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CONVERSION OF AGRICULTURAL FIBER AND POST-CONSUMER PLASTIC WASTE INTO BIOCOMPOSITE AND BIOPOLYMERIC BINDER

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Abstract

The recycling of post-consumer plastics is of increasing importance as landfilling and incineration becomes more expensive and environmentally risky. Furthermore, North American interest in natural fibers is increasing rapidly and great efforts are being made to utilize natural fibers to replace synthetic fibers in fiber reinforcement such as automotive applications. It is of great interest to develop a cost effective and environmentally acceptable approach to tackle the utilization of plastic-waste and convert it to partially biodegradable molded grade biocomposite. This can be achieved by incorporating natural fibers up to 50% and biopolymeric binder and the product could be used in various products including construction, furniture manufacturing, and insulation materials. A proper cleaning mechanism and technique of disinfection from toxic and hazardous contamination and sorting of the plastic waste should be followed prior to chopping, grinding, and compounding with natural fibers/shives. The fibers can be chemically pre-treated to ensure proper bonding strength and compatibility with the physical and mechanical properties of the final products. In this paper, we will present how post-consumer plastics can be utilized as a binder. An example of flax and hemp shives for manufacturing construction blocks for insulation and other engineering applications is also presented.

Keywords: recycling, plastic waste, biopolymer, biodegradable, biopolymeric binder, biocomposite, polyethylene, flax fiber, natural fiber

Introduction

Plastics are used in a wide range of applications and some plastics items, such as food packaging, become waste only a short time after purchase. It is estimated that about 80% of post-consumer plastic waste is sent to landfill, 8% is incinerated and only 7% is recycled. In addition to reducing the amount of plastic waste requiring disposal, recycling plastic can have several other advantages such as conservation of non-renewable fossil fuels, reducing energy consumption, reducing carbon-dioxide emissions, and many others. It is therefore of great interest to develop an integrated, cost effective, and environmentally acceptable approach to utilize plastic waste and convert them to a useful partially biodegradable molded grade biocomposite and other products such as biopolymeric binders by incorporating natural fiber. The disposal of surplus specific plastic waste (e.g: electronic plastic) is emerging as an important issue due to significant hazardous materials they contain, which cause concern for the safety of ground and surface water sources and health if disposed in landfills. Also, when flax and hemp stocks are processed, 70-80% of the initial raw materials are rejected as shive. Flax and hemp shive are not very suitable for utilization; however, sometimes it can be used for low-quality building materials such as shive-containing fiberboards, gypsum, concrete, etc. The incorporation of agricultural byproducts such as flax/hemp fiber and shive into plastic will create another important source of income for the farming industry and will utilize the maximum potential of the waste stream to make products which are useful to the society. This material by using different kinds of processing techniques such as extrusion, injection, and rotational molding processes. The biocomposite that can be developed by utilizing plastic waste and biofibers can replace a number of plastic applications. To name a few**,** biocomposites are used in building materials, absorbents, adhesives and bonding agents, and degradable polymers. A fairly new utilization of plastic waste is conversion of post-consumer plastic waste into oil by two methods, namely: 1) direct liquefaction; and 2) pyrolysis followed by hydro-processing of the pyrolysis liquids. Post-consumer waste plastics can be used in cement-based composite. Also, mechano-chemical treatment can be used to develop composite plastic materials from post-consumer plastic waste.

There is always room for growth and expansion in many areas of the biodegradable plastic industry. It is estimated that plastic waste generation will grow by 15% per year for the next decade. There are also a number of challenges in developing new technologies for biodegradable plastic applications. As an example, health and safety concerns have arisen over potentially hazardous chemical additives to plastics and consumer pressure has contributed to manufacturers switching to plant-based plastics.

There are about 50 different groups of plastics, with hundreds of different varieties. It is of increased importance that the plastic manufacturers label their products according to a standard marking code such as that of the American Society of Plastics Industry to make sorting and thus, recycling easier.

