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Morphological and mechanical properties of chemically treated municipal solid waste (MSW)/banana fiber and their reinforcement in polymer composites

Abstract: Municipal solid waste (MSW) generation increased rapidly due to the change in food habits, increasing urbanization and changed lifestyle of people. The aim of the present study was to analyze the possible use of MSW as filler in fiber-reinforced urea formaldehyde composites. The mechanical properties of the composites were investigated as a function of different volume fractions (V_f) of filler (MSW and banana fiber) and its chemical modification. The MSW was chemically treated using $NaClO/H_2O$ (1:1) at 60°C and was analyzed using density measurement, X-ray diffraction, Fourier transform infrared spectroscopy, and scanning electron microscopy (SEM). The water absorption and thermal behavior of both raw and treated MSW were also studied. The chemical composition of treated MSW showed decreased cellulose and lignin content compared to that of raw MSW. MSW/banana fiber-reinforced urea formaldehyde composites with different filler ratios were prepared. The composites were analyzed by SEM and tensile, flexural and impact strength tests. The tensile, flexural and impact strength increased up to 40% V_f of filler and then decreased, which indicates effective stress transfer between fillers and matrix. The chemically treated composites showed higher tensile and flexural strength compared to untreated composites due to the strong interfacial interaction between the resin and the fiber.

Keywords: chemical treatment; municipal solid waste; volume fraction.

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1 Introduction

Rapid industrialization and population explosion in the recent years have led to the migration of people from villages to cities. Globally, the estimated quantity of municipal solid waste (MSW) generated was estimated to be 1.6 billion tonnes in the year 2002. It is estimated that 19 billion tonnes of solid waste are expected to be generated annually by the year 2025. Asia alone generates 790 million tonnes (MT) of MSW of which 6% are generated in India. Urban India generates 188,500 tonnes per day (68.8 MT per year) of MSW at a per capita waste generation rate of 500 g/person per day. This is expected to increase significantly in the near future, reaching approximately 300 MT, and land requirement for disposal of this waste would be nearly 169.6 km^2 in the year 2047 [1–3]. As the disposal of so much volume of MSW would be difficult through the landfills, alternate methods of disposal or applications of MSW have become the need of the hour. For environmental, technical, and cost reasons, there is an increased interest in using MSW as filler in composite manufacturing. After paper and plastics are removed from MSW, it can be used as filler for making particle board. The use of these MSWs from institutional units as fillers for making particle board will make a better solution for management of MSW compared to present options such as landfill, open dumping, incineration, etc. However, not much work has been carried out on the application of MSW as filler in composite materials. Ashori [4] analyzed the potential of using MSW for making wood plastic composites. The possibility of using waste wood, waste paper and waste plastics in the composite panel development was also discussed. Chemical treatment in general improves the filler-matrix adhesion, interfacial strength and thermal and water barrier properties of MSW. Geng et al. [5] developed sodium

hydroxide-treated black bruce bark boards. The results indicated that treated bark boards have higher internal bonding strength and higher bending strength compared to untreated bark boards. The effect of enzyme treatment on the properties of wheat straw board was analyzed. The surface wax content of wheat straw, which is the main adhesion inhibitor, was reduced by this treatment. Better bending, internal bond and thickness swelling properties were observed after the enzyme treatment [6]. Sareena et al. [7] analyzed the use of coconut shell powder as filler in natural rubber. The results showed that coconut shell powder is the most effective filler in natural rubber at 10 parts per hundred loading. The reinforcement ability of modified coconut shell powder is more when compared to that of unmodified coconut shell powder. Also, modified coconut shell powder-reinforced natural rubber shows better physicomechanical and thermal properties. In another study [8], the mechanical properties of peanut shell powder-reinforced natural rubber composites were analyzed. The results indicated that modified peanut shell powder composites show better mechanical properties. Also, the transport behavior of benzene, toluene and xylene in peanut shell powder-reinforced natural rubber composite at various temperatures was analyzed by conventional weight-gain experimental method [9]. The estimated Arrhenius activation energies (E_D) for the sorption, diffusion and permeation process showed the highest E_D value in xylene solvent in terms of peanut shell powder contents. The diffusion mechanism was found to follow a Fickian trend in benzene.

Hybrid composites are made of two or more different types of short fibers having different lengths and diameters. Many researchers have developed composites using various natural fibers such as coir, sisal and ramie. Out of these natural fibers, banana fiber as filler was extensively studied [10, 11]. India and Brazil are the largest producers of bananas. Approximately 1.5 million acres of land are utilized for banana cultivation, and this yields approximately 3×10^5 tonnes of fibers [12]. The influence of the fiber volume fraction, fiber length and alkali treatment of banana fiber on the mechanical and thermal properties was evaluated by Claudia et al. [13]. The treated banana fiber showed higher tensile strength and shear interfacial stress when compared to the untreated fiber. Joseph et al. [14] reported that tensile strength and Young's modulus of banana fiber-reinforced phenol formaldehyde composite increased on increasing the fiber length up to 30 mm. Also, there is an increase in tensile, flexural and impact properties with increasing of fiber loading. However, to date, not much work has been carried out on hybridization of MSW as filler in banana fiber composite panels. The use of MSW as filler for making composite panels may lead to a better solution for management of MSW compared to present options such as landfill, open dumping, incineration, etc.

