Materials and Design 40 (2012) 103–108

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Thermal and mechanical properties of waste grass broom fiber-reinforced polyester composites

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ARTICLE INFO

Article history:
Received 6 January 2012
Accepted 20 March 2012
Available online 30 March 2012

ABSTRACT

The main focus of this study is to utilize waste grass broom natural fibers as reinforcement and polyester resin as matrix for making partially biodegradable green composites. Thermal conductivity, specific heat capacity and thermal diffusivity of composites were investigated as a function of fiber content and temperature. The waste grass broom fiber has a tensile strength of 297.58 MPa, modulus of 18.28 GPa, and an effective density of 864 kg/m^3. The volume fraction of fibers in the composites was varied from 0.163 to 0.358. Thermal conductivity of unidirectional composites was investigated experimentally by a guarded heat flow meter method. The results show that the thermal conductivity of composite decreased with increase in fiber content and the quite opposite trend was observed with respect to temperature. Moreover, the experimental results of thermal conductivity at different volume fractions were compared with two theoretical models. The specific heat capacity of the composite as measured by differential scanning calorimeter showed similar trend as that of the thermal conductivity. The variation in thermal diffusivity with respect to volume fraction of fiber and temperature was not so significant.

The tensile strength and tensile modulus of the composites showed a maximum improvement of 222% and 173%, respectively over pure matrix. The work of fracture of the composites with maximum volume fraction of fibers was found to be 296 Jm^{-1}.

1. Introduction

Many countries have imposed rules and regulations to reduce solid waste in material manufacturing industries in order to protect the environment. Now a days, the energy consumption is increasing continuously and there by cost of the products is also increasing simultaneously. Therefore, various researchers and material scientists all over the world are focusing their attention on reducing energy consumption and operating costs. Vehicle manufacturers are also, making good use of improved resins and reinforcements to produce higher performing, lightweight automotive components that outperform and cost less than the parts they replace [1,2].

Earlier investigators have used natural fibers as reinforcement in the development of polymer composites [3–13]. Vegetable fibers can be extracted from different parts of the plant like stems, leaves, roots, fruits and seeds [3]. Symington et al. [4] studied the effect of moisture content on tensile properties of natural fibers: jute, kenaf, flax, abaca, sisal, hemp and coir, and concluded that the jute fiber exhibited better mechanical properties than other fibers. The low density and high porosity fraction of sansevieria cylindrica fiber is favorable for light weight applications and thermal, and acoustic insulation [5]. Different methods have been adopted to extract the fiber from elephant grass and found that in case of retting the yield of fiber was more when compared to the chemical and manual process [6]. Tensile, flexural strengths and elastic moduli of the unidirectional kenaf/PLA composites increased linearly up to fiber content of 50% [7]. Fiber extracted from waste water bamboo husk and disposable chopsticks has been used as reinforcement for making composite materials primarily for cost effectiveness and high volume applications [8,9]. Oil palm biomass waste is a suitable material for the production of binder less particle board composite panels [10]. Tensile modulus and impact strength of rice straw reinforced composites is about 1.66 and 18 times to that of pure polyester resin, respectively [11]. The tensile properties of sisal, hemp, coir, kenaf, and jute reinforced composites have been studied [12], and reported that among all the composites, hemp reinforced composite exhibited the highest mechanical properties whereas coir showed the lowest. Mechanical properties of jowar, bamboo and sisal fiber reinforced polyester composite were investigated, and found that modulus of jowar fiber composite is higher than sisal and bamboo fiber reinforced composites [13].

In addition to the mechanical characterization, the thermal behavior of composites is of great importance since they will be

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http://dx.doi.org/10.1016/j.matdes.2012.03.034

subjected to thermal loads in many applications. Thermal conductivity of composite is anisotropic property similar to elastic modulus [14]. Some theoretical and empirical models have been developed to predict the thermal conductivity of composites [15–19]. Heat flow meter [20] or the transient plane source method [15] was used to measure the thermal conductivity of polymer composites. Specific heat capacity of composites can be measured by differential scanning calorimeter (DSC) [21,22].

