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Thermomechanical properties of glass fabric/epoxy composites filled with fly ash

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ABSTRACT

The mechanical activation of fly ash was carried out using ball milling to promote adhesion with epoxy. The 5 h of wet pulverization was found to result into particle size of less than 500 nm. The obtained nanoparticles were incorporated into epoxy to prepare three layered laminated composite of glass fabrics. The results revealed substantial improvement in mechanical properties of nanocomposites as compared to neat and unmilled fly ash composites. Moreover, the storage modulus exhibited 85.71, 38.09, 104.76 and 80.95% increment over neat composites for 1, 3, 5 and 10 wt% of activated fly ash at 200 °C.

1. Introduction

In recent years, the demands for damping performance of polymeric materials have increased significantly as a result of developments of structural applications in aerospace, marine, automobile, construction, etc. The epoxy resin is widely used for such applications but shows poor performance in high damping structural fields due to its limited mechanical properties, shrinkage ratio and acclimatization [1]. To overcome these problems, incorporation of inorganic nanoparticles into epoxy resin was carried out in previous studies [2–8]. The inorganic nanoparticles are attractive fillers because of their light weight, high strength, corrosion resistance, and elevated temperature applicability [9–11]. The addition of sand, chalk dusts, etc into epoxy matrix was found to improve its mechanical, electrical or rheological properties [12,13]. However, in the present scenario, the utilization of inorganic fillers obtained from waste materials has gained an importance due to increased burden on the environment. One such source is the utilization of waste fly ash particles, which are interesting because of their low density, low cost, strong filling ability, and smooth spherical surface [10,12].

Fly ash is the residue from combustion of pulverized coal in thermal power stations. It is a mixture of oxides, rich in silicon (SiO_2), iron (Fe_2O_3), and aluminum (Al_2O_3). The benefits of fly ash are realized for variety of structural products like sport equipments, insulation, automobile bodies, marine craft bodies, fire and heat protection devices [14,15]. Fly ash based light weight composite materials are also reported to be suitable in automotive, chemical and furniture manufacturing industries due to their improved strength, stiffness and thermal resistance.

The studies on the fly ash filled polymer composites are carried out extensively over the past several years [16–21]. The effect of volume fraction of fly ash on the mechanical properties of unsaturated polyester composites have been studied by Chand [22], and found that increasing the volume fraction of fly ash reduced the tensile and impact strengths of the composites. The creep tests of polyoxymethylene composites were conducted by Koszkul and Kwiatkowski [23], who pointed out that the rupture property was enhanced 20% by filling the matrix with 30% microspheres from fly ash. The effect of addition of fly ash into recycled polyethylene terephthalate have been studied by Li [24], and found reduction in its thermal decomposition and shrinkage. There are number of such studies which indicated unpredictable improvements in properties after addition of fly ash. This behavior is attributed to the variations in interfacial properties between fly ash and matrix [25–27].

The size and surface of fly ash are important factors to decide the interfacial properties. The size of filler is important factor to govern

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the size of interface, whereas surface of filler decides the strength of interface [13,28]. The surface of fly ash is usually modified based on silane or non-silane (i.e. stearic acid, titanate, etc) coupling agents [12,14]. However, there is limited information on modification of size of fly ash together with their surface modification. In present study, ball milling process is employed to simultaneously modify the size and surface of fly ash particles in a single stage. The present study is mainly concerned on mechanical activation of fly ash particles by the action of high energy wet milling process and subsequent improvements in mechanical or thermo-mechanical properties of glass fabric/epoxy laminated composites filled with those particles. The wet milled fly ash is expected to improve the interfacial adhesion between fly ash and epoxy, thereby changing the deformation and fracture mechanisms of epoxy composites [29]. The study also includes a comparison of properties of composites containing unmilled fly ash particles in as received condition with multimodal distribution.

2. Experimental methods

2.1. Materials

The woven fabric of 600 Tex glass fiber, having 2027 g/m^2 areal density, 2.15 mm thickness and 0.34 fiber volume fraction was selected as reinforcement. The epoxy resin LH 288 and the hardener HY 951 were purchased from Havel Composites Czech Republic. The resin and hardener were mixed in a ratio of 130:10 by weight as recommended by the supplier. Fly ash was obtained from the city of Plzeň located in the Czech Republic with the help of SILO Transport organization. The fly ash was light gray in color with density of 2 g/cc. The main constituents of fly ash as determined by elemental analysis are shown in Table 1, where maximum amount of silica and alumina with traces of other metal oxides can be seen. According to the composition, fly ash was classified in class-F category (ASTM C618) based on more than 70% total content of silica and alumina together.

