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Natural cellulose fibers from soybean straw

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ABSTRACT

This paper reports the development of natural cellulose technical fibers from soybean straw with properties similar to the natural cellulose fibers in current use. About 220 million tons of soybean straw available in the world every year could complement the byproducts of other major food crops as inexpensive, abundant and annually renewable sources for natural cellulose fibers. Using the agricultural byproducts as sources for fibers could help to address the concerns on the future price and availability of both the natural and synthetic fibers in current use and also help to add value to the food crops. A simple alkaline extraction was used to obtain technical fibers from soybean straw and the composition, structure and properties of the fibers was studied. Technical fibers obtained from soybean straw have high cellulose content (85%) but low% crystallinity (47%). The technical fibers have breaking tenacity (2.7 g/den) and breaking elongation (3.9%) higher than those of fibers obtained from wheat straw and sorghum stalk and leaves but lower than that of cotton. Overall, the structure and properties of the technical fibers obtained from soybean straw indicates that the fibers could be suitable for use in textile, composite and other industrial applications.

1. Introduction

In our endeavor to develop natural cellulose fibers from agricultural byproducts, we have discovered that soybean straw could be used to produce natural cellulose technical fibers with structure and properties similar to the cellulose fibers currently in use. About 220 million tons of soybeans and an equivalent amount of byproducts (straw) are produced in the world every year (Galletti, 1991; FAO, 2007). Although soybean straw is an inexpensive, abundant and annually renewable source suitable for producing technical fibers, no previous reports are available on studying the suitability of using soybean straw for fibers or other industrial applications. Also, there is very limited literature available on the composition, structure and properties of the soybean straw and especially on the properties of cellulose in the straw (Galletti, 1991). Using soybean straw as a source for fibers will not only add value to the soybean crops but also provide a sustainable source for fibers. However, it will be necessary to develop appropriate fiber production conditions and understand the structure and properties of the soybean straw fibers in order to utilize the soybean straw for various industrial applications.

Finding alternative sources for fibers is important due the concerns on the future price and availability of both the natural and synthetic fibers in current use. Although more than 50% of the 70 million tons of fibers consumed annually in the world are from petroleum based resources, limited efforts are made to find alternative sources to replace at least a part of the synthetic fibers (Huda et al., 2007). Such concerns on the price and availability of the fibers in current use are legitimate since the price of the most common synthetic fiber polyester, has more than doubled in the last decade and can only be expected to increase further. The cultivation of natural fibers such as cotton is also declining due to farmers shifting to crops such as corn and soybeans that are being used for biofuels and are easier to grow and provide a better economic return than fiber crops (Huda et al., 2007). These limitations on the price and availability of the natural and synthetic fibers will inevitably make finding alternative sources for fibers a necessity in the near future.

The major cereal crops in the world, corn, wheat, rice, soybeans and sorghum have annual world production of 700, 630, 619, 214 and 58 million tons, respectively (FAO, 2007). This means an availability of about 2200 million tons of byproducts that are suitable for fiber production. Even using 10% of the available byproducts for fiber production and assuming that about 20% of the byproduct by weight can be obtained as high quality technical fibers, more than 40 million tons of fibers can be obtained from these byproducts every year. The 40 million tons of fibers from the currently

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limited value byproducts is substantial production since it is about 57% of the current total annual world consumption of fibers (70 million tons). Since most of the five crops mentioned earlier are ubiquitous and the byproducts have almost no use at present, using them as sources for fibers would add value to the crops and also provide a cheap, abundant, renewable and sustainable source for fibers. Although some of the byproducts generated need to be left on the ground to keep the soil fertile for succeeding crops, it has been documented that 30–50% of crop residues can be removed from the fields without causing soil erosion and affecting the growth or yield of succeeding crops (Hasche et al., 2003).

It has been reported that many lignocellulosic byproducts including cornstover, rice and wheat straw, sorghum stalks and leaves, pineapple and banana leaves can be used to obtain natural cellulose fibers with properties suitable for textile, composite and other industrial applications (Reddy and Yang, 2005a–d, 2006, 2007a–c; Sinha and Ghosh 1977; Sinha, 1974; Doraiswamy and Chellamani, 1993). In this research, we have studied the potential of using soybean straw as a source for natural cellulose fibers. The fiber production conditions were optimized and the technical fibers obtained were characterized for their composition, structure and properties in comparison to the most common natural cellulose fibers, cotton and linen.

2. Experimental

2.1. Materials

Soybean straw was collected from an experimental research field in Lincoln, NE after the seeds had been harvested. The straw was manually cleaned to remove leaves and other waste materials and later used for chemical extraction of technical fibers. All chemicals used in this study were reagent grade chemicals obtained from VWR International, Bristol, CT.

