Strength Enhancement of Basalt Fiber-Reinforced Epoxy Laminates with Biowaste Catalyst Free Carbon Nanospheres

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Abstract

This study aims to analyse the effects of carbon nanospheres (CNSs) on the tensile properties of basalt fibre-reinforced epoxy composite laminate (BFR). The CNSs were obtained from an economical fibrous residue attained from the sago palm tree, which is known as biowaste sago bark. Hand lay-up method was used to fabricate the unidirectional basalt fibre-reinforced epoxy composite laminates. The epoxy resin was mixed with carbon nanosphere particles (i.e., 0.6 wt% - 1 wt %). Tensile tests have been conducted as per ASTM standards. In addition, emphasis on the microstructural investigation using Scanning Electron Microscopy (SEM) is given, in order to study the fracture surfaces of the composite laminates. The results demonstrated significant improvement in tensile strength when carbon nanosphere particles were included in the basalt fibre-reinforced epoxy composite laminate. The best result was obtained at 1.0 wt% CNSs. It displayed an increment of 80.6% in tensile strength, and 120% increment in Young's modulus, respectively, in comparison to neat basalt fibre-reinforced epoxy composite laminate. The improved accomplishment of CNSs/ basalt fibre-reinforced epoxy composite laminate is due to good distribution of CNSs particles in the epoxy matrix.

Keywords: Nanospheres; In-plane shera; Basalt fiber; Biowaste; Sago bark

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INTRODUCTION

Fibber-reinforced polymer composites (FRCs) have been used extensively in many applications, especially in areas such as construction, aerospace, recreational equipment, automotive, marine and other high performance applications. This is due to the advantages of having high stiffness to weight ratio and their ease of processing (Dean et al., 2006, Liu et al., 2006). To enhance the overall properties of the composite laminate, fibres, for instance carbon fibre, glass fibre, and basalt fibre are used as filler for epoxy-based laminates. Recent research demonstrated the advantages of utilizing natural fibres in the reinforcement of polymers in order to improve the environmental safety (Manikandan et al., 2012). As a waste material, the use of natural fibres as the reinforcement for the composite of the polyester is a good way move towards eco-reusing (Bodros et al., 2007). Furthermore, the benefits of natural fibres over glass fibres are in terms of the cost, density, strength-to-weight ratio, resistance to breakage during processing, energy content and recyclability (Wambua et al., 2003). Among the natural fibres, basalt fibre (BF) has been proven as a potential reinforcement of composite materials because of its good mechanical properties. Basalt fibres originated from basalt rocks through melting process. The basalt rocks can be broken down into smaller particles to produce fibres characterized by high strength, excellent fibre/resin adhesion, ability to be easily processed using conventional processes and equipment (Wang et al., 2002), sound insulation properties, low water absorption (Sim et al., 2005), good resistance to chemical attack, ecologically friendly, free from carcinogens and health hazards, high operating temperature range, and can be produced at considerably lower cost than carbon fibre (Lopresto et al., 2011; Wei et al., 2011; Colombo et al., 2012; Liu et al., 2006). In addition, BFs do not contain any other additives in the production process, which makes them cost effective. Furthermore, BFs are known to have higher tensile strength than E-glass fibre and they have larger strain to failure than carbon fibre (Wei et al., 2011). The excellent heat resistance and low water absorption capability make them suitable as thermal insulation materials and hot fluid conduits. BFs also have advantages over the glass and asbestos fibres in terms of environmental cleanness (Olexandr et al., 2005). Moreover, the basalt fibre has high chemical stability and sound mechanical properties as well as being non-toxic and non-combustible (Berozashvili, 2001).

Basalt fibres which are extracted from the volcanic rock are preferably used for reinforcing polymer matrices (Goldsworthy et al., 2000). The chemical composition of BF is approximately identical to glass; the basic components of both elements are SiO_2, Al_2O_3, CaO, MgO, K_2O, Na_2O, Fe_2O_3 and FeO (Militky et al., 2002). It is also important to highlight the melting temperature of the basalt fibres which ranges between 1350 and 1700°C. Basalt will solidify as a partial crystalline structure when it undergoes slow cooling process. In fact, basalt fibres can be used from 200 to 600°C without any significant losses of the mechanical properties. Basalt fibres can be applied for structural strengthening of material based on the advantages that they possess. Besides that, they also have great potential as transportation and construction materials. Before using fibre-reinforced polymer (FRP) materials as a strengthening material, preferably the mechanical and durability issues of the material are tested first.

