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Towards sustainable micro and nano composites from fly ash and natural fibers for multifunctional applications

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ABSTRACT

Manufacturing of petroleum based synthetic materials, exploitation of timber products from forest reserves, improper management of industrial wastes and natural resources greatly persuade the environmental contaminations and global warming. To find viable solutions and reduce such alarming issues, innovative research work on recycling of unutilized materials such as fly ash and natural cellulosic polymers has been reported in this work to develop advanced sustainable hybrid micro/nano composites. In this study, the use of natural cellulosic sisal fibers with fly ash has enhanced the tensile properties and surface finish of composites. Fly ash particulates acted as fillers, additives, as well as surface-finishing medium and sisal fibers as reinforcing elements in achieving glossy finish sustainable composites. The developed composites have been found to be stronger than wood, plastics and have many opportunities for multifunctional applications.

1. Introduction

Recently composites are becoming more fascinating materials and competing with the traditionally available metallic/ceramic materials and their conventional counterparts due to many significant advantages [1–8]. In particular, natural fiber reinforced polymer matrix composites offers unique features in terms of their inherent advantages such as environmental friendliness, specific strength, low cost, saving energy etc. to name a few [9–14]. Annually, more than 22 billion tons of wastes particulates are produced and disposed, universally on the earth and in ocean, which leads to many challenges to our environment. Among all other wastes, the quantity of Coal Combustion Residues (CCRs), so called fly ash, produced both in developing and developed countries alone are about 1.5 billion tons. In India and USA alone, during 2014–2015, thermal power stations produced about 240 million tons and 135 million tons of fly ash respectively. Frequently, CCRs comprises of different prime constituents namely pond ash, boiler slag, fly ash, bottom ash, along with some other solid fine particles released during the process of coal combustion [15]. It is apparent that one of the cause for environmental pollution is due to combustion of coal at high temperature above 1200 °C for power generation, worldwide, and has become a major challenge to safeguard air, soil, ground water, vegetation, aquatic flora and fauna and human health [16,17]. Though, fly ash has been used for many applications, maximizing the fly ash consumption and safe management has become a great challenge and issue to the producers, users and researchers [18].

1.1. Coal ash: world production and their characteristics

Due to the technological advancement, to meet the demand of energy requirements universally, there has been a considerable increase in power plant every year [19]. Presently, the major producers of coal ash are United States of America (~135 MTPA), Russia (~155 MTPA), India (~240 MTPA) and China (~520 million tons per annum MTPA) [20]. Different physical properties such as porosity, shape, size, density, water retention capacity etc. has significant influence on the safe disposal and recycling in different appropriate

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applications [17]. Particle size and other physical properties of Indian coal ash varies widely and specific surface area found to be greater than 0.1038 m^2 gm^{-1} [18]. It is evident from the work done that chemical constituents in fly ash tend to exist in the finer particles, which are mostly siliceous material. Such materials are used to chemically react with lime (CaO), in water and improve pozzolonic characteristics resulting enhanced mechanical strength in concrete composites [20,21]. The major mineral phases in fly ash has been found to be hematite, tricalcium aluminate, quartz (SiO_2), mullite, ($3Al_2 \cdot 2SiO_2$), and ferrite [20,21]. Some of the other mineral phases include albite tenorite (CuO), ($KalSi_3O_8$), nepoutite (NiMg) $3Si_2O_{15}(OH)_4$, esperite (CaPb) $ZnSiO_4$, and mullite ($Al_6Si2Ol3$). The geo-technical studies showed that co-efficient of permeability of coal ash varies from 10^{-4} to 10^{-3} mm/sec and young's modules of coal ash found to be 13–126 GPa, which depends on various characteristics of coal ash [22,23].