In this paper, we will introduce a method of manufacturing plastic waste into binder. By combining the plastic waste and flax and hemp fibers/shives and under controlled heat and pressure, we can make valuable engineering construction blocks with good compression loading, thermal insulation and possibly sound insulating properties.

Plastics and Solid waste

Plastics that occur in the waste stream, and particularly those used for packaging, have been a subject of special attention and legislation. The Council on Plastics in Packaging and the Environment in the United States (Washington, D.C.) has counted more than 500 local or state regulatory initiatives regarding plastics (Basta and Johnson, 1989). The initiatives range from recycling feasibility studies to outright bans on the use of plastics packaging (Thayer, 1989). Recently, the use of expanded polystyrene (EPS) foams, which fast food restaurants often use for cups and "clamshell" hamburger containers, is restricted in many communities. Obviously, the awareness of the danger of not treating the plastic waste properly is increasing and solutions such as recycling and reusing are welcome.

Post-consumer Plastic Waste Recycling

Post-consumer plastic can be described as plastic material arising from products that have undergone a first full service life prior to being recovered. The biggest source of plastic waste is households. It is a big challenge though to collect and sort the plastic waste. The processes of separating materials according to resin types are very important because most resin types are thermodynamically incompatible with other resins. Mixed plastics molded product generally have poor, brittle properties unless a modifier is added to improve compatibility .Recycling plastic usually involves processes such as melting, shredding or granulation of waste plastics. Sorting of plastic is an important step prior to recycling. Currently, manual sorting into polymer type is common in the recycling industry. New technologies are being developed to sort plastics automatically, using various techniques such as X-ray fluorescence, infrared and near infrared spectroscopy (Scott, 1995), and others.

Experimental-Materials & Methods

In general, bast fiber is the most commonly used in composite applications. Flax fiber is an important bast fiber. Its color is pale cream to brown. Flax is a plant with a single stem, nearly one meter in height. The diameter at the base varies between 1 to 2 mm. The length of a fibril is around 15-20 mm. Table 1 shows the chemical composition of flax fiber. Flax fibers have density of about half that of glass fibers. These fibers can withstand processing temperatures up to 250ºC. They are fully combustible without the production of either noxious gases or solid residues. The strength characteristics of fiber depend on the properties of the individual constituents, the fibrillar structure and the lamellae matrix. Flax fibers possess moderately high specific strength and stiffness and can be used as reinforcement in polymeric resin matrix to make useful composite materials.

Table 1. Chemical composition of flax and hemp fiber (Mohanty et al., 2000).

Fiber	Cellulose (%)	Hemi-cellulose (%)	Pectin/ Lignin (%)	Wax (%)	Water soluble	Moisture content (%)
Flax	71-78.5	18.6-20.6	4.4	1.7	3.9	10.0

SARCAN Recycling is the recycling division of the Saskatchewan Association of Rehabilitation Centres (SARC), which has a network of over 70 depots in Saskatchewan and provides a comprehensive provincial collection, processing, transportation, and marketing system to recycle most ready-to-serve beverage containers.

In this experimental work, the plastic waste used in this project was collected from SARCAN, mainly plastic milk jugs. These milk jugs are made out of food grade HDPE (high density polyethylene) through blow molding process. HDPE also known as linear polyethylene or low-pressure polyethylene, is the preferred polyethylene for containers of all sizes primarily due to its exceptional environment stress crack resistance It has excellent stiffness from room temperature to the boiling point of water. Even though HDPE is frequently called linear polyethylene, it still has some short chain branching. Nevertheless, its linear nature and its high backbone mobility allow it to crystallize from 75% to 90% of theoretical. The crystalline structure causes the product to have a milky, translucent appearance. Since the crystallite is more ordered and more tightly packed than the amorphous phase, the density of HDPE is typically around 960 kg/m^3 approaching the theoretical value of 1000 kg/m^3 (Table 2).

