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Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass

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ABSTRACT

Corn stover and switchgrass are two important feedstocks considered for producing renewable fuels and energy in the US. Densification of these biomass feedstocks into briquettes/pellets would help reduce the problems and costs of bulk transportation, handling, and storage of biomass feedstocks. In this study, the role of the natural binders in corn stover and switchgrass to make durable particle–particle bonding in briquettes/pellets was investigated by micro-structural analyses. Scanning Electron Microscopy (SEM) images of briquettes made by using a uniaxial piston-cylinder densification apparatus in the laboratory, briquettes made by using a pilot-scale roll-press briquetting machine, and pellets made by using a pilot-scale conventional ring-die pelleting machine were analysed. The SEM images showed that the bonding between particles was created mainly through solid bridges. The solid bridges between particles were made by natural binders in the biomass expressed during the densification process. UV auto-fluorescence images of briquettes and pellets further confirmed that the solid bridges were made mainly by natural binders such as lignin and protein. It was found that activating (softening) the natural binders using moisture and temperature in the range of glass transition is important to make durable particle–particle bonding.

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1. Introduction

Corn stover and switchgrass are potential biomass feedstocks for producing liquid transportation fuels such as ethanol, combined heat and power, and chemicals in the US (Sokhansanj and Turhollow, 2004; Colley et al., 2006; DOE, 2007; Kaliyan et al., 2009). These biomass materials are often handled in baled forms, which involve a lot of handling, transportation and storage costs because of low bulk density of bales. One of the solutions to reducing handling, transportation and storage costs is densification of the biomass materials into briquettes, pellets, or cubes with bulk densities of 450–700 kg m^{-3} (Sokhansanj and Turhollow, 2004; Colley et al., 2006; Kaliyan et al., 2009). Densification (briquetting, pelleting, or cubing) of particulate matter is achieved by forcing the particles together by applying mechanical force to create inter-particle bonding, which makes well-defined shapes and sizes such as briquettes, pellets, and cubes. The bonding of particles in briquettes, pellets, or cubes can be understood at microscopic or macroscopic level.

Chung (1991) presented a microscopic level of interpretation of bonding between particles. Chung (1991) reviewed several prior adhesion theories and derived two criteria for strong adhesion between molecules: intimate molecular contact of closer than 9 Å (necessary condition), and maximum attractive force with minimum potential energy (sufficient condition). The driving force of adhesion is in the electronic interactions between molecules. When the maximum attractive force is near the minimum potential energy, chemical bondings are established. Pressure, heat (above glass transition temperature), and solvent such as water are the industrial techniques to promote adhesion by increasing molecular contact between two sets of molecules (Chung, 1991).

Macroscopically, the binding forces between the particles can act through two binding mechanisms (Rumpf, 1962; Pietsch, 2002): (i) bonding without a solid bridge, and (ii) bonding with a solid bridge between particles. Without a solid bridge, attraction forces between solid particles help bond the particles. Short-range forces such as molecular [valance forces (i.e., free chemical bonds), hydrogen bridges, and van der Waals' forces], electrostatic, and magnetic forces can cause solid particles to adhere to each other if the particles are brought close enough together. Valance forces are effective only if the inter-particle distance is about 10 Å. van der Waals' forces believed to make the most contribution to all intermolecular attractive effects and are partly responsible for the adhesion between particles less than 0.1 μm apart. Electrostatic forces help binding when there is an excess charge or electrical double layer, which may be created during grinding or by inter-particle friction. If magnetic forces exist in the powder

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system, this could contribute to the particle bonding. The effectiveness of short-range forces diminishes dramatically as the size of the particles or inter-particle distance increases (Rumpf, 1962; Pietsch, 2002).

Solid bridge type binding mechanisms can occur in several modes (Rumpf, 1962; Pietsch, 2002). Due to the application of high pressures and temperatures, solid bridges may be developed by diffusion of molecules from one particle to another at the points of contact. Solid bridges may also be formed between particles due to crystallization of some ingredients, chemical reaction, hardening of binders, and solidification of melted components. Solid bridges are mainly formed during cooling/drying of densified products. During the compression process, fibers, flat-shaped particles, and bulky particles can interlock or fold about each other resulting in interlocking bonds. Mechanical interlocking bonds can resist the disruptive forces caused by elastic recovery following compression.

Table 1
Compositions of corn stover and switchgrass grinds.