In this work, MSW was treated with sodium hypochlorite ($NaClO/H_2O$). The treated MSW was characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) methods. The aim of the present study was to analyze the possible use of MSW as filler in the development of MSW/banana fiber/urea formaldehyde (UF) composite panel. Mechanical properties of the composites were also investigated through SEM and tensile, flexural and impact tests.

2 Materials and methods

2.1 Chemical treatment of MSW and banana fiber

MSW collected from local educational institution National Institute of Technology, Tiruchirappalli, Tamilnadu, India, mainly consisted of vegetable waste, fruit peels, food, etc. It was dried in sunlight for 24 h and ground by a pulverizer (VB Ceramics Consultants, Chennai, India). The powdered MSW was screened to remove excess fines using a sieve shaker machine (VB Ceramics Consultants, Chennai, India) over a screen size of 25 mesh (600 μm). To obtain the treated MSW, the powdered MSW was dipped in $NaClO/H_2O$ solution in 1:1 proportion under heating for 4 h. Consequently, the powdered samples were cleaned with distilled water and dried in a hot-air oven (60°C) for 24 h.

Banana fibers used for this study were chemically treated in the laboratory as explained in our previous work [15]. Banana fibers were obtained from YMCA, Kanyakumari district, Tamilnadu, India. Sodium hypochlorite (NaClO) was procured from Rabi Chemicals, Trichirappalli, Tamilnadu, India. UF resin and ammonium chloride (NH_4Cl) were procured from the Mayore Polymers Ltd, Bangalore, India.

2.2 Chemical analysis of MSW

The composition of MSW, namely, lignin, cellulose, wax and ash, and moisture content were determined following the procedure reported in the literature. Klason method was used to determine the lignin content of MSW samples [16]. The cellulose content was measured by Kurschner and Hoffer's method [17]. The wax content present in the MSW was determined using Conrad's method [18]. The

moisture content was determined by drying a particular quantity of MSW samples in an oven at 104°C for 4 h.

2.3 Physical property determination of MSW

The particle size of MSW was analyzed using a laser particle size analyzer, Blue wave model 10.5.4. The particle size and volumetric distribution of particle size were expressed by the intensity of light scattered on the population of particles [19]. The absolute density of both raw and treated MSW was measured by using True Density Meter SMART PYCNO 30 [20]. The method of calculating the density of MSW sample is as follows:

$$\text{Absolute density of MSW}(\rho) = \text{sample weight / sample volume measured}(V_P) \quad (1)$$

$$V_P = V_C - V_R[(P1/P2) - 1] \quad (2)$$

where V_P is the sample volume (cm^3), V_C is the volume of sample cell (13.12 cm^3), V_R is the volume of reference cell (7.21 cm^3) and $P1/P2$ is the pressure ratio between the volumes of the sample cell and the reference cell.

2.4 Instrumentation techniques

X-ray spectra (scan range 2θ=10–30°, scan speed=0.5°/min) of raw and treated MSW samples were obtained with a Rigaku X-ray diffractometer model with an X-ray tube producing monochromatic Cu-Kα radiation operating at 40 kV/30 mA. The crystallinity of cellulose was determined from the diffraction intensity data. The normal diffraction planes of the cellulose I are 101, $10\bar{1}$, 021 and 002, which are present at 14.8°, 16.7°, 20.7° and 22.5°. The crystallinity index was calculated using Eq. (3) [21]:

$$\text{Crystallinity index} = \frac{I_{002} - I_{\text{amorph}}}{I_{002}} \times 100 \quad (3)$$

where I_{002} is the maximum intensity of the (002) lattice diffraction and I_{amorph} is the intensity diffraction at 18°.

FTIR studies were carried out by pelletizing the powdered samples of MSW with KBr and using a Perkin Elmer model Spectrum Rx1 FTIR spectrometer in the range of 400 to 4000 cm^{-1}. TGA studies of MSW were carried out using a horizontal differential type thermobalance TG/DTG EXSTAR 6200 in nitrogen atmosphere. Approximately 4 mg of samples was heated in a temperature range of 30–900°C at a heating rate of 40°C/min. DSC analysis of the MSW was carried out by using a DSC Q20 V22.4 build 116. MSW samples of approximately 6 mg were placed in an aluminum pan and were heated from 0°C to 400°C at 10°C/min under dynamic flow of air (20 ml/min).

2.5 Water absorption test of MSW

Water absorption measurement was carried out by immersing the raw and treated MSW in distilled water. The weight of the dried sample (W_d) before immersion was measured. The immersed MSW samples were taken out at regular periods and weighed. The percentage of water content was calculated using Eq. (4):

$$\text{Water content}(\%) = \frac{(W_i - W_d)}{W_i} \times 100 \quad (4)$$

where W_d is the initial weight of dried sample (g) and W_t is the weight of sample after immersion (g).

