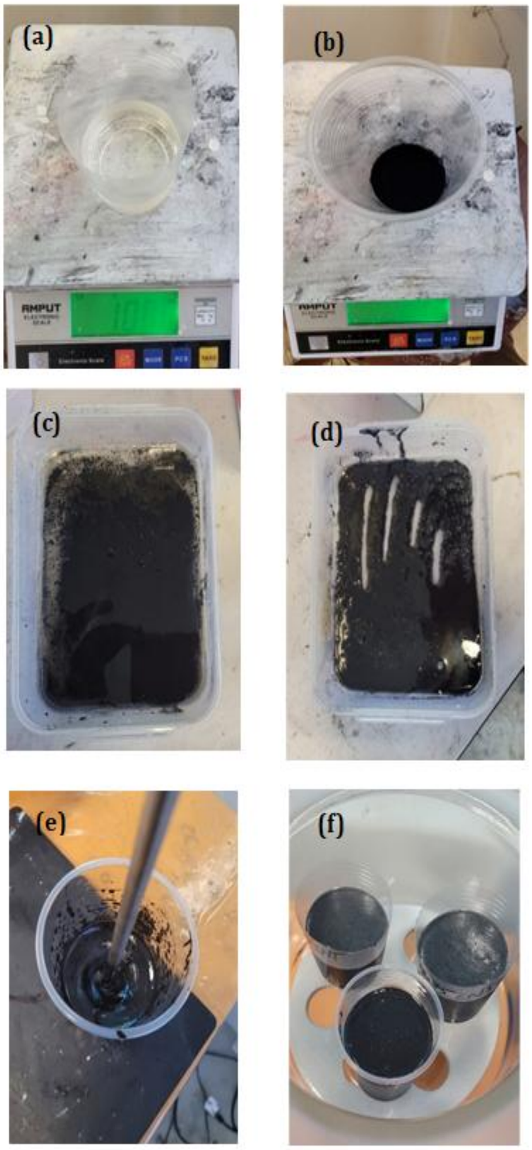

Figure 1. The preparation of MWCNT: (a) resin weighing; (b)MWCNT weighing; (c) acetone poured on the weighed MWCNT; (d) acetone been let to dry; (e) mixing the epoxy with MWCNT; (f) fully prepared MWCNT resin.

Table 1. Designation of composite specimens with descriptions

Unmodified matrix composites		**Modified matrix composites**	
Specimen	**Details**	**Specimen**	**Details**
BFRP	Basalt fibre reinforced polymer	0.5CNTH	Textile waste and basalt fibre hybrid with 0.5 wt.% of MWCNT
TWFRP	Textile waste fibre reinforced polymer	0.75CNTH	Textile waste and basalt fibre hybrid with 0.75 wt.% of MWCNT
TWBFH	Textile waste and basalt fibre hybrid reinforced polymer	1.0CNTH	Textile waste and basalt fibre hybrid with 1.0 wt.% of MWCNT