A considerable amount of literature is available on thermal behavior of synthetic fiber reinforced polymer composites [23–25]. But, little information is available on thermophysical properties of natural fiber reinforced composites over and above room temperature [26,27].

Broom grass (Scientific name: *Thysanalaena maxima*) is a tall grass and also known as tiger grass. It belongs to the family Poaceae and grows along banks of the rivers. The stems of grass brooms arise centrifugally during the peak growing season (April–July) and bear inflorescence on shoot apex at the end of the vegetative growth. The inflorescence that is about 30–90 cm long resembles a foxtail and used as broom.

The main purpose of grass broom is to clean the floors in domestic environment. It is quite usual to throw it out as a waste, after it is worn out. But, in this work, an attempt is made to utilize this household waste in the development of low cost, light weight novel composite materials. The present work reports the thermophysical properties such as thermal conductivity, specific heat capacity, thermal diffusivity and density besides mechanical properties of broom grass fiber reinforced composites.

2. Experimental procedures

2.1. Materials

Unsaturated polyester resin of grade ECMALON 4411, methyl ethyl ketone peroxide and cobalt naphthanate were purchased from Ecmass resin (Pvt) Ltd., Hyderabad, India.

2.2. Preparation of fiber

Used grass brooms (Fig. 1) were obtained from local sources. Cut fibers of required size from waste grass brooms, were soaked in water for about 4 h and washed thoroughly with detergent in order to remove dust that might have been accumulated in the grass broom during usage. The washed fibers were dried under the sun for 1 week, followed by oven drying at 70 °C for 2 h.

2.3. Testing of single fiber

In accordance with ASTM D3379–89 [28], the tensile properties of grass broom fibers were determined. Each fiber specimen was prepared by mounting on a piece of stiff cardboard with a gauge length of 50 mm. The ends of the fibers were glued onto the cardboard with epoxy resin and tested at a crosshead speed of 5 mm per minute. The diameter of the fibers was measured using an optical microscope at five different locations along the gauge length. The test was carried out for 25 specimens to get valid evidence. The picnometric procedure was adopted for measuring the density of fiber.

Fig. 1. Waste grass broom.

2.4. Fabrication of composites

Unidirectional composites were prepared, using polyester matrix to assess the reinforcing capacity of grass broom fibers. The quantity of accelerator and catalyst added to resin at room temperature for curing was 1.5% by volume of resin each. Hand lay-up method was adopted to fill up the prepared mould with an appropriate amount of polyester resin mixture and unidirectional fibers, starting and ending with layers of resin. Fiber deformation and movement should be minimized to yield good quality, unidirectional fiber composites. Therefore at the time of curing, a compressive pressure of 0.05 MPa was applied on the mould and the composite specimens were cured for 24 h. The specimens were also post cured at 70 °C for 2 h after removing from the mould.

2.5. Thermal conductivity measurement

The transverse thermal conductivity of the composites (Fig. 2) was measured using guarded heat flow meter (Unitherm model 2022, ANTER Corp., Pittsburgh, PA) in accordance with ASTM E1530–99 [29]. The test sample of size 50 mm in diameter and 10 mm in thickness were prepared. Eqs. (1)–(3) correspond to the calculation of thermal conductivity [30,31]:

$$q = \frac{k(T1 - T2)}{L} \tag{1}$$

$$R = \frac{(T1 - T2)}{q} \tag{2}$$

$$k = \frac{L}{R} \tag{3}$$

Where q is the heat flux (Wm^{-2}), k is the thermal conductivity ($Wm^{-1}\,K^{-1}$), $T1 - T2$ is the difference in temperature (K), L is the thickness of the sample (m), and R is the thermal resistance of sample ($m^2\,K\,W^{-1}$).