2.6 Fabrication of composites

A banana fiber of 30-mm length, which was the optimum length of the fiber that gives the maximum tensile strength to the fiber composite, was used for this study [14]. Curing of UF resin was done by adding 1% NH_4Cl as hardener. The composites were prepared by varying the filler volume ratio of MSW and banana fiber. The MSW, banana fiber and UF resin were mixed in a blender. The blended particles and fiber were transferred to a molding box of size 380 mm×300 mm×3 mm and pressed with a load of 40 tonnes under hydraulic press. Curing was done at a temperature of 150°C under constant pressure of 2.5 MPa for 24 h.

2.7 Mechanical properties and morphology of composites

Tensile and bending tests were carried out using an Instron Tensile Testing machine 8801 at a crosshead speed of 5 mm/min as per ASTM D 638-03. Test specimens were cut from the fabricated composite panel as per the standards. The three-point bending properties were determined at a crosshead speed of 1 mm/min in accordance to ASTM D 790-86. The Izod impact test was done on an unnotched specimen using a digital impact tester as per ASTM D 256-10. In each case, five specimens were tested to obtain the average value. The morphology of raw and treated MSW was analyzed by using SEM. The fracture surface behavior and fiber-matrix interaction of tensile specimens were also analyzed. The fracture surfaces were dried and coated with gold particles for conductivity. Then, the micrographs were obtained using field emission SEM with an INCA PENTAFET X3 7421.

3 Results and discussion

3.1 Morphology and particle size distribution of MSW

The raw and NaClO-treated MSW, which is brownish in color, are shown in Figure 1A and B, respectively. The SEM images of the MSW particle before and after chemical treatment are shown in Figure 2A and B. Treated MSW shows rougher surfaces compared to raw MSW. This is expected due to the removal of wax and other constituents present in the sample. Raw MSW particles show the presence of some flaky structure and pores, whereas the SEM micrograph of treated MSW shows the presence of wide pores.

Particle size distribution of raw and treated MSWs is shown in Figure 3. The accurate determination of particle size distribution of these MSWs is particulary important for improving the mechanical properties of particle board. It is observed that the size disribution curve slightly moves toward the large size zone after chemical treatment. It can be seen that particle size distribution of raw MSW is in the range from 5.86 to 53.93 μm, whereas for treated MSW it is in the range of 69.93–320.6 μm. One half (50%) of the raw particles are smaller than 25.83 μm, whereas for treated MSW, it is smaller than 226.9 μm. The percent of weight reduction after chemical treatment is 6%. The properties of both raw and treated MSW are given in Table 1. The absolute density is a measure of the solid matter of the MSW, which excludes all the pores and lumen. The

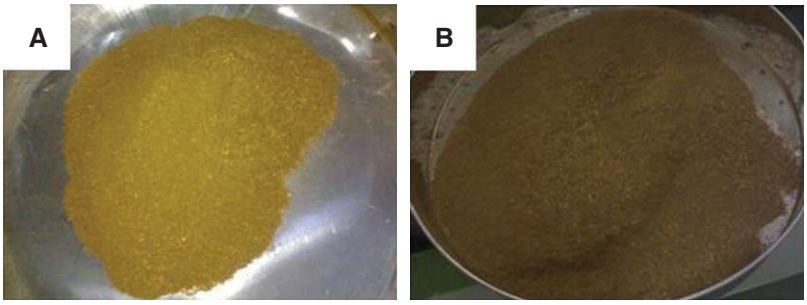

Figure 1 Municipal solid waste: (A) raw and (B) treated.