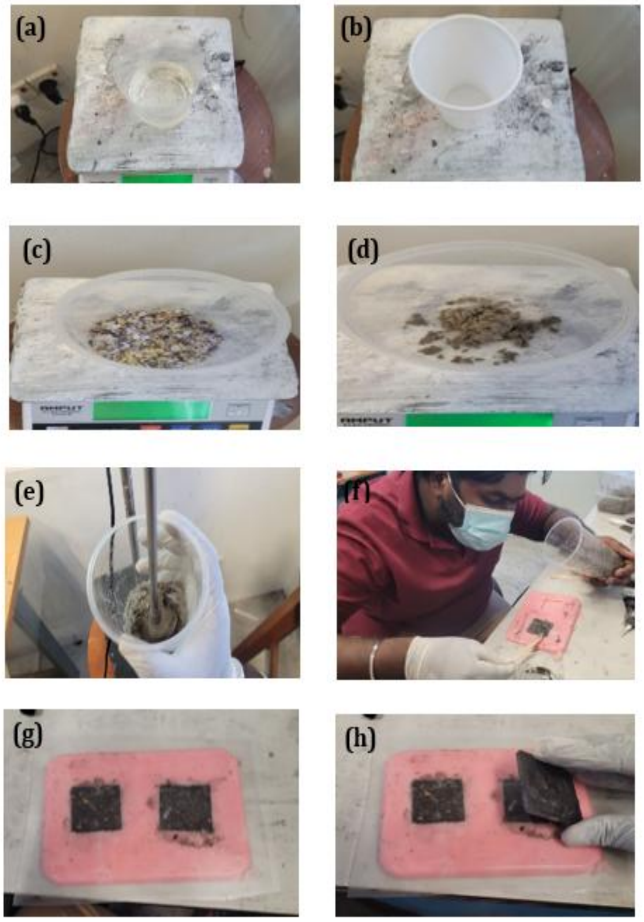

Figure 2. The hybrid composite material fabrication process: The weighing of (a) epoxy resins; (b) hardener; (c) textile waste; (d) basalt fibres; (e) the stirring process of the mixtures; (f) filling the mould with the composites mixture; (g) covering the top of mould with plastic laminates; (h) weights placed on top of the mould

2.4. Testing

2.4.1. Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) analysis is a type of thermomechanical method conducted in an inert atmosphere filled with nitrogen gas or noble gases such as helium and argon that evaluates the thermal degradation of a material that is identified through weight loss [19]. Weight obtained for each corresponding temperature. TGA was conducted in a nitrogen gas atmosphere using a Thermal Analysis (TA) instrument, a TGA SDT Q600 machine, and Thermal Advantage software according to ASTM E1131. The weight loss of composites was investigated at a heating rate of 10°C/min at temperatures ranging from 30 to 1000°C. The beginning decomposition temperature (T), maximum degradation rate temperature (T), and residue were determined at 700°C. The results obtained were then plotted into graphs, manifesting the weight loss trend of the specimens.

2.4.2. Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) is a method of determining the viscoelasticity of a material under a cyclic loading (i.e., sinusoidal) monitored as a function of temperature, time, or frequency. The output response would be classified as elastic if the periodic stress is in phase with the periodic strain, while the viscous response would show a lagging phase angle of strain corresponding to the periodic stress [20]. The storage modulus represents the elastic portion, which measures the energy that has been stored. Whereas, the loss modulus represents the viscous portion, which measures the energy loss dissipated as heat [21]. In this study, a DMA test was conducted according to ASTM D7028 using the TA Instrument Q800 DMA. The cyclic loading was set to 1 Hz, and the heating rate created a temperature gradient from 30°C to gradually increase to 150°C.

2.4.3. Water Uptake Test

A water uptake test was performed to assess the relative water absorption capacity in the composite system. This is crucial since moisture would interrupt the interfacial bonding between the hydrophobic matrix and the hydrophilic fibres, compromising the physical performance of a composite system [22]. The overall method of ASTM D5229 testing is that specimens are dried for a predetermined period at a specific temperature before cooling down in a desiccator prior to water absorption test. The specimens are measured immediately after finishing cooling. The specimens are then submerged in 100 ml of distilled water for 24 hours or until it reaches equilibrium, whichever occurs first, at a temperature of 23°C. At this stage, the specimens are removed from the water, dried off with a lint-free towel, and weighed.

3. RESULTS AND DISCUSSION

3.1. Thermal Properties of Composites

3.1.1. Hybridisation Effect on Thermal Degradation Properties

According to Figure 3, basalt fibre (BF) demonstrated no substantial mass loss up to 1000°C, with the exception of a minor loss (1.66%) due to disintegration and vaporisation. Textile waste (TW) had the greatest weight loss in thermal degradation in regions of moderate volatility and combustion, with 80.98%. This occurred, resembling any natural fibre dictated by the cellulosic nature of the material, with the expectancy to be completely thermally degraded above 400°C [23], while at the same time another major loss was caused by epoxy of 72.42%. Similarly, Wu *et al.* [24] reported 65%–70% weight loss for various types of epoxies. When the composites are hybridised and nanomodified, the degradation of both source materials displays a higher degree of degradation and higher expectations. The degradation temperature and residual content of TGA-obtained specimens of raw materials are displayed in Table 2.