2.6. Specific heat capacity and density measurement

The specific heat capacity of samples was measured using a differential scanning calorimeter (TA Instrument, Model No Q20) at a

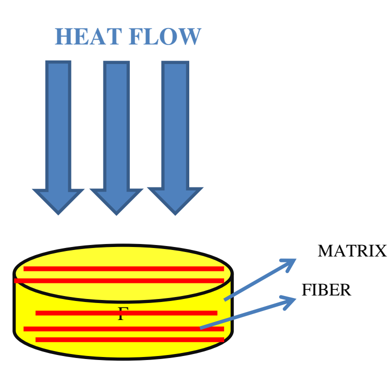

Fig. 2. Representation of transverse thermal conductivity.

heating rate of 10 °C/min. The picnometric procedure was adopted for measuring the density of the composite.

2.7. Tensile testing

The tensile properties of the composites were measured as per the standard test method ASTM D638–89 [32]. The test specimens with 160 mm long, 12.5 mm wide and 3 mm thick were prepared. Five identical specimens were tested for each percentage volume of fiber. Overlapping aluminum tabs were glued to the ends of the specimen with epoxy resin filling the space at the tab overlap to prevent compression of the sample and also for effective gripping in the jaws of the chuck. The specimens were tested at a cross head speed of 2 mm/min, using an electronic tensometer (Model METM 2000 ER-1), supplied by M/s Mikrotech, Pune. India.

2.8. Impact strength testing

Izod impact test notched specimens were prepared in accordance with ASTM D256–88 [33] to measure impact strength. The specimens were 63.5 mm long, 12.7 mm deep and 10 mm wide. A sharp file with included angle of 45° was drawn across the center of the saw cut at 90° to the sample axis to obtain a consistent starter crack. The samples were fractured in a plastic impact testing machine (capacity-21.68 J), supplied by M/s International equipments, Mumbai, India.

3. Results and discussion

3.1. Properties of single fiber

Before preparation of the composites, the authors studied the suitability of waste broom grass fibers as reinforcement. The density and tensile properties of some of important natural fibers along with broom grass fibers are presented in Table 1 for better comparison [34–36]. From this Table, it is clearly evident that, the density of broom grass fibers is very less compared to the established fibers like sisal, coir and hemp, which is an attractive parameter in designing light weight material. Even though the tensile modulus of broom grass fiber is better than that of coir fiber only, the tensile strength is more than those of sisal and hemp fibers and much higher than that of coir fiber. The percentage elongation at break is also much less than those of coir and sisal fibers.

3.2. Thermal conductivity measurement

The measured transverse thermal conductivity of pure polyester resin and broom grass fiber composites with different fiber loadings are presented in Table 2.The results show that thermal conductivity of the composites decreases as fiber content increases. This behavior of composite may be due to lower thermal conductivity of grass broom fiber. The thermal conductivity of fiber and matrix have been evaluated by extrapolating the linear regression of thermal conductivity values of the composite to 100% fiber and 0% fiber and are found be 0.1303 $Wm^{-1} K^{-1}$and 0.2457 $Wm^{-1} K^{-1}$, respectively.

The behavior of the thermal conductivity of different composites can now be explained using thermal conductivity values of the fiber. With the addition of grass broom fiber in the polyester matrix, the conductivity decreases by 8.75% and 24.35% for 0.261 and 0.358 volume fraction of fiber, respectively. Further, the measured thermal conductivity of composites was compared with series model (Rule of mixture) [15] and E-S model [17].The expressions for these two models are:

$$\text{Series model}: \frac{1}{kc} = \frac{vf}{k} + \frac{(1 - vf)}{kf} \tag{4}$$

$$\text{E-S model}: \frac{k_c}{k_m} = 1 - \frac{1}{c} + \frac{\pi}{2d} - \frac{c}{d\sqrt{(c^2 - d^2)}} \cos^{-1}\left(\frac{d}{c}\right) \tag{5}$$

where $c = \sqrt{\pi\rho/v_f}/2$, $d = \rho(1/\beta - 1)$, $\beta = k_f/k_m$, and v_f is volume fraction of fiber. k_c, k_f and k_m are the thermal conductivity of composite, fiber and matrix respectively.

