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Sustainable Use of Lignocellulosic Biorefineries Co-Products in Geotechnical Bulk Applications: Comparative Analysis of Lab Data

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Abstract

This paper discusses the effect of two co-products from lignocellulosic biorefineries on a typical Iowa subgrade soil in terms of laboratory measured strength and compaction properties. Emphasis is given to detailed data analysis of laboratory test results in comparing treated soils with untreated soils under different moisture conditions and additive concentrations. Results reveal that the bio-energy co-product (BCP) additives investigated in this study are promising materials to improve strength property of the typical Iowa soil classified to CL or A-6(8) for geotechnical applications. Especially, the co-product A containing higher lignin content is a more effective additive to reduce plastic property and optimum moisture content of soil.

Introduction

The natural soil deposits do not always possess the requisite engineering properties to serve as qualified geotechnical materials for construction. As a result, well-established techniques of soil stabilization are often used to improve the properties of geotechnical materials through the addition of binding agents into soil (Basha et al. 2005). The idea of sustainable development in construction has opened up avenues for various industrial by-products to be applied in soil stabilization (Petry and Little 2002) alone or combined with traditional soil stabilizers such as hydrated lime, portland cement, and bituminous bitumounious materials. Among the industrial by-products investigated, lignin co-products derived from paper industry, have been implicated as having a positive role in soil stabilization (Kozan, 1955; Nicholls and Davidson, 1958; Lane et al. 1984; Palmer et al., 1995; Puppala and Hanchanloet, 1999; Tingle and Santoni, 2003). Adding lignin to clay soils increases the soil stability by causing dispersion of the clay fraction (Davidson and Handy, 1960; Gow et al., 1961). Most of the previous lignin-based soil stabilization research studies investigated sulfite lignin (lignosulfonates).

Recently, bio-energy from plant biomass has attracted attention globally to replace fossil based energy and reduce carbon dioxide contribution to greenhouse gases. Since plant biomass are annually renewable, available in abundance and of limited value at present (Reddy and Yang, 2005), this material has been recognized as one of the most renewable and economical resources for energy. Bio-energy production from plant biomass also produces many different co-products that have many unexplored uses (Bothast and Schlicher, 2005). The type of co-products produced depends upon the method of bio-energy production and co-products recovery methods, as well as the source of the biomass. A lignin containing co-product is one of the largest portion materials among many different co-products. The lignin obtained from biofuel production is the sulfur-free lignin and the study of these materials in soil stabilization has seldom been carried out until recently when researchers at Iowa State University (ISU) started exploring this novel idea (Ceylan et al. 2009, Ceylan et al. 2010, Gopalakrishnan et al. 2010).

Even though sulfur-free lignin has been known for many years, the use of sulfur-free lignin has recently gained interest as a result of diversification of biomass processing schemes (Lora and Glasser, 2002). Considering that lignin represents the third largest fraction of plant biomass, significantly larger amounts of lignin as bio-energy co-product (BCP) will become available with increase of lignocellulosic biorefineries. Newer uses of lignin-based BCP need to be developed to provide additional revenue streams to improve the economical benefit of lignocellulosic biorefineries.

This paper discusses the effect of two BCP additives on a typical Iowa subgrade soil in terms of laboratory measured compaction and strength properties. Emphasis is given to detailed data analysis of laboratory test results in comparing treated soils with untreated soils under different moisture conditions and additive concentrations regarding the sustainable use of BCP in geotechnical bulk applications.

Experimental Program

Materials

Natural soils were collected from a new construction site for U.S. 20 in Calhoun County, Iowa. The engineering properties of the soil samples characterized are shown in Table 1. The collected soil samples can be classified as an A-6(8) soil and CL in accordance to the American Association of State Highway and Transportation Officials (AASHTO) soil classification system and Unified Soil Classification System (USCS), respectively, and as Class 10 soil per Iowa Department of Transportation (Iowa DOT) specifications (Iowa DOT 2008). The Class 10 soil is the typical excavated soil that includes all normal earth materials, such as loam, silt, clay, sand, and gravel. Based on the engineering properties and Iowa DOT specifications, the Class 10 soil can be limited in construction use under specification or should be removed.