Similarly, carbon-based nanomaterial's have potential function in ultra-capacitors (Lee et at., 1999; Yang et al., 2002; Stroller et al., 2008), nanoelectronics (Berger et al., 2006), catalysis (Li et al., 2010), micro-electrical devices (Gilje, 2007), sensors (Quercia et al., 2004) and electrochemistry (Guo et al., 2006; Yuan et al., 2006). Among the various forms of carbon nanomaterials, carbon nanospheres are getting more attention. This is because, in its spherical form, they are usually unclosed shells with little waving flakes that follow the curvature of the sphere. Many studies found that the mechanical, electrical and thermal properties of polymer composites are enhanced when CNSs are used as fillers in the resulting composites (Green et al., 2009; Gauthier et al., 2005; Oh et al., 2006; An et al., 2012; Tijing et al., 2012).

In the present study, carbon nanosphere particles will be used to enhance the tensile properties of basalt fibre/epoxy composite laminates. The carbon nanospheres (CNSs) are obtained by a simple environmentally benign catalyst-free pyrolysis procedure from biowaste sago bark, which is a low-priced fibrous residue acquired cheaply from the local sago palm tree (Hedge et al., 2015). The sago bark is rich in cellulose and hemicellulose, contain a small percentage of lignin and have a porous structure. The basalt fibre/epoxy laminates dispersed with 0.6–1.0 wt% carbon nanosphere particles will be fabricated by hand lay-up method. To the best knowledge of the authors, no one has yet reported on the use of carbon nanospheres particles for the reinforcement in basalt composite laminates. The present work aims to study the new approach to investigate the effect of the incorporation of inexpensive carbon nanosphere particles in a basalt fibre-reinforced-epoxy matrix on the mechanical properties (i.e., tensile properties) of the composite laminates. The fractured surfaces will then be characterized by scanning electron microscopy (SEM).

MATERIALS AND METHODS

Basalt fibre (300 g/m^2 unidirectional 0°), was supplied by Suretex Composite International China. The epoxy used was epocast (Bisphenol) and the curing agent was amine based epoharden (cycloaliphatic amine). Both epocast and epoharden were supplied by Portal Trading Malaysia. The resin hardener mix ratio was 2:1 by weight. The prepared carbon nanospheres were in powder form. Scanning electron microscopy (SEM) was used to present the structure of the carbon nanospheres particles. Fig 1 shows the formation of carbon nanoparticles. The average particle size was 45-60 nm.

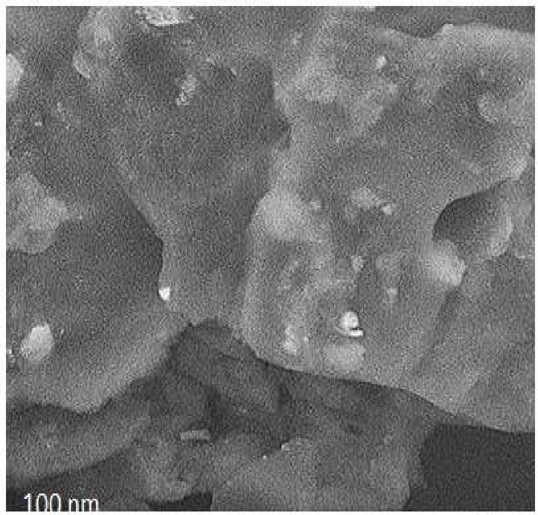

Figure 1: The particle size distribution of CNSs using SEM

Fabrication of composite laminate

First, the epoxy resin was dispersed in the acetone (10 wt% to resin). The CNSs powder was then mixed with the epoxy acetone solution (without hardener). The suspension was mixed for 24 hours using automatic mixer. After that, the hardener was added to the solution. The solution was stirred manually for 15 minutes to homogenise it. The mixture was then degassed for 1 hour in a desiccator to remove the entrapped air bubbles. CNSs powder concentrations added varied from 0.6 wt% to 1 wt% with respect to the mixture of the epoxy/hardener.

The basalt fibre reinforced composite laminates were fabricated by the hand lay-up method. A total of four plies of basalt fibres fabric with a size of 300 mm x 300 mm were stacked together. Three laminates were fabricated for this work. First laminate was of neat basalt, second laminate was of basalt with 0.6 wt% of CNSs particles, and third laminate was of basalt with 1.0 wt% of CNSs particles. The laminates were cured at room temperature for 24 hours. Then the specimens for tensile test and in-plane shear test were cut according to the ASTM standards from the prepared laminates. The schematic layout of fabrication of BFRP laminates is shown in Fig 2.