The calculated and measured thermal conductivity of boom grass fiber-polyester composites as a function of fiber content are presented in Fig. 3. It is observed that the two theoretical models overestimate the value of thermal conductivity with respect to the experimental ones. This may be attributed to the fact that some of the assumptions taken for model are not practical. In E-S model, the cross section of the fibers was assumed to be elliptical, while in the present it is circular. Further, in theoretical models, orientation of the fibers was assumed to be perfect, but in actual practice when liquid matrix is poured over the fibers some of the fibers may be misaligned. However, at higher volume fractions of fiber, the experimental values of thermal conductivity are in close agreement with the predicted values (Fig. 3).These results indicate that the broom grass fiber reinforced composites considered in this study have good thermal insulation properties. The core of the fibers is porous and air is entrapped. This may be the reason for higher thermal insulation properties of the composites. Hence; these materials may be considered as building components to reduce heat transfer in air conditioned buildings in order to decrease energy consumption.

Also, thermal conductivity of broom grass/polyester composites with different fiber loadings is displayed as a function of temperature in Fig. 4. The thermal conductivity of all the samples increases with the increase of temperature because in this case the vibration of the phonons is the thermal carrier and the moisture in the fiber begins to evaporate and escape from the sample.

3.3. Specific heat capacity and density measurement

The specific heat capacity values of polyester resin matrix and fiber reinforced composites measured in the range of 30 °C–120 °C are shown in Fig. 5. The results show that the specific heat of composite decreases with increasing fiber content. This behavior of composite is attributed to the lower specific heat capacity of the fibers.

The variation in density of composite with respect to volume fraction of fiber is presented in Fig. 6. It is clearly evident that the density of the composite decreased with fiber content. The porous nature of the fibers may be responsible for decrease in the density of the composites under study. This means that with increase in fiber content, composites become light in weight. Hence, it is an attractive parameter for design of light weight structures.

Table 1
Comparison of the tensile properties of waste broom grass fibers along with other natural fibers [34–36].

Fiber name	Density (kg m^{-3})	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	% Elongation at break
Sisal	1450	50–300	227–700	9–20	3–14
Hemp	1480	80–250	270	19.1	0.8
Coir	1150	100–460	131–175	2.5–6	15–40
Waste broom grass	864	185–520	297.58	18.28	2.87

Table 2
Thermal conductivity, specific heat capacity and thermal diffusivity of grass broom fiber reinforced polyester composites at various volume fraction of fiber.

Volume fraction of fiber	Thermal conductivity ($Wm^{-1} K^{-1}$)			Specific heat capacity ($J kg^{-1} K^{-1}$)	Thermal diffusivity $\times 10^7$ ($m^2 s^{-1}$)
	Experimental	Rule of mixture model	E-S model		
0.163	0.231	0.2146	0.219	1986	0.953
0.227	0.225	0.2045	0.2103	1835	1.0313
0.261	0.219	0.1995	0.2059	1791	1.0482
0.358	0.196	0.1866	0.193	1639	1.0921

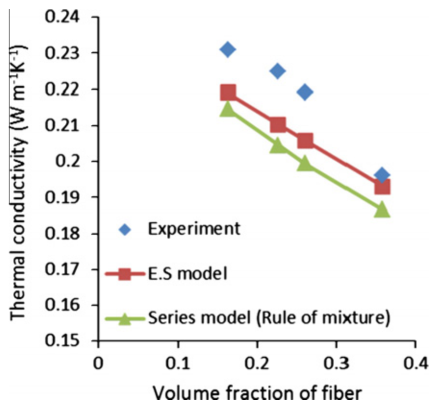

Fig. 3. The variation of thermal conductivity of fiber reinforced composite with volume fraction of fiber.