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Table 1. Engineering properties of test soil

Property	Soil
Classification	
AASHTO (group index)	A-6(8)
USCS group symbol	CL
USCS group name	Sandy lean clay
Grain size distribution	
Gravel (> 4.75 mm), %	7.6
Sand (0.075–4.75 mm), %	40.4
Silt and clay (< 0.075mm), %	51.9
Atterberg limits	
Liquid limit (LL) , %	39
Plasticity limit (PL), %	16.
Plasticity index (PI), %	23
Proctor test	
Optimum moisture content (OMC), %	17.7
Maximum dry unit weight ($\gamma_{d\ max}$), kg/m^3(pcf)	1,691 (105.7)

Two types of BCPs containing lignin were used as additives and designated as co-products A and B in this study. Co-product A, shown in Figure 1(a), was obtained from a commercial biomass conversion facility located in Canada. This BCP is a dark brown, free-flowing liquid fuel with a smoky odor reminiscent of the plant from which it is derived. It is formed in a process called fast pyrolysis where plant material (biomass), such as forest residues (bark, sawdust, shavings, etc.) and agricultural residues (sugar cane, cornhusks, bagasse, wheat straw, etc.), are exposed to 400°C to 500°C in an oxygen-free environment (Dynamotive Energy Systems Corporation 2007). Recently, several qualification trial tests of co-product A for heating the Iowa Capitol Complex were conducted by the State of Iowa Department of Administrative Services-General Services Enterprise (Iowa DAS-GSE) in partnership with Dynamotive Energy Systems Corporation and Biogreen Resources (Iowa DAS 2008). Co-product A contains about 25% lignin and up to 25% water with a pH value of 2.2. The water component in co-product A to be used as liquid fuel is not a separate phase because it lowers the viscosity of the fuel. Co-product B, shown in Figure 1(b), was obtained from a full-scale, wet-mill, corn-based ethanol plant of Grain Processing Corporation (GPC) of Muscatine, Iowa (GPC 2009). Alkaline-washed corn hull is obtained in the process of converting the corn into ethanol, and co-product B is a powdered version of this. Co-product B contains about 5% lignin, 50% hemicellulose, 20% cellulose, and other components. These lignin-type components are not high molecular weight lignin like those found in wood but are specific to maize.

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(a) (b)

Figure 1. BCPs containing lignin: (a) Co-product A, (B) Co-product B.

Test plan and procedures

The experimental tests in this study included the unconfined compressive strength (UCS) test as a strength property test and Atterberg limits and standard Proctor compaction tests as engineering properties tests. For comparison purposes, the experimental plan for the strength property test encompassed preparing and testing three broad categories of treatment types: (1) untreated soil sample (control), (2) soil sample treated with the BCP A, and (3) soil sample treated with the BCP B. Table 2 lists the treatment group combinations evaluated for the UCS test during this study. Soil was mixed with each additive (BCPs or fly ash) at variable percentages to examine their influence. Each co-product contents evaluated are 1%, 6%, and 12% by dry soil weight. The untreated soils were also tested without the addition of any co-product. Similarly, the moisture contents and curing periods were incorporated as variables into the test factorial. The levels of water content (WC) for the testing samples were optimum moisture content (OMC), OMC+4%, and OMC-4% of untreated soil. The curing periods primarily investigated were one and seven days after sample fabrication for strength tests.

Table 1 Experimental plan for UCS test

Moisture content level	Curing period	Additives[a], %	
		Co-product A	Co-product B
OMC-4	1 day	0, 1, 6, 12	0, 1, 6, 12
	7 days	0, 1, 6, 12	0, 1, 6, 12
OMC	1 day	0, 1, 6, 12	0, 1, 6, 12
	7 days	0, 1, 6, 12	0, 1, 6, 12
OMC+4	1 day	0, 1, 6, 12	0, 1, 6, 12
	7 days	0, 1, 6, 12	0, 1, 6, 12

a. Numbers indicate percent of additive added by dry soil weight

The natural soil collected was dried, broken down to particle sizes that could pass a #4 (4.75 mm) sieve. Additives were also dried to remove the initial water in the co-products. The required amount of water and additives calculated by dry weight of the soil was added and mixed thoroughly to produce a homogenous soil blend. The blended soil samples used in the UCS test was statically compacted in the cylindrical mold (51 mm by 51 mm). The compacted sample was sealed in a plastic wrap and then placed in a temperature-controlled room where it was allowed to cure at 25°C and 40 percent relative humidity to represent field condition. The UCS test was conducted following ASTM D2166 (2006) after various cure times. A sample of the broken material was used to determine the moisture content of the materials according to ASTM D2216 (2005).