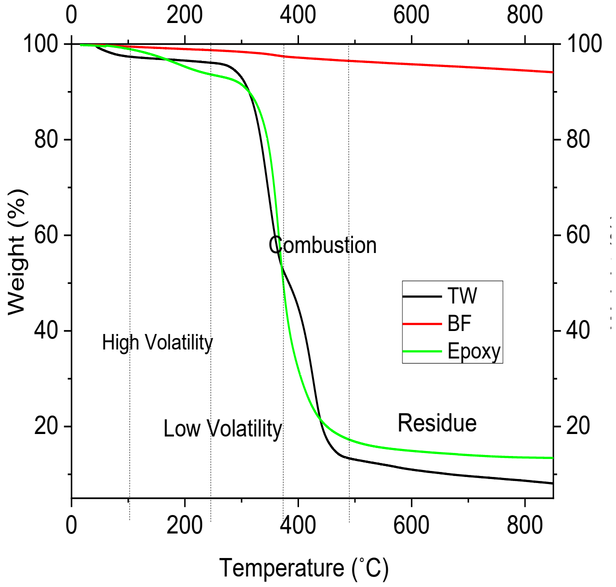

Figure 3. TGA curves of raw materials

Table 2. Degradation temperature and residual content of raw materials

Composite specimens	Degradation temperature (˚C)	Weight loss (%)	Final residue (%)
BF	208.46	1.66	-
TW	268.29	80.98	7.18
Epoxy	308.22	72.42	7.80

On the TGA test, composite materials such as BFRP, TWFRP, and TWBFH were analysed. Figure 4 shows the TGA temperature curves of the unmodified composite specimens. 4.80% of BFRP's weight loss happened in volatile locations, compared to 4.63% for TWBFH and 4.16% for TWFRP. BFRP composite evaporates more quickly than TWFRP composite due to the moisture content embedded in textile waste fibres. Rani and coworkers also obtained comparable observations in their study [25]. In low-volatility zones, both basalt fibre-reinforced specimens lose weight with rising temperature: 65.84% for BFRP and 51.1% for TWBFH. With basalt fibre's excellent thermal resistance, deterioration should be reduced. Similar findings were observed by Abolfazli *et al.* [26]. BFRP, TWFRP, and TWBFH reduce residual weight by 2.01% to 5.55% to 6.54%. The thermal stability of TWFRP was at 281.8 ˚C, whereas BFRP and TWBFH were at 295.01 ˚C and 290.18 ˚C, respectively. Table 3 shows the degradation temperature and residual content of unmodified composites obtained from TGA.

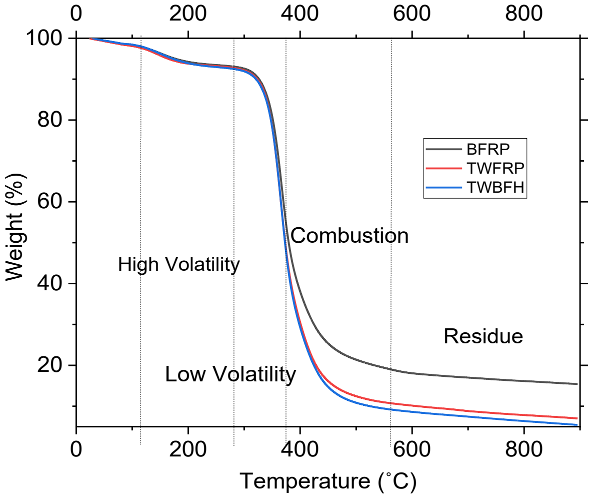

Figure 4. TGA curves of unmodified composites

Table 3. Degradation temperature and residual content of unmodified systems

Composite specimens	Degradation temperature (˚C)	Weight loss (%)	Final residue (%)
BFRP	295.01	75.07	2.01
TWFRP	281.78	80.08	5.55
TWBFH	290.18	80.37	6.54