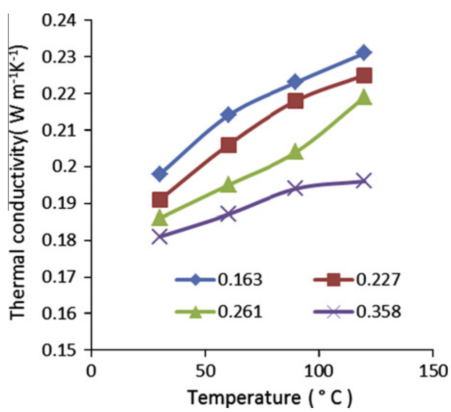

Fig. 4. Variation of thermal conductivity of composite with temperature at different volume fractions of fiber.

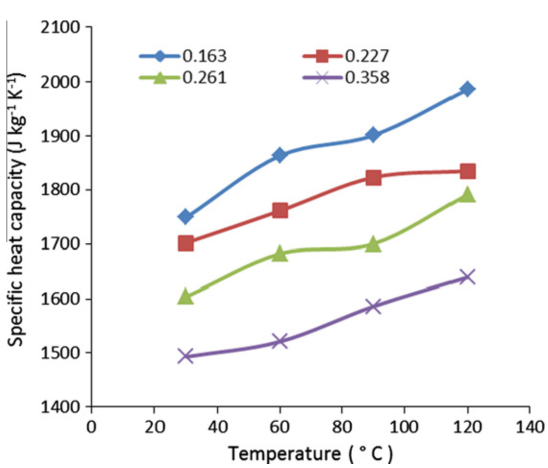

Fig. 5. Variation of specific heat capacity of composite with temperature at different volume fractions of fiber.

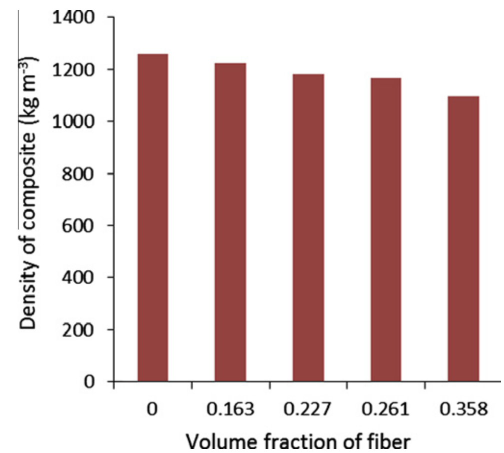

Fig. 6. Variation of density of composite with volume fraction of fiber.

3.4. Thermal diffusivity

The physical significance of thermal diffusivity is associated with propagation of heat into the medium during changes of temperature with time. The smaller the thermal diffusivity, more the time required for heat to penetrate into the solid. Thermal diffusivity (α) is a function of the thermal conductivity (k_c), specific heat capacity (C_p), and density (ρ) and can be calculated from the relationship [30].

$$\alpha = \frac{kc}{\rho Cp} \tag{6}$$

The thermal diffusivity of the composites was determined over a temperature range of 30 °C–120 °C and the values are presented in Fig. 7.The results show that the variation in thermal diffusivity with respect to volume fraction of fiber and temperature is marginal. The variation of composite density with respect to temperature was not considered, this may be the reason for varied trend of diffusivity with respect to temperature. The thermal diffusivity of grass broom/polyester composite at maximum volume fraction was found to be 1.0921×10^{-7} m^2/s, whereas for copper and ground cork it is about 1140×10^{-7} m^2/s and 1.5×10^{-7} m^2/s, respectively [30]. This indicates that the present composite materials require a longer period of time either for heating up or cooling than that of copper and cork. It is observed that the diffusivity is proportional to thermal conductivity results. It is an added advantage especially in building materials to increase fire resistance.