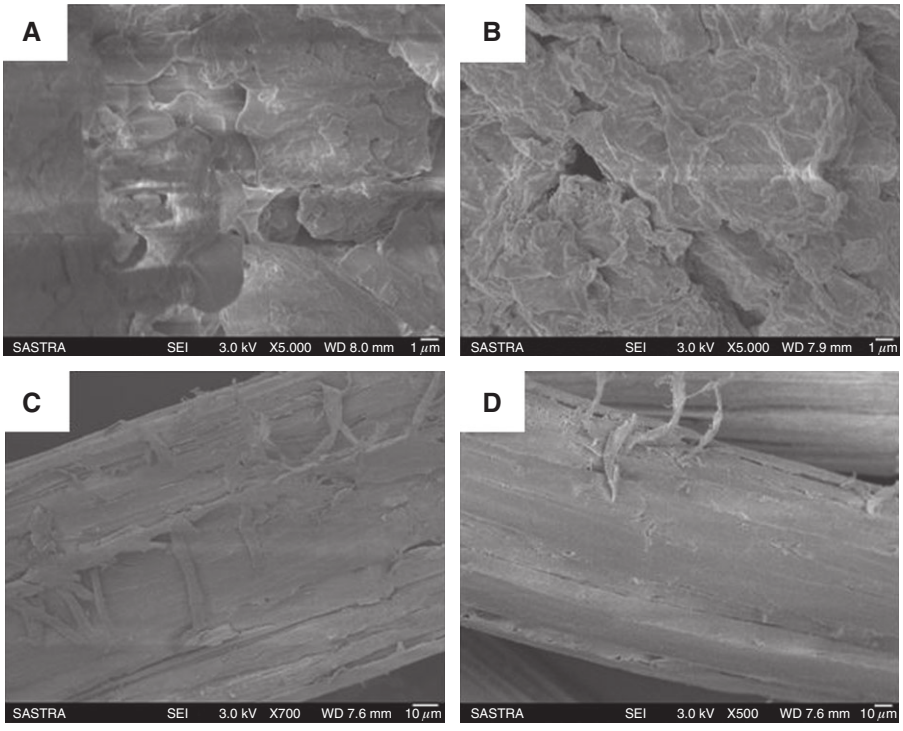

Figure 2 SEM micrograph of (A) raw MSW, (B) treated MSW, (C) raw banana fiber and (D) treated banana fiber.

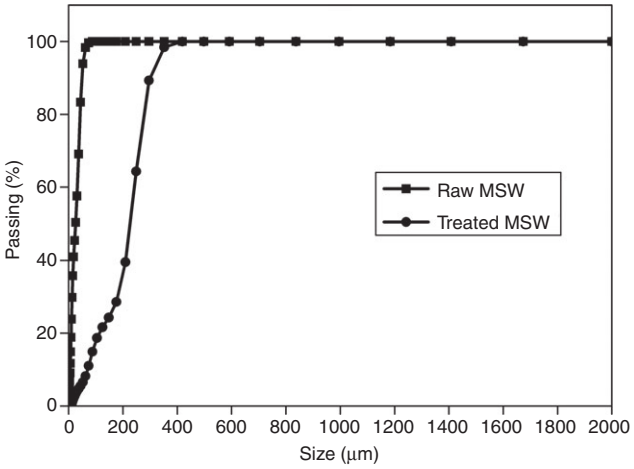

Figure 3 Particle size distribution of raw and treated MSW.

absolute densities of raw and treated MSW are 1.37 and 1.65 g/cm^3, respectively. The absolute density of treated MSW is increased by 20% compared with that of raw MSW, which may be due to depletion of lignin content after treatment [22].

3.2 Chemical anlysis evaluation

The detailed chemical composition of both raw and treated MSW is given in Table 1. The treated MSW shows lower percentage of cellulose and lignin as compared with raw MSW. Bleaching process using sodium hypochlorite reduces the lignin and cellulse content present in the treated MSW. Hypochlorite treatment is usually used in the bleaching process; however, it could delignify lignocellulosics [23]. The moisture content of treated MSW is higher than that of raw MSW. When the raw MSW is exposed to bleaching mediun, hydrophilic ions are induced on the surface of the treated MSW, which leads to more moisture absorption [24]. Chemical analysis results support the possibility of utilization of MSW in the production of composite panels.

3.3 Structural analysis of MSW

XRD patterns of the treated and raw MSW samples are shown in Figure 4. This analysis is done to identify the structural and chemical changes taking place in treated MSW. Cellulose shows a crystalline nature, whereas lignin is amorphous in nature. Two main peaks from amorphous scattering occurred between the diffractometer angle for 101, $10\bar{1}$ planes and 021, 002 planes. The diffractrogram of raw MSW representing normal cellulose pattern shows a peak at 2θ=22° and a shoulder in the region of 2θ=14–17°, which correspond to the presence of cellulose I [25]. Also, mild shoulders are observed at diffractometer angle of 20.9° for raw MSW, which represents diffraction from the 021 plane. The broad peaks of raw MSW are due to the amorphous nature of lignin, whereas celluloses are crystalline in nature. From these results, the crystallinity index of raw MSW is determined to be 68%. The treated MSW shows mere amorphous character. The peak corresponding to 2θ=22° disappears in the XRD pattern of treated MSW. The other peaks in the XRD pattern are related to chemical impurities.

FTIR spectra for MSW before and after treatment are given in Figure 5. The sharp peaks observed in the MSW in the range of 650–715 cm^{-1} correspond to the C-O in-plane bending of carbonate and S-O bending of sulfate [26]. The peak at 1060 cm^{-1} corresponds to the C-O stretching of polysaccharides present in MSW. The peaks at 1370 cm^{-1} correspond to COO^- antisymmetric stretching, C-H and bending of CH_2 and CH_3 groups [27]. The peak at 1590 cm^{-1} corresponds to C=C aromatic skeleton. The peaks at 3200 cm^{-1} correspond to SiO-H stretching of silica [26]. These peaks have been found to be decreased in treated MSW. However, the peak between 3400 and 3700 cm^{-1} corresponds to the OH stretching of bonded and nonbonded hydroxyl groups, and water increased in treated MSW compared to raw MSW. The peak at 2920 cm^{-1} corresponding to C-H stretching of aliphatic methylene groups increased in treated MSW [26]. The FTIR peaks at 3100–3700 cm^{-1} indicate increase of hydrophilicity in treated MSW.