2.2. Fiber extraction

Several treatment conditions were studied to obtain technical fibers from soybean straw by varying the alkali concentration, time and temperature of treatment. The amount (yield) of technical fibers obtained and the quality (composition, fineness and strength) of the fibers were affected by the treatment conditions. The optimized treatment conditions developed were based on the yield and the fineness of the technical fibers obtained. In the optimized condition, the soybean straw was boiled in a 8% (w/w) sodium hydroxide solution for 2 h with about 10% (w/w) of the material in the alkali solution. The treated material was then washed thoroughly to remove the dissolved substances. The technical fibers formed were neutralized using dilute acetic acid (3% w/w) and the washed and neutralized fibers were dried under ambient conditions. The technical fibers obtained here are multicellular with several single cells held together by lignin and other binding materials. The technical fibers have a length to width ratio of at least 1000:1.

Single cells are the smallest morphological units in fibers. These single cells that are a few millimeters in length are commonly referred to as "ultimates" and used in the paper and pulp industry as opposed to the technical fibers characterized in this study.

The technical fibers obtained from soybean straw were macerated to determine the single cell dimensions in the fibers. Maceration was done using a 10% (w/w) nitric acid and 10% (w/w) chromic acid solution. Technical fibers were dipped in equal volumes of the two solutions for about 24 h after initiating the reaction by heating the solution at 60 °C for 5 min (Ruzin, 1999). The single cells obtained were thoroughly washed in water and dried using acetone.

2.3. Fiber composition

The amount of cellulose in the technical fibers obtained from soybean straw was determined as Acid Detergent Fiber (ADF) according to AOAC method 973.18 (Helrich, 1990). Lignin in the fibers was determined as Klason lignin according to ASTM method D1106-96. Ash in the fibers was determined according to ASTM method E1755-01. Three replications were done for each compositional analysis and the average and ±1 standard deviation is reported.

2.4. Physical structure

The physical structure of the technical fibers in terms of the % crystallinity of cellulose and orientation of the microfibrils to the fiber axis in terms of the multifibrillar angle (MFA) was determined using X-ray diffractometers. A Rigaku D-max/BΘ2Θ X-ray diffractometer (Rigaku Americas, Woodlands, TX) with Bragg – Brentano parafocusing geometry, a diffracted beam monochromator, and a copper target X-ray tube set to 40 kV and 30 mA was used to determine the % crystallinity. The measurements were taken on fibers that were made into pellets of about 5 mm thick. To make the pellets, fibers were powdered in a Wiley Mill (Thomas Wiley, Swedesboro, NJ) to pass through a 250 μm mesh and the powdered fibers were pressed into a pellet using a hydraulic press operated at approximately 20,000 PSI. The % crystallinity of the fiber was obtained by integrating the area under the crystalline peaks after subtracting the background and air scatter.

A Bruker D8 Discover model diffractometer (Bruker AXS Inc., Madison, WI) equipped with an area detector and GAADS software was used to calculate the orientation of the microfibrils in the fiber to the fiber axis in terms of MFA and also to observe the diffraction pattern of the cellulose crystals in the fiber. The diffraction patterns were collected by mounting a bundle of fibers vertically in a specially designed sample holder. The diffraction patterns were collected for 10 min with the X-ray beam set to 40 kV and 30 mA. The 002 peak intensities in the diffraction patterns were fit into two Gaussian curves using a non linear least square algorithm with the software program Microcal ORIGIN to obtain the MFA. Details of the methods used to calculate the MFA have previously been reported (Hu and Hsieh, 1996; Cave, 1997).

2.5. Morphological studies

A Hitachi S3000 N model variable pressure Scanning Electron Microscope (SEM) (Hitachi High Technologies America, Inc., Schaumburg, IL) was used to observe the longitudinal features of the soybean straw and also the technical fibers and single cells obtained from the straw. The samples were mounted on conductive adhesive tape, sputter coated with gold palladium and observed under the SEM. The widths of the single cells were measured from the SEM pictures and the lengths of the single cells were measured using a digital microscope. Approximately 50 single cells were measured for the dimensions and the average and standard deviations are reported.

2.6. Tensile properties and moisture regain

The tensile properties of the technical fibers from soybean straw in terms of the breaking tenacity, % breaking elongation and Young's modulus were determined using an Instron (Model 4000, Instron, Norwood, MA) tensile testing machine. A gauge length of 25 mm and a crosshead speed of 18 mm/min were used for the testing. About 100 fibers were tested and the average and standard deviations are reported. The moisture regain of the fibers was determined according to ASTM standard method 2654 using standard conditions of 21 °C and 65% relative humidity.