Table 2.Typical properties of HDPE.

Polymer type	Density (g/cm^3)	Degree of Crystallinity	Glass Transition Temperature (°C)	Crystal Melting Temperature (°C)	Tensile Strength (MPa)	Elongation at Break (%)	Flexural Modulus (GPa)
HDPE	0.95-0.97	high	-120	137	20-30	10-1,000	1-1.5

Treatment of Fiber

Flax fibers were derived from linseed flax grown in Saskatchewan and decorticated on a standard scutching mill at Biofiber Ltd. in Canora, SK. Flax fiber has gone through mercerization process which causes changes in the crystal structure of cellulose. Fibers were soaked in 5-18% NaOH for about half an hour in order to activate the OH^- groups of the cellulose and lignin in the fiber. The fibers were then washed many times in distilled water and finally dried. Then the dried fibers were dipped in an alcohol water mixture (60:40) containing triethoxyvinylsilane coupling agent. The pH of the solution was maintained between 3.5 and 4, using the METREPAK Phydrion buffers and pH indicator strips. Fibers were washed in double distilled water and dried in the oven at 80°C for 24 h. This modification improved the interfacial properties of flax fiber.

Treatment of SARCAN Plastic Waste

Labels and glue from the milk jars were peeled off and removed manually from the plastic and sorting of the plastic was done manually. Then, the plastic jug was chopped into small pieces. For that purpose, a cutting field machine was mechanically modified at U of S to chop the plastic jars into small size pieces (length and width 1 cm each) before it was washed by a washing machine with regular antibacterial household detergents at a temperature of 100 C^0 for 1 hour.

Biocomposite and Biopolymeric binder Preparation

Pre-treated fibers were ground by the grinding mill (Falling Number, Huddinge, Sweden) and oven-dried to reduce the moisture content to less than 2%. Following sorting and cleaning, the plastic was pulverized to powder form. Mixtures of thermoplastic powder, additives and 10% by weight of flax fibers were prepared by using a blender (Waring Products Corporation, New York, NY). This blended material was fed into the twin-screw extruder (Werner & Pfleiderer Engineers, Ramsey, NJ) using a barrel-to-die temperature profile of 150°C, a screw speed of 150 rpm and feed rate to the extruder of 20 kg/h to make Biocomposite Flaxtic^{TM}, a material that was solely developed in our labs. Blends prepared in this manner were extruded using a six-hole strand die. Extruded strands were then pelletized. The pellets were ground using a grinding mill (Retsch GmbH 5657 HAAN, West Germany) and the ground product was used for molding. In this experiment, residence time is kept short to avoid degradation and prevent the creation or release of volatiles, but they are long enough to attain levels of heat sufficient to destroy harmful bacteria. This Flaxtic^{TM} will work as a supplement to existing HDPE and it can be comparable and used as a raw materials for the plastic industry.

The main constituent of polymeric binder is SARCAN collected milk jugs which is HDPE. After cleaning, the plastic was pulverized to powder form. Mixtures of thermoplastic powder, additives such as flow enhancer, fungicide, antibacterial agent, fire retardant, elastomer, and UV stabilizer and impact modifier and 5% by weight 35 micron flax fibers were prepared by using a blender. This blended material was fed into the twin-screw extruder (Werner & Pfleiderer Engineers, Ramsey, NJ) using a barrel to die temperature profile of 150°C, a screw speed of 150 rpm and feed rate to the extruder of 20 kg/h to make a biopolymeric binder. Extruded binders were then pelletized and pulverized to powder form. The ground product was used for binder for construction block.

The biopolymeric binder was compounded with shives at a ratio of 30:70 to make the slurry for the construction block. The compound is then subjected to heat while being thoroughly mixed in a specially designed mixer. At the right timing, the compound is transferred to a mold and compressed and cured. Different tests that complied with ASTM standards were conducted to assess the physical and mechanical properties to obtain quality and compatibility with end-user application.