Table 1 Properties of untreated and treated MSW and banana fiber.

Properties	Untreated		Treated	
	MSW	Banana fiber	MSW	Banana fiber
Cellulose content (%)	46.97	72.03	45.43	83.07
Lignin content (%)	39.91	7.27	29.36	0.24
Moisture content (%)	9.31	12.07	10.40	10.43
Diameter (μm)	5.86–53.93	150±0.0749	69.93–320.6	100±0.0840
Density (g/cm^3)	1.37	1.36	1.65	1.49

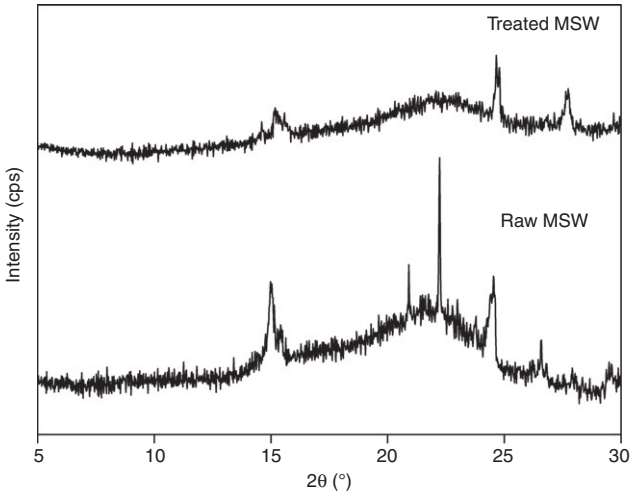

Figure 4 XRD of raw and treated MSW.

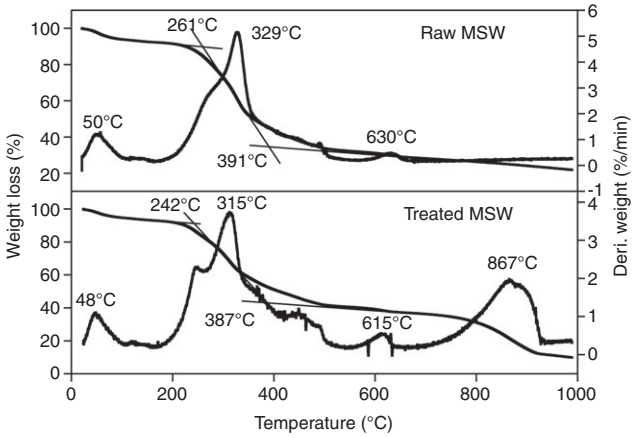

Figure 6 TG/DTG of raw and treated MSW.

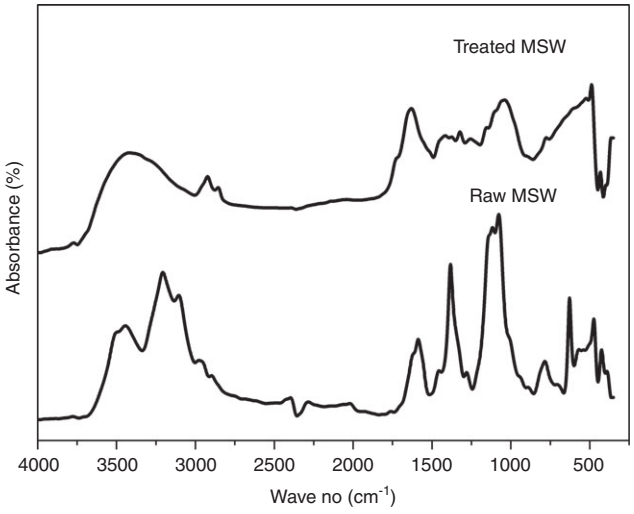

Figure 5 FTIR of raw and treated MSW.

3.4 Thermal and water absorption analysis of MSW

Thermogravimetric/differential thermogravimetric (TG/DTG) analysis of raw and treated MSW is shown in Figure 6. When the raw MSW is heated from room temperature to 100°C, there is a decrease in weight of the sample of about 6%. This process corresponds to loss of moisture content present in the raw MSW. During further heating, there is a two-stage process of mass loss reflecting thermal decomposition of cellulose. As the temperature increases, the first step, the weight loss of cellulose, occurs between 261°C and 391°C. This is followed by the second stage in the range of 391°C–980°C. These two steps are attributed to the change in initial mass of cellulose of 60% and 25%, respectively. This two-stage process is reflected in two peaks of 329°C and 630°C, respectively. The decomposition of cellulose leads to volatile gases, whereas lignin decomposition leads to char and tar. During the early stages of cellulose degradation, the molecular weight is reduced by depolymerization due to dehydration reactions [28].