1.2. Recycling opportunities

Significant efforts are currently being made to improve the pozzolanic property of ash through grinding and classification to increase the surface area of coal ash particles to increase the reactivity in cement concrete mixtures. High volume use of lignite coal ash (60%) with rice husk ash (25%) and fine aggregates were used to attain 40–50 MPa compressive strength of self-consolidating concrete [24]. Glass-ceramics were prepared using coal ash for use in wall-covering panels, floors tiles equivalent quality to that of marble and granite [25]. Processed coal ash has many application potential to be used as raw materials in construction sectors such as bricks, cement, concrete, adhesives, road embankment etc. [17,20,26], . In some coal ash specimens, the unburned carbon amount has been found to be 10%–45%, that hinders the use of such ash in cement production, however it helps in broadening its use in waste water treatment as an effective adsorbent [27]. Considerable research has been done universally for effective utilization of coal ash in mine reclamation, composites, paint, agriculture, hazardous waste immobilization, geo-polymeric concrete, waste water treatment and recovery of value added materials [28]. Unfortunately, not much work has been done on the usage of coal ash for the preparation of polymeric composites [29]. Indeed, the coal ash exhibit a very high potential to be used as a low cost reinforcement and an important component in polymer matrix composites (PMC) as well as in other composites systems such as metal/ceramic/cement/concrete matrix composites. Coal ash is potentially a resource materials and can be used as a particulates in composites and its availability become certain till the living system exists. Along with fly ash, sisal fibers represents another important economic biorenewable resource. The usage of these cellulosic sisal fibers have not yet effectively exploited for their use for value added engineering reinforcement. So, in this work, the properties of the raw materials, process development in fabrication of composites, performance of the composites and possible applications for multifunctional utility have been reported and discussed in detail.

2. Materials and methods

In the current study, fly ash was procured from the Electro Static Precipitator and was collected from Satpura Thermal Power Station (STPS), Central India (Fig. 1a). The term ash in this work refers to the fly ash. Different Fly ash specimens were dried in an oven at 105 °C ± 2 °C and were used for physico-chemical characterization as well as conducting experiments for the preparation of polymer composites. Sisal leafs used in this study were harvested from the known source of cultivation at CSIR-AMPRI Bhopal, Central India. Fibers were extracted from the sisal leafs by an instantaneous mechanical process, without affecting its quality, using a Respador machine [30]. Extracted sisal fibers were sun dried at 36 °C± 2° for 2–3 h till these fibers reached the moisture as low as 12% and were subsequently combed to remove unwanted residues including wax (Fig. 1b). Such processed sisal fibers were cut into about 3.5 cm length uniformly and perform mats were fabricated using a motorized rolling screen drum and are shown in Fig. 1c and d respectively.

Fig. 1. (a) Fly ash of STPC, Sarni, Madhya Pradesh, India (b) Processed sisal fibres from CSIR-AMPRI Bhopal, India (c) Processed sisal fibres cut into about 3.5 cm length 3–4 cm (d) Perform mats fabricated out of sisal fibres.

2.1. Test methods adopted for raw materials characterization

Particle size analysis of fly ash particulates was done using Laser Diffraction Particle size analyzer (Model HELOS, Sympatec GMBH, Germany) and $Na_4P_2O_7$ was used for facile dispersion of Fly ash in water medium. pH and conductivity studies were done using Orion analyzer (Model 1260, Orion Research Inc., USA) in a 1:2 solid: water suspension. Fly ash particulates were digested in a microwave digester (QLAB 6000, Canada) and chemical elements were analyzed from the digested extracts using Atomic Absorption Spectrophotometer (Z-5000, Hitachi, Japan) with flame and graphite system. However, the presence of silicon, aluminum, iron, calcium, magnesium, sodium and potassium was estimated by Field Emission Scanning Electron Microscope (FESEM) with Energy Dispersive Spectrometer and Electron back Scattered Diffraction system, Model 1E Synergy 250, Oxford Instrument UK) facility. High purity water distilled from Prima1-3 and Elgastat Maxima, England was used for all chemical analysis. Sisal fiber microstructure was studied using Scanning Electron Microscope (SEM), Model JOEL JSM-5600 Japan. Tensile properties of sisal fibers (ASTM 5526) were studied using Universal Testing Machine (UTM), 5 KN capacity, LRX Plus, Lloyd, UK employing 2.5 KN load cell at a rate of speed 5.0 mm/min with a gauge length 50.0 mm. The preload/stress was 20.0 gf with preload/stress speed of 2.0 mm/min.

2.2. Preparation of composites

Composite specimens were fabricated using fly ash as a reinforcement in the epoxy polymeric system using hand lay-up process followed by compression molding system. Composites developed in the present study using fly ash with and without sisal