Results and Discussions

Flax fiber is a hydrophilic material and moisture absorption leads to a significant deterioration of mechanical properties of the composite. Flax fiber properties are controlled by the molecular fine structure of fibers. The pretreatment directly influences the cellulosic fine structure of plant fiber. Consequently, the chemical treatments have a lasting effect on the mechanical behavior of flax fibers, especially on fiber strength and stiffness. On the other hand, HDPE is hydrophobic in nature and due to this divergent behavior, the interface in natural fiber composites is rather poor. Any alteration of the characteristics of the cell wall, either chemical or morphological, has an effect on the mechanical properties of the fibers. Due to surface modification of flax fiber through pretreatment, the interlocking of the fiber surface to the polymer matrix increases the mechanical properties of the composite.

The properties of natural fiber-based biocomposite products are, in many cases, affected by the moisture content. These fibers are hygroscopic in nature and absorb moisture from a moist atmosphere, and release it in a dry atmosphere. Moisture absorption can result in swelling of the fibers. The moisture absorption and release process of natural fibers cause dimensional instability of the flax fiber-based biocomposite products and give negative impact on properties. It can be seen from Table 3 that moisture absorption is less then 1% at 50 % RH. This is due to a reduction of hydroxyl groups in fibers as a result of chemical pretreatment. Strong intermolecular fiber-matrix bonding decreases the rate of moisture absorption in biocomposite.

Hardness of composite was measured by the Shore (Durometer) test (D Scale). This method measures the resistance of plastics to indentation and provides an empirical hardness value that does not correlate well to other properties or fundamental characteristics. The hardness value is determined by the penetration of the Durometer indenter foot into the sample. The results obtained from this test are a useful measure of relative resistance to indentation of various grades of polymers. Ten readings were taken for each specimen, as material properties were expected to vary with location on the sample; the hardness value given is average. The hardness of this recycled HDPE composite was 15 (Table 3)

The properties of the developed biocomposite in this experiment are summarized in Table 3. The melt flow index indicates that this material can be used for compression and injection and rotational molding process.

Table 3. Flax fiber (10%) and HDPE recycle plastic based biocomposite.

Properties	Unit	Value
Melt Flow Index	g/10 min	1.6
Melting point	ºC	135
Hardness (Shore Durometer)*		15
Water absorption@50 RH	%	<1

*Average of 10 readings

The construction block samples were made of 30% plastic and 70% hemp shive. The plastic is polyethylene in nature. To test the applicability of the binder made of waste plastic, we made construction blocks and tested it for thermal conductivity, water absorption, rheological properties and compression loading. We needed to assess the end product for thermal insulation hoping that it could be used as insulating material for building walls, ceilings, and floors or like structure. For possible outdoor use, we tested the blocks for water absorption. To study the deformation and flow of the material, rhelogical testing was also conducted. We also tested the possibility that the construction blocks can bear compression loading.

Table 4. Biocomposite samples outline

Sample Number	Binder Type	Production Technique	Shape	Outer Seal
1	White glue	Manual Pressing	Rectangle	No
2	White glue	Manual Pressing	Rectangle	No
3	Recycled HDPE	Manual Pressing	Rectangle	No
4	Recycled HDPE	Manual Pressing	Rectangle	No
5	Recycled HDPE	High Pressure	Rectangle	No
6	Recycled HDPE	High Pressure	Rectangle	No
7	Recycled HDPE	High Pressure	Cylindrical	Yes
8	Recycled HDPE	High Pressure	Cylindrical	Yes