After chemical treatment, the onset degradation temperature is reduced to 242°C. The first stage of decomposition occurs in the temperature range of 242–387°C with 55% degradation for treated MSW. The second stage of degradation occurs in the range of 387–950°C with 20% degradation. Also, it is reflected in the two peaks of 315°C and 615°C, respectively. In treated MSW, the first- and second-stage moisture loss peak is less compared to that of the raw one. Percentage weight loss for both raw and treated MSW is shown in Table 2. Percentage weight loss of treated MSW is less compared to raw MSW for the temperature range between 100°C and 900°C. This is due to the partial removal of cellulose and other constituents after chemical treatment.

DSC of both raw and treated MSW is shown in Figure 7. The broad endothermic peak observed in the temperature

Table 2 Percentage weight loss of treated and raw MSW.

Sample	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C	Char (%)
Raw MSW	6	8	26	56	66	69	72	74	85	21
Treated MSW	5	8	26	49	59	61	64	64	80	10

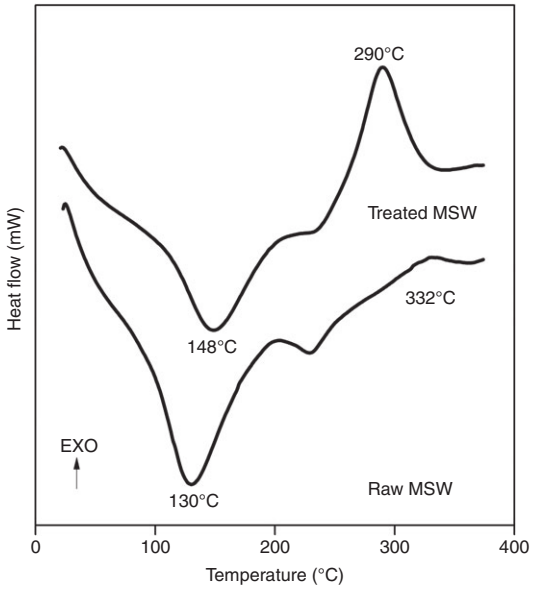

Figure 7 DSC thermograms of raw and MSW.

range of 50–150°C in both raw and treated MSW corresponds to heat of vaporization of water absorbed in the MSW. The region between 150°C and 250°C shows no endothermic peaks, which implies that both the treated and the raw MSW are stable between these temperatures. The exothermic hump for raw MSW is about 290°C, where it was associated with depolymerization that causes the formation of 1,6-anhydroglucose [29]. Yang et al. reported that pyrolysis reactions of lignin are exothermic [30].

Figure 8 shows the water absorption values of MSW as a function of time. It shows that water absorption in treated MSW is less than that of raw MSW. A 55% weight increase is identified in raw MSW; whereas 37% weight increase is observed in NaClO-treated MSW. Initially, water absorption properties increase with respect to time and then decreases gradually after 8 h. It can be understood that raw MSW dissolves more in water, whereas treated MSW is protected from dissolution. This shows a reduction of 1.48 times water absorption after chemical treatment due to the partial removal of lignin and cellulose. Chemical treatment results in the removal of surface materials opening up the MSW particles with more scooped individual cells [31]. However, it is interesting to note that composites with chemically treated MSW have lesser water uptake compared to raw MSW.

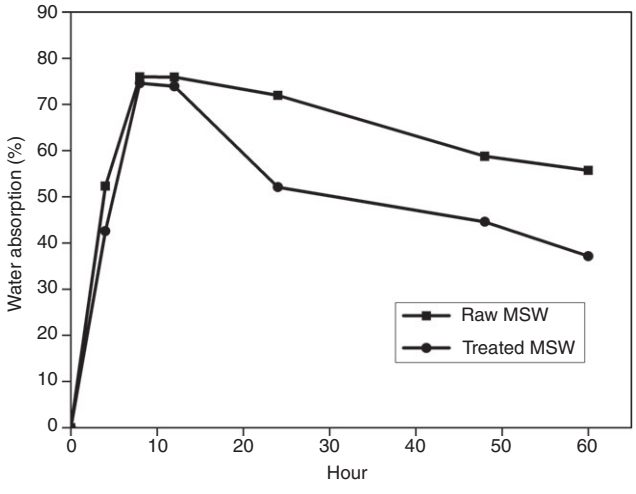

Figure 8 Water absorption properties of raw and treated MSW.

3.5 Morphology of raw and treated banana fiber

The effect of chemical treatment on morphological, physical and thermal properties of treated banana fibers are explained in our previous work [15]. The SEM images of the banana fiber before and after chemical treatment are shown in Figure 2C and D, respectively. It is observed that raw banana fiber has a regular structure with discrete net fibrils (Figure 2C). The presence of hemicelluloses and lignin provides a homogeneous morphology to the raw fiber. The surface of treated banana fiber is smoother than that of untreated fiber and there is a visible separation of fibrils in the case of treated fibers (Figure 2D). The properties of both raw and treated banana fibers are given in Table 1.