3.5. Tensile properties

The variation of mean tensile strength and tensile modulus with varying fiber content is presented in Figs. 8 and 9, respectively. It is clearly evident that with increasing fiber content in the polyester matrix, the tensile strength and tensile modulus are also increasing. This is due to the fact that the polyester resin transmits and distributes the applied stress to the broom grass fibers resulting in higher strength. Therefore, the composite can sustain higher

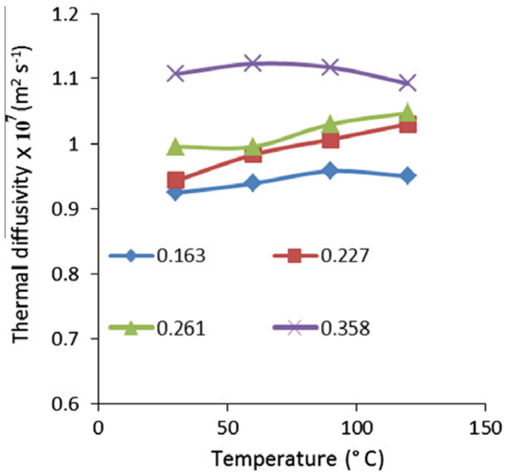

Fig. 7. Variation of thermal diffusivity of composite with temperature at different volume fractions of fiber.

load before failure compared to the unreinforced polyester. The maximum percentage increment in tensile strength and tensile modulus of the composites over the pure polyester at the maximum fiber content is found to be 222 and 173, respectively. The tensile strength of composite considered in this study is higher than that of vakka, and very close to banana fiber reinforced polyester composites [37].

The effect of volume fraction of fiber in the composite on the specific values of tensile strength and modulus are presented in Figs. 10 and 11. The results show similar trend as that of strength and modulus. This is understandable that the feasibility of developing inexpensive new composite incorporating broom grass fiber which is abundantly available as waste material, to be used in many applications that do not require very high load bearing capabilities such as sport goods, low cost building materials, automobile interior parts etc.

3.6. Impact strength

The results of pendulum impact test are shown in Fig. 12. As the volume fraction of grass broom fiber increases, the value of impact strength increases. The composites with the highest volume fraction of fibers have work of fracture of 304 J/m which is eight times higher than that of pure polyester matrix. The impact strength of broom grass fiber composite is higher than that of the rice straw fiber reinforced composite [11]. Hence, broom grass fiber composites have potential applications where light weight and resistance to impact are primary requirements. The mechanical and thermal properties of the waste broom fibers/polyester composites indicate the feasibility of developing low cost and high strength light

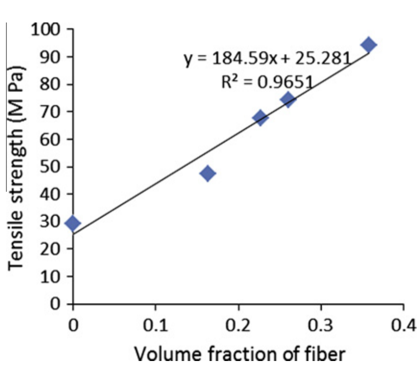

Fig. 8. Variation of tensile strength of composite with volume fraction of fiber.

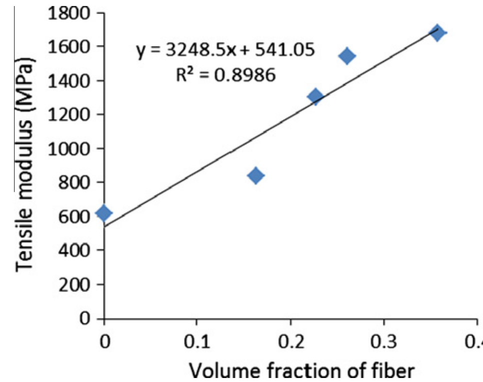

Fig. 9. Variation of tensile modulus of composite with volume fraction of fiber.