Soil samples prepared with additives at selected percentages were subjected to engineering properties tests to determine their physical properties and compaction characteristics. Engineering properties tests included Atterberg limits (liquid limit [LL] and plastic limit [PL]) according to ASTM D 4318 (2005) and moisture/density relationship in general accordance with ASTM D 698 (2007). The final selected percentage of co-products was one at which the compression strength values were maximum.

Results and Discussion

Strength property

The effects of co-product types and contents on UCS were evaluated under different moisture conditions: OMC represented moisture condition providing the maximum dry density of soil and used for quality control of construction, OMC-4% represented the more dry side of soil condition, and OMC+4% represented the more wet side of soil condition. The evaluations were also made under different curing periods. The results are shown graphically in Figures 2 through 4. The UCS values at 0% additive content in these figures indicate untreated soil after one and seven days of curing. The strengths of untreated soils are in all cases lower than the strengths of additive-treated soils. Overall, the strengths under the more dry side of soil condition are higher than the more wet side of soil condition. A high increase in strengths occurs with 12% of co-product A in all cases.

As shown in Figure 2, both co-products (A and B) are effective in enhancing the strength of soil under the dry condition (OMC-4%). Soil samples treated with co-products obtained more strength with the increased addition of co-products. Especially, the increase in strength of co-product A–treated soil with increased additive content is higher than the strength of co-product B–treated soil under the dry condition of soil. The curing periods influence the strength gain of soil treated by co-product A but not soil treated by co-product B.

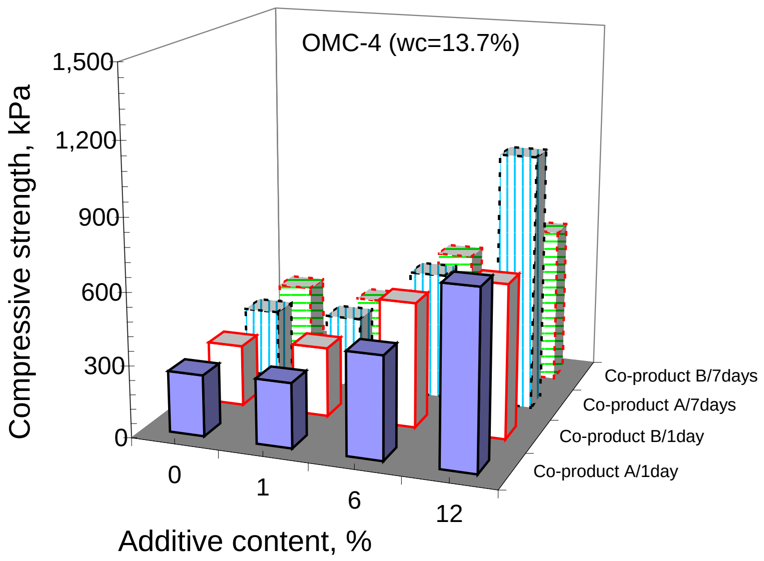

Figure 2. Variation of UCS at OMC-4 condition.

Similar to the dry condition of soil (OMC-4%), each of the co-products–treated soil UCS test results in Figure 3 shows strength improvements under the OMC condition of soil, which represents moisture condition for construction. The curing periods influence the strength gain of soil treated by co-product A, but not soil treated by co-product B. The 1-day strengths of co-product A–treated soil are lower than the strengths of co-product B–treated soil. However, the 7-day strengths of co-product A–treated soil are higher than those of co-product B–treated soil.