3.1.2. MWCNT Effect on Thermal Degradation Properties

Table 4 denotes the overall MWCNT-modified composites' degradation temperature and weight loss after testing. The degradation temperature of hybridised carbon nanotubes is greater than TWBFH by 0.5CNTH, 0.75CNTH, and 1.0CNTH modified matrices, respectively. As more MWCNTs are added, thermal stability increases accordingly. Figure 5 shows the TGA curves of modified composites. 0.5CNTH loses 6.76% of its weight, followed by 5.93% for 0.75CNTH and 5.95% for 1.0CNTH. In comparison, 1.0CNTH lost 47.37% more weight than 0.5CNTH in contrast to 0.75CNTH, which lost only 1.24%. This demonstrates that the introduction of MWCNTs into the basalt fibre polymer enhances its thermal stability, since carbon content increases the resistance to disintegration at higher temperatures [27].

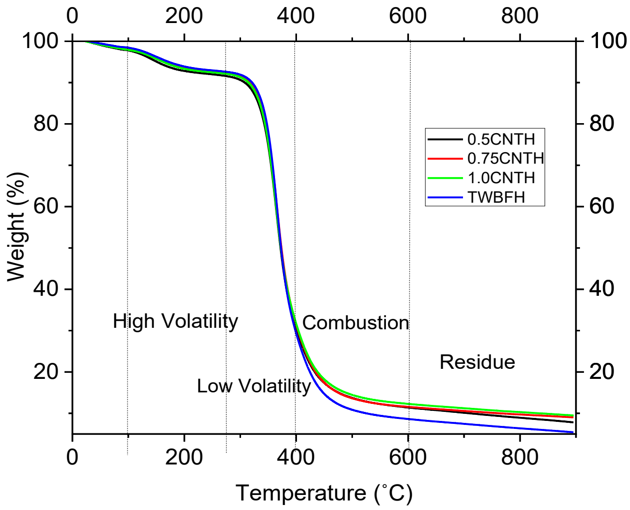

Figure 5. TGA curves of modified composites

Table 4. Degradation temperature and residual content of modified system

3.1.3. Hybridisation Effect on Dynamic Mechanical Properties

The DMA thermal test began with an epoxy specimen and then hybrid composites. Figure 6 indicates the hybridisation effect on the storage modulus of raw epoxy and unmodified reinforced polymer matrix at 30 to 150 ˚C. At 54 ˚C, the epoxy material had a higher storage modulus than BFRP, TWFRP, and TWBFH. Raw epoxy outperformed BFRP by 17.9%, while epoxy glassy results are 53.5% better than TWFRP and 41.8% better than TWBFH. In the rubbery condition, epoxy exhibited the most losses in storage modulus, declining from 1172.79 MPa to 37.30 MPa. This observation of a drastic reduction in storage modulus was likely due to the viscous nature of polymers, as also observed by Arputham *et al.* [28].

Figure 7 manifests the hybridisation effect on the damping factor of epoxy and unmodified polymer composites. Raw epoxy's glass transition temperature (T_g) exhibited the largest damping factor (tan δ) of BFRP, TWFRP, and TWBFH. Unmodified composites have peak damping factors between 0.5 and 0.6. TWFRP had the highest T_g. Incorporating textile waste into reinforced polymer composites limited the movement of matrix molecules, which led to a 0.66 damping factor [29]. According to Gupta and coworkers [30], as a result of hybridisation, the composite has shown the least loss of modulus, elucidating the balance between viscosity and elasticity. The storage modulus and mean T_g of the epoxy and unmodified reinforced polymer composites at peak tan δ are shown in Table 5.