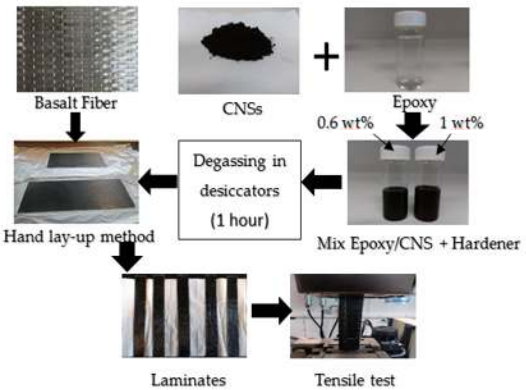

Figure 2: Schematic layout of the preparation and fabrication process of the BFRP and composite laminates.

Material testing

A tensile test was carried out to determine the stress-strain behaviour of the basalt fibre- reinforced polymer composites. The uniaxial static tensile tests were performed at room temperature under standard laboratory conditions (23±5°C and 50±10% relative humidity) according to ASTM D 3039. The ultimate tensile strength, ultimate tensile strain, and modulus were measured in longitudinal direction through the obtained stress-strain curves. Scanning electron microscopy (SEM, JEOL JSM-5900) was utilized to identify the morphological structure of the carbon nanospheres particles and the cross-section of the fracture surface of the composite laminates.

RESULTS AND DISCUSSION

The results of the tensile tests are reported in Table 1, which consist of the average values of five samples for each condition. The obtained stress-strain curves are presented in Fig 3. The value of stress was calculated based on the load recorded from the universal testing machine and the average cross section of laminates (average of three measurements).

Table 1: Summary of the tensile properties of BFRP and CNSs particle-reinforced composite laminates

Sample	Tensile properties			
	Tensile strength (MPa)	% Gain in strength	Young's Modulus (GPa)	% Gain in modulus
Neat Basalt	376	0	20	0
Basalt with 0.6wt% CNS	546	45.2	33	65
Basalt with 1.0 wt% CNS	679	80.6	44	120

Neat basalt showed the lowest tensile strength, while the addition of CNS particles has raised the tensile strengths of the composites. Fig 4 shows the average tensile strength and Young's modulus of the prepared samples. The neat basalt indicates a tensile strength of 376 MPa and Young's modulus of 20 GPa. The addition of CNS particles in the composite laminates enhanced both tensile strength and modulus and further increase of the properties was observed with the increase of CNS content. The composite laminates showed an increase in tensile strength of 45.2% and 80.6% for basalt with 0.6 wt% CNS and basalt with 1.0 wt% CNS, respectively compared to that of neat basalt (see Table 1). The modulus of elasticity is shown to increase steadily with increasing content of CNS particles. The increase of the tensile strength and the modulus of elasticity might be due to stronger fiber/matrix interfacial bonding (Rahmandoust et al., 2016). Among all the samples, basalt with 1.0 wt% CNS showed the best results for the tensile strength and Young's modulus.

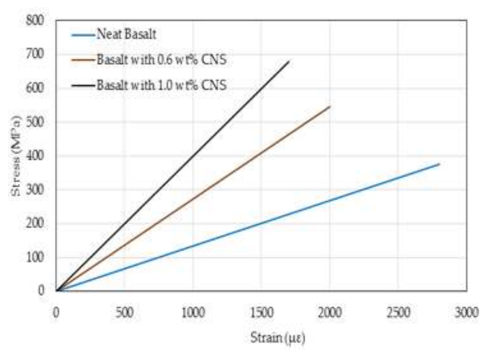

Figure 3: Typical tensile stress-strain curves of the laminates

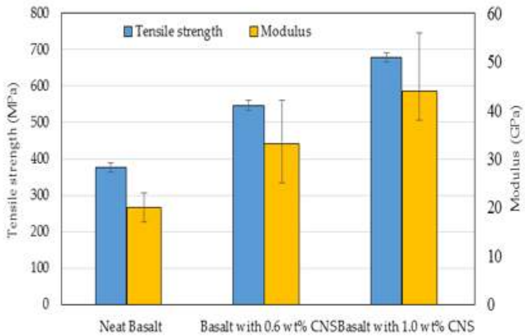

Figure 4: Average tensile strength and modulus of the BFRP and CNSs particle-reinforced composite laminate

Fractography

The portions of the fractured face of the basalt-CNS/epoxy composite samples were experimentally observed in SEM. It was aimed to study the microstructure of the basalt-CNS/epoxy composite material under load. Figure 5 shows the SEM images of the fractured surfaces for all three composite laminates after tensile test. In neat basalt, cracks in the resin have been observed with fibre-matrix interfacial debonding and separation and broken fibres (see Fig 5 (a)). Also, it was observed that most fibres are pulled out from the matrix. The composite laminates with different CNS particle contents showed better fibre-matrix bonding. In the case of basalt with 0.6 wt % CNS as shown in Fig 5 (b), the fracture surface was observed to be very flat with a small number of fibre breakages being identified. However, there was delamination growth within the interface of basalt with 0.6 wt% of CNS particles. In the case of basalt with 1.0 wt % CNS as shown in Fig 5 (c), general flat surface was observed with single fibre pull out.