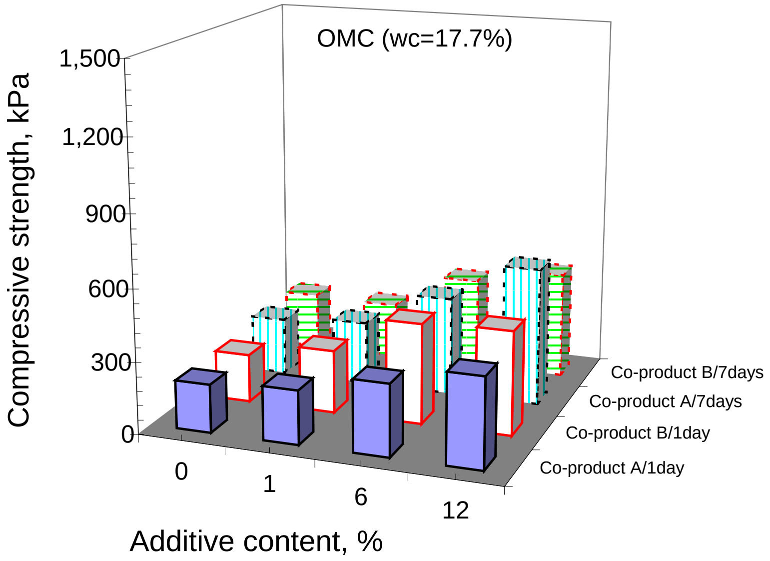

Figure 3. Variation of UCS at OMC condition.

Figure 4 shows that both co-products are still effective in improving the strength of soil at wet conditions of soil (OMC+4%). The strengths of treated soil increase with the increase in co-product concentrations and curing periods. The strengths of soil treated by co-product B are higher than the strengths of soil treated by co-product A. All the results under different moisture conditions indicate that co-product A is more effective in improving strength under dry conditions while co-product B is more effective in improving strength under wet conditions.

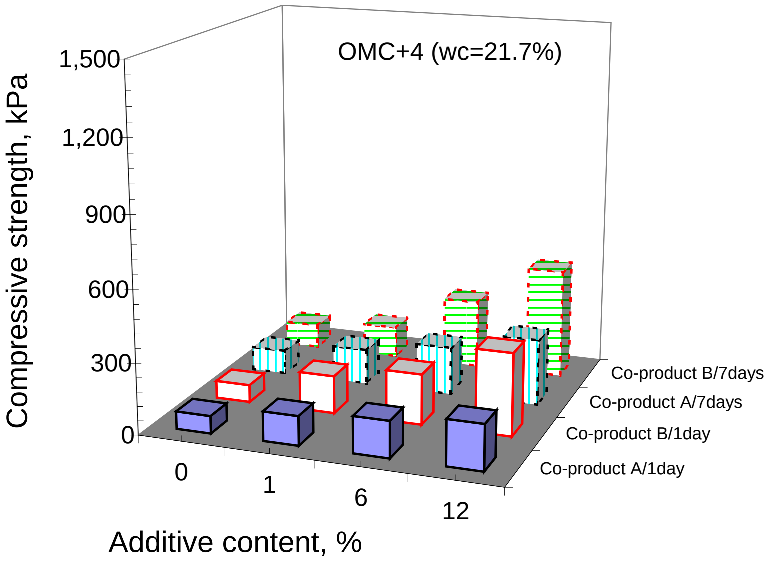

Figure 4. Variation of UCS at OMC+4 condition.

Engineering properties

Figures 5 and 6 present the effect of additives on consistency limits and compaction properties of soil, respectively. Twelve percent of co-product content was selected in this evaluation because a high increase in UCS occurred with 12% of co-products in this study. The co-product A reduced the plasticity of soils as a result of an increase in the plastic limit value, but the co-product B increased the plasticity of soils as a result of an increase in the liquid limit and plastic limit values.