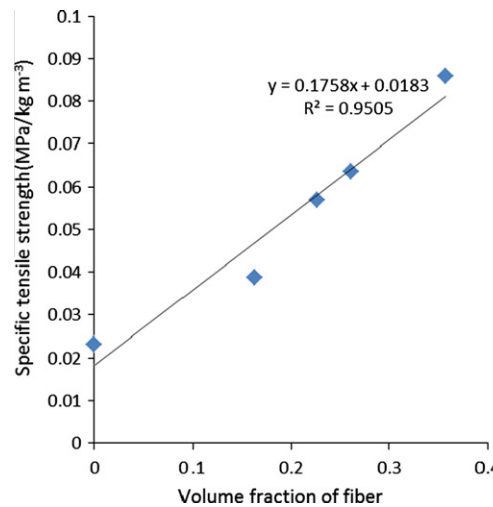

Fig. 10. Variation of specific of tensile strength of composite with volume fraction of fiber.

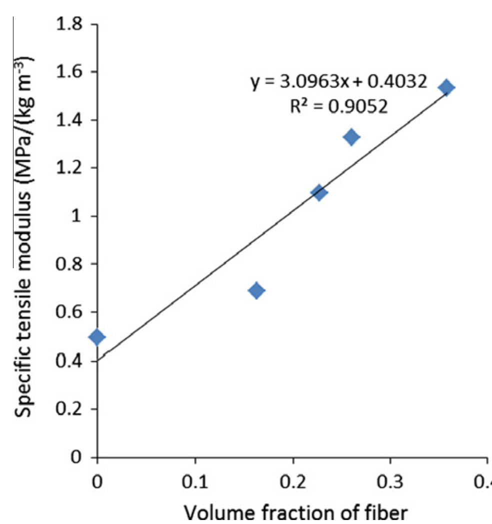

Fig. 11. Variation of specific of tensile modulus of composite with volume fraction of fiber.

weight insulating composites with broom grass fibers which are abundantly available as waste. These composites can be considered for manufacturing sports goods, low cost building materials, automobile interior parts etc.

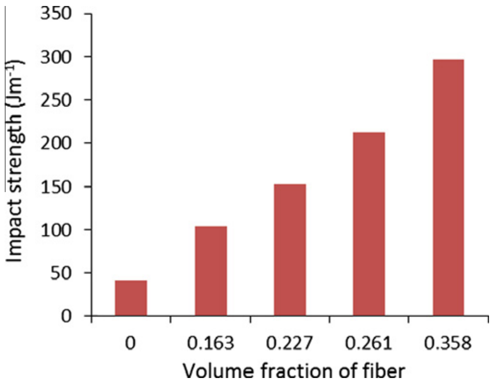

Fig. 12. Variation of impact strength of composite with volume fraction of fiber.

4. Conclusions

In this work, partially biodegradable green composites with various volume fractions of waste grass broom fibers were successfully developed and their thermal and mechanical properties were investigated. From the results obtained, the following conclusions are drawn:

- The tensile strength of broom grass fiber is relatively more than those of sisal and hemp fibers and much higher than that of coir fiber.
- The thermal conductivity of the composites has decreased with increase in volume fraction of fibers.
- At maximum volume fraction of fiber, the thermal conductivity of the composites has varied from $0.181\ W\ m^{-1}K^{-1}$to $0.196\ W\ m^{-1}K^{-1}$in the temperature range of 30 °C–120 °C.
- The influence of fiber content and temperature on specific heat capacity of composite was similar as the thermal conductivity.
- The variation of thermal diffusivity of composite with respect to fiber content and temperature is marginal.
- The tensile properties of the composites with these fibers are found to be higher than that of the matrix and have increased with fiber content. The measured tensile strength and tensile modulus of composite at maximum fiber content are found to be 94.08 MPa and 1679 MPa, respectively.
- The impact strength of composite is eight times to that of pure polyester matrix.

The results of this study indicate that the waste grass broom fiber reinforced composites are light in weight, economical and possess good thermal insulating and mechanical properties. Hence, the newly developed composite material can be used for applications such as automobile interior parts, electronic packages, building construction, and sport goods.

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