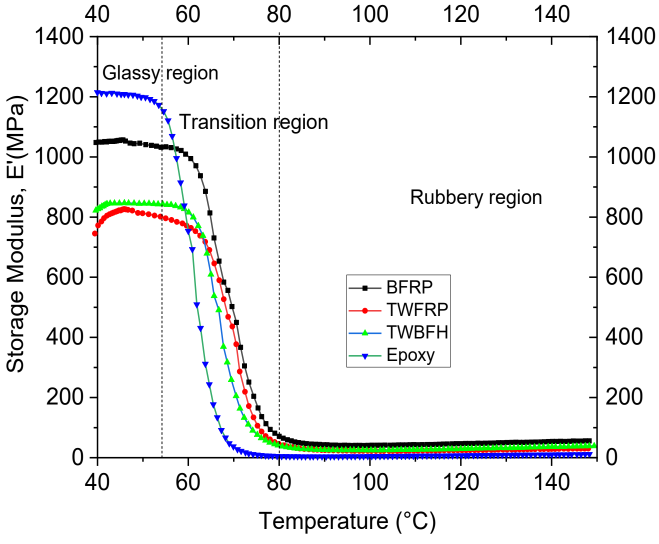

Figure 6. Storage modulus of unmodified systems

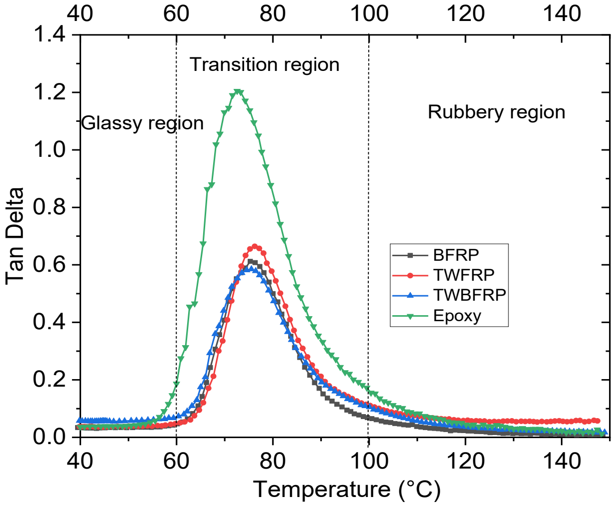

Figure 7. Damping factor of unmodified systems

Table 5. Storage modulus and mean T_g of the epoxy and unmodified reinforced polymer composites

System	Storage Modulus, E' (MPa)		Mean Tg (˚C) at tan δ Peak	
	Glassy state (60˚C)	Rubbery state (80˚C)	Tg(˚C)	tan δ
Epoxy	1172.79	37.30	72.58	1.205
BFRP	994.43	64.41	75.31	0.612
TWFRP	763.81	41.05	76.23	0.664
TWBFH	827.15	37.81	75.54	0.585

3.1.4. MWCNT Effect on Dynamic Mechanical Properties

Figure 8 depicts the carbon-modified polymer matrix composite storage modulus from 30 to 150 ˚C. The modified 1.0CNTH composite had a higher storage modulus than 0.5CNTH and 0.75CNTH at 60 °C. According to Her and Lin [31], Lee *et al.* [32], and Park and Seo [33], this is most probably due to basalt fibre's strong resistivity and the composite's 1.0% carbon concentration. As expected, the storage modulus with respect to the increment of MWCNTs causes the modified composites to increase progressively. Entering the rubbery condition, 1.0CNTH dropped to 40.23 MPa, followed by 0.75CNTH at 40.3 MPa, and 0.5 CNTH at 50.06 MPa. According to Park *et al.* [34], the weakening of the matrix and MWCNT bond, which was unavoidably a result of agglomeration, can account for the decline in storage modulus. The tendency for agglomeration to increase as more MWCNT is incorporated into the matrix has been shown in the results, which was also concluded by Rubel *et al.* [35]. Regardless, results have shown the unmodified composite is indeed inferior to the modified composites with 35.91 MPa. Hence, it is apparent that MWCNT enhances the composite stiffness of the hybrid composites by up to 39.4%.