Co-product A decreases the OMC with 1,664 kg/m3 of the maximum dry unit weight when compared to the maximum dry unit weight of untreated soil. However, co-product B decreases the maximum dry unit weight with 17% of OMC when compared with the maximum dry unit weight of untreated soil. The decrease in maximum dry unit weight with co-product B is attributed to the lower specific gravity of co-product B than that of soil. These results indicate that co-product A is a more promising additive, considering the reduction in the plastic property and the decrease in OMC with increasing maximum dry unit weight as indicators of improvement for soil stabilization purposes.

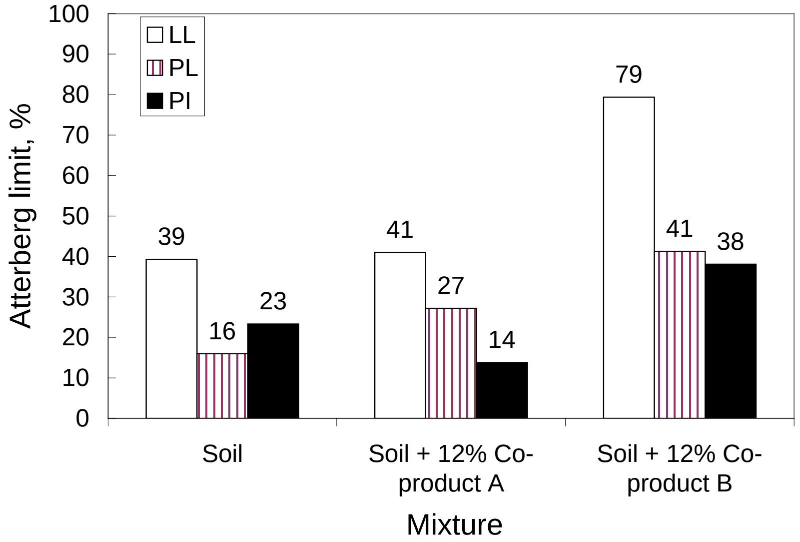

Figure 5. Effect of BCPs on consistency limits of soil.

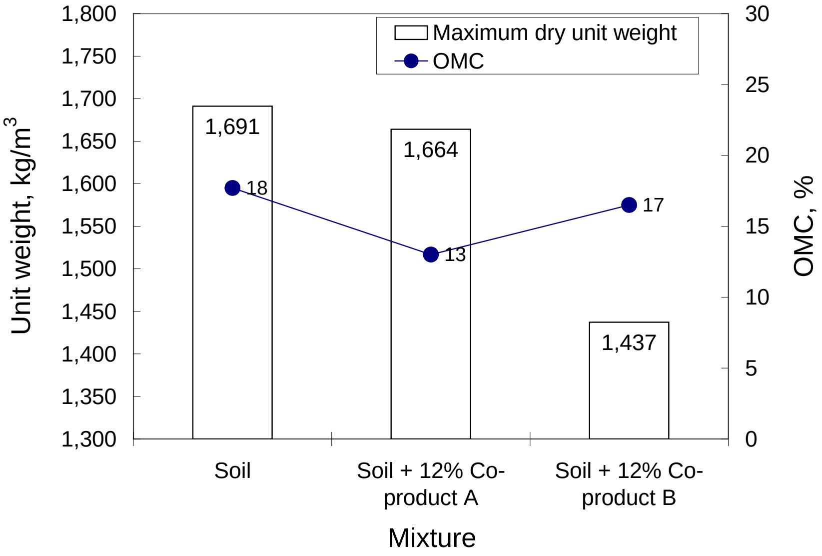

Figure 6. Effect of BCPs on compaction properties of soil.

Conclusions

This study investigated sustainable use of co-products from lignocellulosic biorefineries in geotechnical applications. The laboratory tests were conducted to evaluate the effect of two bio-energy co-product (BCP) additives on a typical Iowa subgrade soil in terms of strength, consistency limits and compaction properties. Emphasis is given to detailed data analysis of laboratory test results in comparing treated soils with untreated soils under different moisture conditions and additive concentrations. BCP additives investigated are promising materials to improve strength of the Iowa class 10 soil classified to CL or A-6(8). Especially, the co-product A containing higher lignin content is considered a more effective additive to reduce plastic property and optimum moisture content of soil. Future research is recommended to investigate the use of lignin-based BCPs for a variety of soils.

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