3.6 Mechanical properties of composites

3.6.1 Effect of filler loading on tensile strength

In the filler loading, the total volume ratio of MSW and banana fiber is kept as 50:50. The tensile strength of neat UF resin is low. The tensile strength is found to increase as filler content increases up to 40% V_f and then decreases. The addition of randomly oriented fibers and MSW slows the crack propagation. Then, gradual debonding of the fibers from the matrix occurs during plastic deformation. The tensile strength and tensile modulus are found to decrease by 11% and 23%, respectively, with increasing filler volume fraction from 40% to 50%. It is found that the optimum filler ratio for composites is 40% V_f. It was reported that optimum filler ratio depends on the nature of fiber, matrix, fiber aspect ratio and interfacial bonding between the fiber and the matrix [32]. The percentage

elongation at break is very low for pure UF resin. This value is improved by increasing the filler content up to 40% V_f. The tensile properties of composites having different filler loadings are given in Table 3.

SEM photographs of the tensile fracture of composites (total volume ratio of MSW and fiber as 50:50) at 20% and 40% V_f of filler loading are shown in Figure 9A and B. Fiber-matrix debonding and fiber pullout are shown in 20% V_f composite, indicating less interaction between fiber and matrix (Figure 9A), but in 40% V_f composite, better fiber-matrix bonding and fiber breakage can be identified in the fracture surface. Resin particles are also found to adhere to the banana fiber surface, indicating good filler-matrix interaction (Figure 9B).

3.6.2 Effect of filler loading on flexural strength

In the filler loading, the total volume ratio of MSW and banana fiber is kept as 50:50. As filler loading increases, flexural strength and modulus values also increase up to 40% V_f and then decrease. It is reported that chopped fibers have higher ends and are aligned with higher degree of orientation in the resin matrix. The load applied on the composite is directly observed by the fiber; it transfers the load from one end to the other end, which leads to increase of flexural strength [33]. The flexural strength and modulus values are increased by 71% and 27% for 40% V_f of composite compared to neat resin. However, the flexural strength and Young's modulus are found to decrease by 12% and 10% respectively, with increasing filler volume fraction from 40% to 50%. After 40% V_f of filler, there is the possibility of increasing fiber-to-fiber contact, which leads to fiber agglomeration and reduction of stress transfer between matrix and banana fibers. The flexural properties of composites having different filler loading are given in Table 3.

3.6.3 Effect of filler loading on impact strength

The effect of filler loading on impact strength of composites and neat UF resin is analyzed. The impact properties of composite at different filler loading are given in

Table 3 Tensile, flexural and impact strength properties of untreated composites having different filler loading and treated composite at 40% V_f of filler (ratio of MSW/banana fiber=50:50).

Volume ratio of the filler (MSW+banana fiber)	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m²)
Neat resin (UF)	4.5	88	1.3	12	1620	8
20% V_f (untreated)	15	350	7.5	25	1835	15
30% V_f (untreated)	21	460	9.7	31	1981	21
40% V_f (untreated)	28	1150	11.02	42	2234	28
50% V_f (untreated)	25	890	11.01	37	2012	26
Chemically treated composite (40% V_f)	31	1342	11.4	44	2446	25

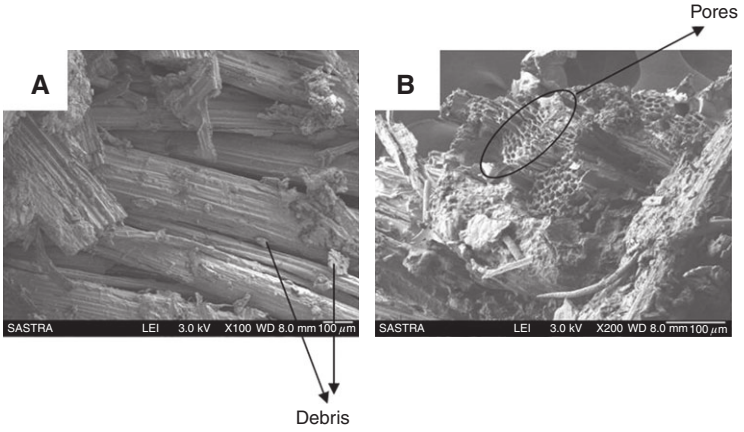

Figure 9 Scanning electron images of the tensile fracture surface of composites at (A) 20% V_f of filler loading, (B) 40% V_f of filler loading (ratio of MSW/banana fiber=50:50).

Table 3. In the filler loading, the total volume ratio of MSW and fiber is kept at 50:50. The impact strength is found to increase with increase of filler loading up to 40%. As the lignocellulosic fibers are more porous, the impact strength also increases with filler loading. The impact strength of neat UF resin is low. By incorporating 40% V_f of filler, the impact strength is increased by 71% compared to neat cured resin. When the filler ratio is greater than 40% V_f, there is a slight decrease in impact strength. The impact strength is found to decrease by 7% with increasing filler volume fraction from 40% to 50%. This is due to the large fiber-to-fiber contact in which matrix breakage is the predominant failure mechanism [34].