Figure 9 shows MWCNT-modified composites' damping factor. The transition temperature slightly increased as more carbon content was introduced. It was suggested that this may be caused by CNTs that hold the molecule of the epoxy, hindering the motion [36]. 1.0CNTH has the lowest damping factor, suggesting that it has the least loss of modulus resulting from less molecular movement leading to less internal friction [31]. Table 6 shows the storage modulus and mean T_g of the reinforced modified composites.

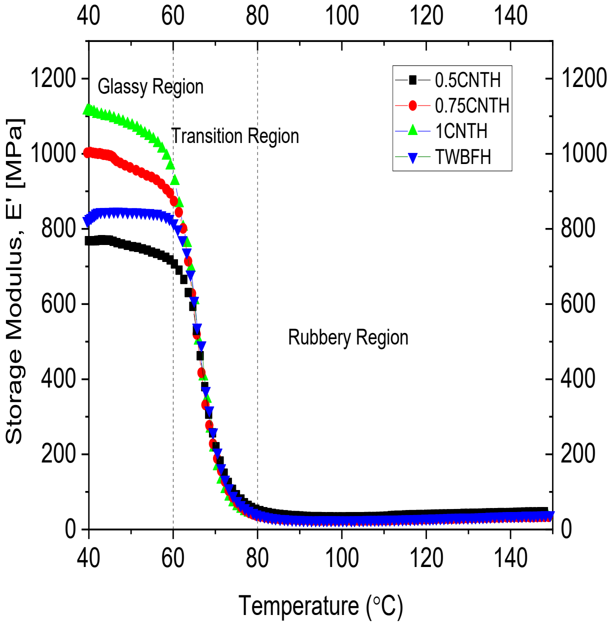

Figure 8. Storage modulus of modified composites

Table 6. Storage modulus and mean T_g of the modified composites

System	Storage Modulus, E' (MPa)		Mean T_g (˚C) at tan δ Peak	
	Glassy state (60˚C)	Rubbery state (80˚C)	T_g(˚C)	tan δ
0.5CNTH	706.77	50.06	73.08	0.491
0.75CNTH	873.93	40.30	73.12	0.511
1.0CNTH	927.17	40.23	73.30	0.490

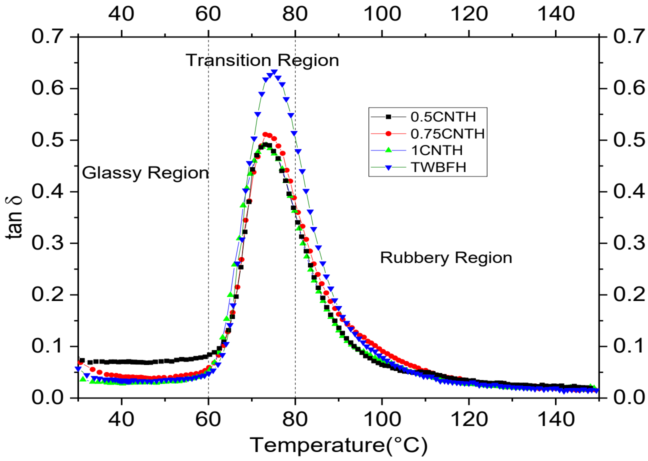

Figure 9. Damping factor of modified composites

3.2. Water Uptake Properties of Composites

3.2.1. Hybridisation Effect on Water Uptake Properties

Figure 10 shows that TWFRP had the highest absorption in comparison to BFRP and TWBFH at 4.44%. Textile waste, which is composed of natural fibres, is highly hydrophilic, and the capillary action through existing microcracks has caused a significant absorption amount [37]. This would be detrimental to the overall composites' mechanical properties due to the weak interfacial adhesion between fibre and matrix [38].