2.2. Mechanical activation of fly ash by ball milling

The mechanical activation of fly ash was carried out using high-energy planetary ball mill of Fritsch Pulverisette 7 in a sintered corundum container of 80 ml capacity using zirconia balls of 3 mm diameter under wet condition in distilled water for the duration of 5 h. The ball mill was loaded with ball to fly ash weight ratio of 10:1. The rotation speed of the planet carrier was kept at 850 rpm. In this mechanical action, fly ash particles are subjected to a severe plastic deformation due to the repetitive compressive loads arising from the impacts between balls and fly ash. The obtained fly ash nanoparticles after wet milling process were dried in an oven at 120 °C for 6 h.

The milled fly ash particles were taken out at a regular interval of every 1 h of milling to test particle size distribution on Malvern Zetasizer Nano based on dynamic light scattering principle. The deionized water was used as dispersion medium. The dispersion was ultrasonicated for 5 min under Bandelin ultrasonic probe before characterization. Refractive index of 1.55 was used for fly ash to calculate particle size. In addition, morphology of fly ash after each stage of ball milling was observed on scanning electron microscope TS5130-Tescan SEM at 30 kV accelerated voltage.

2.3. Preparation of composites

The composite samples were prepared by hand layup technique taking fabric to epoxy weight ratio of 50:50. However, when fly ash fillers were added, weight fraction of epoxy resin was reduced but fabric weight fraction was fixed at 50%. The details are given in Table 2. The calculated amount of dried fly ash particles for 1, 3, 5 and 10 wt% loading was mechanically mixed with epoxy resin at room temperature until a homogenous mixture was obtained. Later, the mixture was ultrasonicated under Bandelin sonoplus for 30 min using horn power of 60%. The three layers of glass fabrics were stacked one on another after application of fly ash filled epoxy resin on every individual layer of fabric. A porous teflon film was used to complete the stack. In order to ensure uniform thickness of the sample, 3 mm spacer was also used. The whole assembly was placed in the convection oven under a predetermined pressure of 50 kPa and allowed to cure at 120 °C for 30 min.

2.4. Characterization of composites

2.4.1. Flexural testing

The flexural properties were measured by three-point bending method using specimens of dimensions 100 mm × 10 mm. The flexural test was carried out on a universal testing machine at a jaw speed of 0.8 mm/min under ASTM D790 standard. The minimum of four samples was tested and the average value was used for analysis.

2.4.2. Tensile testing

The tensile properties including tensile modulus, tensile strength and elongation at break were determined using specimens of dimensions 200 mm × 10 mm. The tensile test was carried out on a universal testing machine at a cross head speed of 50 mm/min under ASTM D 638 standard. In each category, a minimum of four samples was tested and the average value was used for analysis.

2.4.3. Charpy impact testing

The charpy impact test was performed under ASTM D 256 standard on specimens of dimensions 100 mm × 10 mm using a 2.7 J pendulum at a striking velocity of 3.46 m^2/s. The Avery Denison Impact tester was used. The minimum of four samples was tested and the average value was used for analysis.

2.4.4. Knife penetration resistance

Testomeric tester M350-10CT with single sharp pointed knife was used to study the penetration resistance of composite samples. The knife was allowed to penetrate through each sample at a velocity of 1000 mm/min and at 5 N preload. The test was repeated four times and the average value was used for analysis.

2.4.5. Dynamic mechanical analysis

The dynamic mechanical analysis was performed on DMA DX04T RMI instrument. The test was carried out in three point bending mode with gauge length and sample width of 30 mm and

Table 1
Quantitative elemental analysis data of as received fly ash.

Element	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe	Cu	As	Zr
Atomic [%]	53.80	1.84	1.06	14.27	20.25	0.09	0.19	0.25	0.94	1.95	4.72	0.16	0.15	0.34
Standard deviation	1.13	0.22	0.26	0.65	1.87	0.02	0.01	0.04	0.31	0.22	2.32	0.02	0.01	0.04