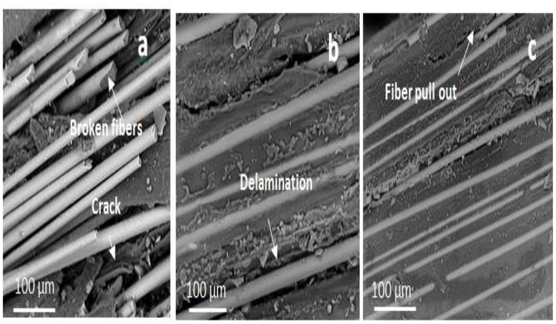

Figure 5: Representative SEM images of the fracture surfaces after tensile test of: (a) Neat basalt, (b) Basalt with 0.6 wt% CNS, and (c) Basalt with 1.0 wt% CNS.

CONCLUSION

In this study, we have demonstrated that tensile strength, Young's modulus and modulus of rigidity are enhanced by reinforcing the basalt fibre with carbon nanospheres particles. To summarise, this paper examined the result of carbon nanospheres particle-loading of 0.6 wt% and 1.0 wt%, on the mechanical properties of basalt fiber-reinforced epoxy composite laminate. The composite laminates with different CNS loading showed better tensile properties compared to the neat basalt fibre-epoxy composite (BFRP). The best result was found for 1.0 wt% addition of CNS particle, where the tensile strength is the highest compared to neat basalt and basalt with 0.6 wt% CNS. The tensile strength increased by 45.2% with 0.6 wt% of CNS addition and increased by 80.6% with 1.0 wt% of CNS addition. Moreover, the Young's modulus increased by as much as 120% when added with 1.0 wt% of CNS particles. SEM images displayed good epoxy-fiber bonding with carbon nanospheres particles. The improvements in the mechanical properties are associated to the good dispersion of CNS particles in the epoxy matrix. This paper indicates that the tensile strength of neat basalt fiber can be improved by the homogeneous dispersion of inexpensive CNS particles obtained from the biowaste sago bark in the epoxy matrix. With proper dispersion of micro/nano fillers, it will enhance the tensile strength of the basalt composite laminate. The applications of basalt fibre in the industries would benefit from this study and could contribute to more knowledge on the exploitation of micro/nano particles to further improve the properties of epoxy-based composite materials.

REFERENCES

- Dean D, Obore AM, Richmond S and Nyairo E. (2006). Multiscale fiber-reinforced nanocomposites: synthesis, processing and properties. Compos Sci Technol 66(13):2135-2142.

- Liu L, Huang ZM, He CL, Han XJ. (2006). Mechanical performance of laminated composites incorporated with nanofibrous membranes. Mat Sci Eng A -Struct 435:309-317.

- Manikandan V, WinowlinJappes JT, Suresh SM., Amuthakkannan P. (2012). Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites. Compos Part B: Eng. 43(2):812-818.

- Bodros E, Pillin I, Montrelay N, Baley C. (2007). Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications. Compos Sci Technol. 67:462–470.

- Wambua P, Ivens J, Verpoest I. (2003). Natural fibres: can they replace glass in fibre reinforced plastics. Compos. Sci. Technol. 63:1259–1264.

- Wang BP, Zhang W. (2002). Basalt fibre properties and applications. Build Mater Technol. Appl. 4:17-8.

- Sim J, Park C, Moon DY. (2005). Characteristics of basalt fibre as a strengthening material for concrete structures. Compos. Part B: Eng. 36(6-7):504-512.

- Lopresto V, Leone C, De Iorio I. (2011). Mechanical characterisation of basalt fibre reinforced plastic. Compos. Part B – Eng. 42(4):717-723.

- Wei B, Cao HL, Song SH. (2011). Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater. Corros. Sci. 53(1):426-431.

- Colombo C, Vergani L, Burman M. (2012). Static and fatigue characterisation of new basalt fibre reinforced composites. Compos Struct. 94(3):1165-1174.