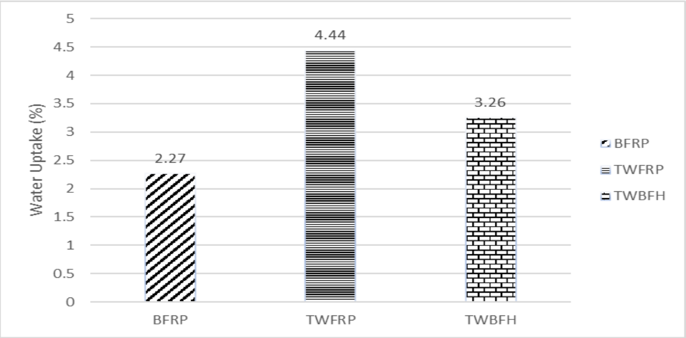

Figure 10. Water uptake properties of unmodified composites

3.2.2. MWCNT Effect on Water Uptake Properties

Figure 11 shows the percentage of water absorbed by 0.5, 0.75, and 1.0 wt.% of MWCNT-modified composites. 0.5CNTH absorbed 2.6%, while 0.75CNTH and 1.0CNTH absorbed 2.51% and 2.33%, respectively. Unmodified composites absorbed the most, up to 3.26%. It can be observed that MWCNT content notably lowers the absorption amount by up to 46% as compared to unmodified composite. Aside from their hydrophobic nature, MWCNTs can minimise their absorption capability by creating a complex pathway for water molecules to enter the composites, as mentioned by Jin *et al.* [39].

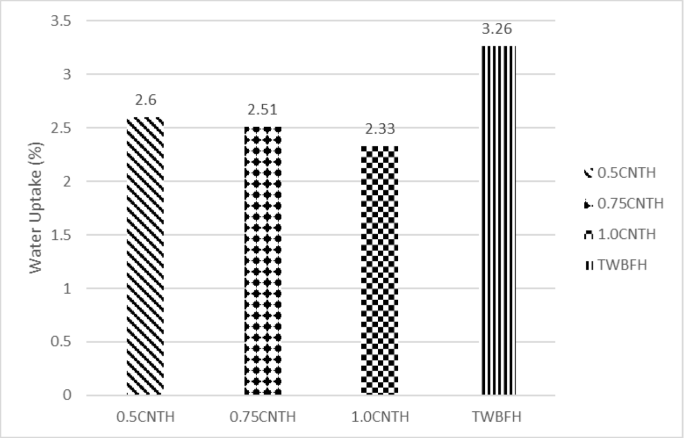

Figure 11. Water uptake properties of modified composites

4. CONCLUSION

Fibre hybridisation and MWCNT-modified matrix improved thermal stability and water absorption properties. Inconsistency in hybridisation and nanomodification rates of composites may be related to fibre aggregation and cavity development during hybridisation. From this study, the following conclusions were drawn:

i. TGA test showed hybridisation boosted the composite's thermal characteristics by 8.2%. Meanwhile, MWCNT-modified hybrids improved thermal degradation temperatures by 8.7%.
ii. The TGA test also showed that TWBFH improves thermal resistance by 17.8% over TWFRP. At higher temperatures, increasing MWCNT content in CNT-modified composites improves disintegration resistance. 0.5CNTH enhances thermal characteristics by 0.7%, 0.75CNTH by 0.8%, and 1.0 by 3%.
iii. DMA shows hybridisation improves the damping ratio by 11.9% and MWCNT by 26.2%. TWBFH enhances TWFRP more than textile waste alone.
iv. The water uptake test showed hybridisation reduces absorption by up to 26.588%. On top of that, incorporating MWCNT also has a substantial impact on the average absorption, up to 28.53%.

Thus, in summary, hybridisation and MWCNT cause composites to become stiffer, have better thermal degradation properties, and provide a certain degree of moisture resistance.

As for the future research directions, several tests and assessments could be considered such as long-term durability testing to assess the composite's performance over time, environmental impact assessment to evaluate the sustainability of the production process and the end-of-life management of the composites, life cycle assessment and detailed cost analysis to determine the economic viability of using textile waste in composites.

ACKNOWLEDGMENTS

This work was financially supported by the SEMESTA-MBI Industry Research Grant (I/SEM-MBI/ST/2020/16).

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