Component	Corn stover			Switchgrass		
	This study (% of dry matter) ($n = 1$)	Mani et al. (2006) (% of dry matter)	DOE (2007) (range, % of mass)	This study (% of dry matter) ($n = 1$)	Mani et al. (2006) (% of dry matter)	DOE (2007) (range, % of mass)
Cellulose[a]	49.4	31.3	30.6–38.1	43.8	44.3	27.8–37.1
Hemicellulose[b]	26.2	21.1	19.1–25.3	28.8	30.0	22.4–28.6
Lignin[c]	8.8	3.1	17.1–21.3	9.2	7.4	13.2–22.5
Crude protein	3.6	8.7	NA[d]	3.9	1.6	NA
Starch	0.4	NA	NA	1.0	NA	NA
Crude fat	0.7	1.3	NA	0.9	1.9	NA
Water soluble carbohydrates	7.9	NA	NA	2.2	NA	NA
Moisture content	5.4	NA	NA	5.7	NA	NA
Ash	11.2	7.5	9.8–13.5	5.0	5.5	2.5–7.6

[a] Cellulose = acid detergent fiber (ADF) – lignin.
[b] Hemicellulose = neutral detergent fiber (NDF) – acid detergent fiber (ADF).
[c] Lignin values measured for the biomass materials used in this study and in Mani et al. (2006) were acid insoluble lignin contents, whereas the lignin contents obtained from DOE (2007) were total lignin in the biomass materials.
[d] NA = data not available.

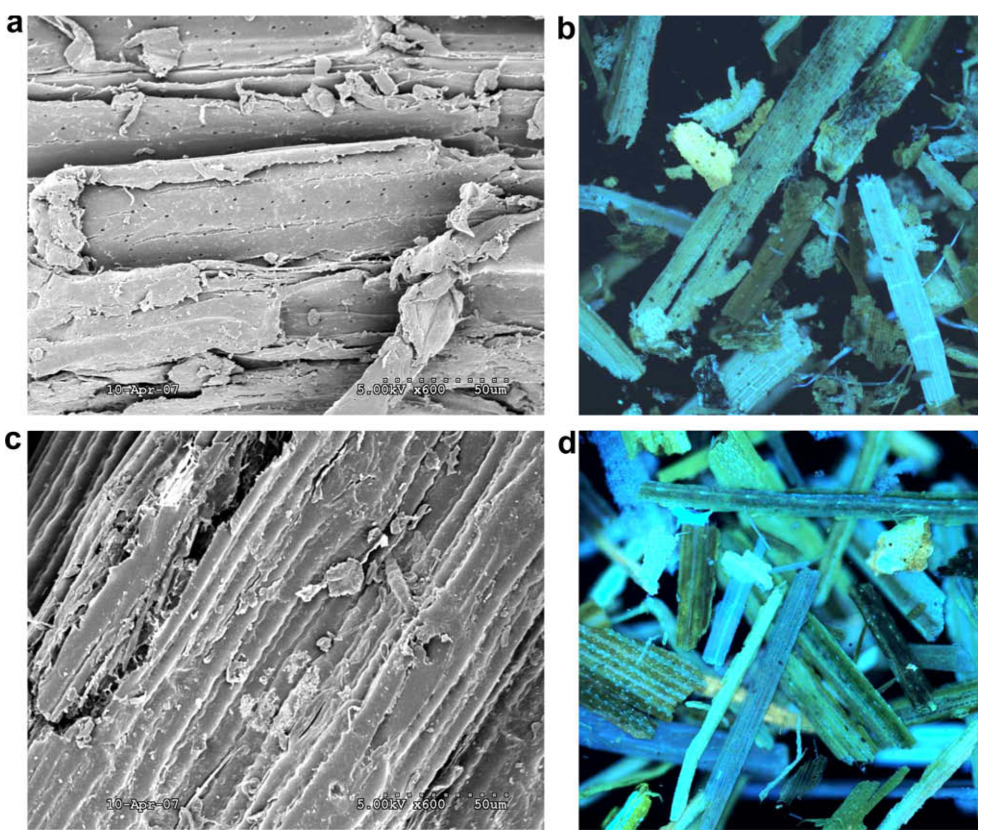

Fig. 1. Scanning Electron Microscopy (SEM) (magnification at 600×) and UV-Auto-Fluorescence (UV-AF) (magnification at 145×) images of corn stover (Fig. 1a and b) and switchgrass (Fig. 1c and d) grinds before briquetting or pelleting. The green or yellow-green fluorescence represents protein compounds, and whitish fluorescence represents the cutin (cuticle). (a) SEM image of corn stover grind (particle size = 0.34 mm). (b) UV-AF image of corn stover grind (particle size = 0.34 mm). (c) SEM image of switchgrass grind (particle size = 0.49 mm). (d) UV-AF image of switchgrass grind (particle size = 0.49 mm).

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