- Liu Q, Shaw MT, Parnas RS, McDonell AM. (2006). Investigation of basalt fibre composite mechanical properties for applications in transportation. Polym. Compos. 27(5):475-483.

- Olexandr M, Yuriy T. (2005). Basalt use in hot gas filtration. Filtr Separat 42:33-37.

- Berozashvili M. (2001). Continuous reinforcing fibres are being offered for construction, civil engineering and other composites applications. Adv. Mater Com News, Compos Worldwide 6:5-6.

- Goldsworthy WB. (2000). New basalt fibre increases composite potential. Compos Technol. 8:15.

- Militky J, Kovacic V, Rubnerova J. (2002). Influence of thermal treatment on tensile failure of basalt fibre. Eng. Fract Mech. 69:1025–1033.

- Lee J, Yoon S, Hyeon T, Oh S, Kim K. (1999). Synthesis of a new mesoporous carbon and its application to electrochemical double-layer capacitors. Chem. Commun 21:2177-2178.

- Yang H, Shi Q, Liu X, Xie S, Jiang D, Zhang F, Yu C, Tu B., Zhao D. (2002). Synthesis of ordered mesoporous carbon monoliths with bicontinuous cubic pore structure of Ia 3d symmetry. Chem. Commun 23:2842-2843.

- Stroller, M.D.; Park, S.; Zhu, Y.; An, J.; Ruoff, R.S. 2008, Graphene-based ultracapacitors. Nano Lett, 8 (10), 3498-3502.

- Berger C, Song Z, Li X, Brown N, Naud C, Mayou D, Li T, Hass J, Marchenkov AN, Conrad EH, First PN, de Heer WA. (2006). Electronic confinement and coherence in patterned epitaxial graphene. Science 312(5777):1191-6.

- Li Y, Fan X, Qi J, Ji J, Wang S, Zhang G, Zhang F. (2010). Palladium nanoparticle-graphene hybrids as active catalysts for the Suzuki reaction. Nano Res. 3 (6):429-437.

- Gilje S, Han S, Wang M, Wang KL, Kaner RB. (2007). A chemical route to graphene for device applications. Nano Lett. 7(11):3394-3398.

- Quercia L, Loffredo F, Alfano B, La Farrera V, Di Francia G. (2004). Fabrication and characterization of carbon nanoparticles for polymer based vapour sensors. Sens. Actuators B 100(1):22-28.

- Guo YG, Hu YS, Maier J. (2006). Synthesis of hierarchically mesoporous anatase spheres and their application in lithium batteries. Chem. Commun 26:2783-85.

- Yuan ZY, Su BL. (2006). Insights into hierarchically meso-macroporous structured materials. J. Mater. Chem. 16(7):663-667.

- Green KJ, Dean DR, Vaidya UK, Nyairo E. (2009). Multiscale fibre reinforced composites based on a carbon nanofiber/epoxy nanophased polymer matrix: synthesis, mechanical, and thermochemical behaviour. Compos Part A – Appl. S 40(9):1470-1475.

- Gauthier C, Chazeau L, Prasse T, Cavaille JY. (2005). Reinforcement effects of vapour grown carbon nanofibers as fillers in rubbery matrices.

Compos Sci. Technol. 65(2):335-343.

- Oh SJ, Lee HJ, Keum DK, Lee SW, Wang DH, Park SY. (2006). Multiwalled carbon nanotubes and nanofibers grafted with polyetherketones in mild and viscous polymeric acid. Polymer 47(4):1132-1140.

- An Q, Rider AN, Thostenson ET. (2012). Electrophoretic deposition of carbon nanotubes onto carbon-fibre fabric for production of carbon/epoxy composites with improved mechanical properties. Carbon 50(11):4130-4143.

- Tijing LD, Park CH, Choi WL, Ruelo MTG, Amarjagal A, Pant HR. (2012). Characterization and mechanical performance comparison of multi-walled carbon nanotube/polyurethane composites fabricated by electro-spinning and solution casting. Compos Part B: Eng. 44(1):613-619.

- Hedge G, Abdul Manaf SA,Kumar A, Ali GAM, Kwok FC, Ngaini Z, Sharma KV. (2015). Biowaste Sago Bark Based Catalyst Free Carbon Nanospheres: Waste to Wealth Approach. ACS Sustainable Chem. Eng. 3:2247-2253.

- Rahmandoust M, Ayatollahi MR. (2016). Characterization of carbon nanotube-based composites under consideration of defects. Springer International Publishing Switzerland, 196.