3.6.4 Effect of chemical treatment of MSW and banana fiber on mechanical properties

In this filler loading, the optimum ratio of treated MSW and banana fiber is kept as 50:50 at constant filler loading of 40% V_f. Chemically treated composite shows increase in tensile strength compared to other untreated composites. It is reported that chemical treatments reduces the moisture absorption properties of fibers due to blockage of -OH groups on the fiber backbone [35]. The OH groups present in the fibers correspond to the hydroxyls. The chemical reaction of the fiber-cell and NaOH is represented by following equation [36, 37]:

$$\text{Fiber-OH} + \text{NaOH} \rightarrow \text{Fiber-O}^{-}\text{Na}^{+} + \text{H}_2\text{O}.$$

Alkali-sensitive hydroxyl (OH) groups present among the molecules are broken down, which then react with water molecules (H-OH) and move out from the fiber structure. The remaining reactive molecules form fiber-cell-O-Na groups between the cellulose molecular chains [37]. As a result, hydrophilic hydroxyl groups are reduced and increase the fiber moisture resistance property. As lignin is the most hydrophilic part of fiber, the removal of lignin on treatment decreases the moisture content of fiber.

It is confirmed from SEM images of MSW and banana fiber, which are represented in Figure 2A–D, that the chemical treatment increases the surface area and decreases the hydrophilic groups such as lignin. Thus, the decrease in hydrophilicity of both fiber and MSW leads to increase in tensile strength of treated composites. Further, it can also be identified from the SEM images of treated composites. Figure 10A and B shows the SEM images of the tensile fracture surface of untreated and NaClO-treated MSW/banana fiber composites. In untreated composites, cavities are clearly identified and brittle failure is observed (Figure 10). This indicates lower adhesion between fiber and resin. Only mechanical adhesion occurs in this composite. In treated composites, there is fiber breakage, which indicates the increased adhesion between the fiber and the matrix (Figure 10B). The chemical treatment allows better contact between the constituents of composites. Hence, improvement in tensile strength and modulus is observed. The tensile strength and modulus of treated composite is found to increase by 9.6% and 10%, respectively, compared to untreated composite having a 50:50 volume ratio of MSW and banana fiber. Treated composites show higher flexural strength and modulus. This is due to the better interfacial adhesion in the composite. The flexural strength and modulus of treated composites having 50:50 volume ratio of MSW and banana fiber are increased by 5% and 8.6%, respectively, compared to untreated composite (50:50). The tensile and flexural properties of treated composites at 40% V_f filler loading are given in Table 3.

However, the impact strength of treated composite is lower than that of the untreated composite (Table 3). Cook and Gordan [38] reported that weak fiber-matrix

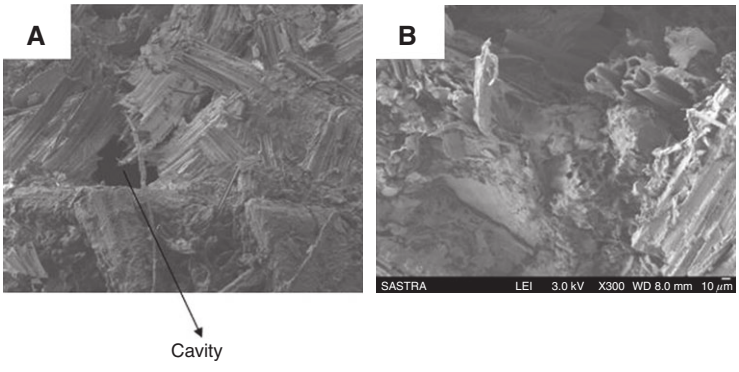

Figure 10 SEM images of tensile fracture surface of (A) untreated and (B) chemically treated MSW/banana fiber composites (ratio of MSW/banana fiber=50:50).

interface will result in tough composites. A weak interface will not support effective stress transfer and the strength of composite is low, but the toughness of the composite is high. The composite having strong interface will have low toughness compared to the composite having a weak interface. The low impact strength of treated composite is due to the strong interface, which is evident from SEM images (Figure 10B). Improved fiber-matrix adhesion leads to a better bonding, which results to failure of composites at low impact.

4 Conclusions

The NaClO-treated MSW shows good physical and less water absorption properties compared to the raw MSW. Chemical treatment confirms the reduction of the hydrophilic character of the MSW. Also, treatment of MSW increases the particle size and reduces the specific surface area. Thermal properties show the overall improved thermal stability of MSW on treatment. Composite having 40% V_f of filler loading provides better tensile, flexural and impact properties. It is found that increase in filler volume fraction increases the mechanical properties of composites. Chemical modification of MSW and banana fiber increases the tensile and flexural strength of treated composites. Hence, chemically treated MSW and banana fiber can be used as good fillers for making composite panels.

Received August 27, 2013; accepted February 9, 2014

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