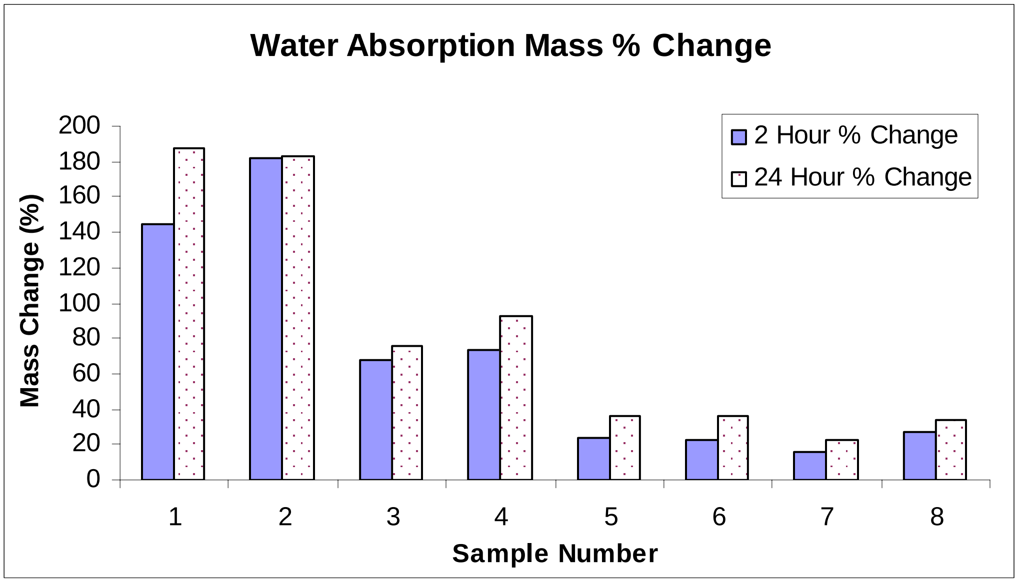

Figure 1. Water absorption properties of biopolymeric binder in construction block.

It is obvious from Figure 1 that water absorption is significantly reduced compared to samples made from white glue binder. The manually pressed samples of HDPE binder number 3 and 4 showed higher water absorption percentage than the high pressure and sealed samples.

Table 5. Thermal conductivity and compression strength of the samples.

Sample number	Thermal conductivity (Watts/mºC)	Compression strength (kN)
1	0.04	4.0
2	0.04	4.5
3	0.04	5.0
4	0.04	4.5
5	0.04	4.75
6	0.04	6.0
7	0.04	8.0
8	0.04	8.0

All the samples including samples 1 and 2 that use white glue as binder showed the same thermal conductivity value of 0.04 Watts/mºC (Table 5). This is a very strong indication that the plastic binder did not play a role in the thermal conductivity of the final product. The biocomposite nevertheless has a good insulating value and can be used in the construction industry. It is clear that the high pressure samples resulted in higher strength.

Table 6 shows that the meltflow index of the biopolymer is better than that of the HDPE. Rheological properties such as melt flow index of the biopolymeric binder material tests showed that the plastic binder constitutes an easy flow and it can be used as a binder for construction material.

Table 6. Melt flow index of this material as follows

Materials	HDPE	Milk container	Biopolymeric binder
Melt flow Index (g/10min)	1.0	0.9	1.4

It is important to mention that preliminary sound insulation testing showed that the blocks are of good sound insulation which is an increasing demand for construction of buildings.

Conclusion

Renewable fibers like flax fibers can be used as reinforcing component and post-consumer plastic waste can be used as the matrix in fiber plastic biocomposite due to the economic and environmental advantages of such materials. However, flax fiber is highly hydrophilic due to the presence of hydroxyl groups from cellulose and lignin. Fiber pretreatment is needed to reduce the hydrophilicity of the fiber. Rheological study showed that the biocomposite produced from SARCAN-collected milk jugs is easy to process and it can be used for various plastic processing industries.

The biopolymeric binder made out of recycled HDPE can be a good binder for a number of constructional applications. It can be used to make dense load bearing, sharply formed building blocks with superior insulating properties. Rheological study showed the binder is easy to process. Further study on the mechanical properties should be conducted.

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