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Renewable biomass-derived lignin in transportation infrastructure strengthening applications

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Abstract

Lignin is considered as nature's most abundant aromatic polymer co-generated during papermaking and biomass fractionation. There are different types of lignins depending on the source (hardwood, softwood, annual crops, etc.) and recovery process. Recently, an emerging class of lignin products, namely sulphur-free lignins, from biomass conversion processes, solvent pulping and soda pulping, have generated interesting new applications owing to their versatility. As the renewable energy industry is expanding into developing the next generation of biofuels based on cellulosic biomass (e.g. corn stover, forest products waste, switch grass), abundant supply of sulphur-free lignin will become available as co-products for which value-added engineering applications are being sought. This paper discusses the potential for utilising lignin-containing biofuel co-products for stabilisation of geo-foundation beneath road pavements. Laboratory test results indicate that the biofuel co-products were effective in stabilising the Iowa class 10 soil (CL or A-6(8) soil classification). Utilisation of cellulosic biomass-derived lignin in transportation infrastructure strengthening applications appears to be one of the many viable answers to the profitability of the bio-based products and the bioenergy business from the perspectives of sustainable infrastructure systems.

Keywords

CNDE, Biofuel, co-product, lignin, pavement, soil stabilisation, sustainability

Disciplines

Civil and Environmental Engineering

Comments

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Renewable Biomass-derived Lignin in Transportation Infrastructure Strengthening Applications

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Abstract

Lignin is considered as nature's most abundant aromatic polymer co-generated during papermaking and biomass fractionation. There are different types of lignins depending on the source (hardwood, softwood, annual crops, etc.) and recovery process. Recently, an emerging class of lignin products, namely sulphur-free lignins, from biomass conversion processes, solvent pulping, and soda pulping, have generated interesting new applications owing to their versatility. As the renewable energy industry is expanding into developing the next generation of biofuels based on cellulosic biomass (e.g., corn stover, forest products waste, switch grass), abundant supply of sulphur-free lignin will become available as co-products for which value-added engineering applications are being sought. This paper discusses the potential for utilizing lignin-containing biofuel co-products for stabilization of geo-foundation beneath road pavements. Laboratory test results indicate that the biofuel co-products were effective in stabilizing the Iowa class 10 soil (CL or A-6(8) soil classification). Utilization of cellulosic biomass-derived lignin in transportation infrastructure strengthening applications appears to be one of the many viable answers to the profitability of the biobased products and the bioenergy business from the perspectives of sustainable infrastructure systems.

Keywords: Biofuel; Soil stabilization; Lignin; Sustainability; Co-product; Pavement; Fly ash

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1. Introduction

Sustainable development has been globally recognized in the context of depleting non-renewable resources (petroleum, natural gas, coal, minerals, and etc.), regulations on using synthetic materials, growing environmental awareness and economic considerations (Kamm and Kamm 2004). Terminologies associated with Life-Cycle Analysis (LCA), sustainable infrastructure, industrial ecology, green energy and technology, eco-efficiency, eco-labelling, green rating, etc. are becoming more and more common in research literature and product marketing. Sustainable development requires safe, sustainable resources to replace fossil-based energy for various industrial applications (Kamm and Kamm 2004). The bioenergy cycle, at least conceptually, does not have the negative environmental impact associated with fossil fuel-based energy sources and is therefore considered an attractive alternative.

Agricultural biomass is one of the sustainable resources having cost-effectiveness and can be transformed into bio-based energy such as biofuel and ethanol. Agricultural biomass such as corn products can be converted into biofuels or ethanol by hydrolysis and subsequent fermentation (Hamelinck et al. 2005). Biofuel production also produces many different co-products that have many unexplored potential uses (Bothast and Schlicher 2005).

Among many different co-products, lignin, which represents the third largest fraction of agricultural biomass, has been considered as a waste material or a low-value co-product with its utilization predominantly limited to use as a fuel in the production of octane boosters, and in bio-based products and chemical productions (Stewart 2008). However, the amount of lignin as biofuel co-product will become abundantly available with the growing biofuel production industry. New uses for biomass-derived lignin need to be developed to provide additional revenue streams to improve the economics of the bio-based products and the bioenergy business. This paper proposes the application of biomass-derived lignin for stabilizing soils to provide good foundation for roads.

A good road (paved or unpaved) requires a suitable foundation which in turn requires stability. Unfortunately, many of the soil deposits do not naturally possess the requisite engineering properties to serve as a good foundation material for roads and highways. As a result, soil-stabilizing additives or admixtures are used to improve the properties of less-desirable road soils (ARBA 1976). Lignin has 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).

Previous studies on the use of lignin-based products in transportation infrastructure have focused on sulfite lignin (lignosulfonates or lignin-sulfonates) which is derived from the paper industry, while the lignins obtained from biofuel or ethanol production is sulfur-free lignin. Even though sulfur-free lignins have been known for many years, the use of sulfur-free lignins has recently gained interest as a result of diversification of biomass processing schemes (Lora and Glasser 2002). Value-added engineering applications of lignocellulosic residues from biofuel production methods are being actively researched and promoted in an effort to maintain economic competitiveness of cellulosic-ethanol processes (Gopalakrishnan et al. 2012).

The primary objective of this study is to examine the potential of lignin-containing biofuel co-product, as a material for stabilising soil. The procedure and the results of testing are presented in this paper highlighting the important findings regarding the utilization of biofuel co-product for roadway soil stabilization. A brief overview of the historical uses of sulphite lignin in transportation infrastructure applications is first provided.

2. Sulfite Lignin in Transportation Infrastructure

The first utilization of lignin in industry began in the 1880s when lignosulfonates were used in leather tanning and dye baths. Since then, a number of studies have been conducted to expand the use of lignin in many applications including the production of dyes, vanilla, plastics, base-exchange material for water softening, and the cleavage products of lignin from nitration, chlorinate, and caustic fusion (Cooper, 1942). Conventional sulfite lignin (lignosulfonates) is the most mature product among all types of lignin. The International Lignin Institute (ILI 1991) lists the following traditional applications that sulfite lignin (lignosulfonates) recovered from sulfite pulping can serve: binder, dispersant, emulsifier, and sequestrant.

Sulfite lignin or lignosulfonate has been used standalone or in combination with other chemicals to achieve soil improvement for supporting pavement infrastructure (Nicholls and Davidson 1958). Lignin as a soil additive causes dispersion of the clay fraction of some soils resulting in the shear strength increase of the soil due to particle rearrangement (Addo et al. 2004). Various studies on lignin as a soil additive have concluded that lignin is primarily a cementing agent (Woods 1960, Ingles and Metcalf 1973, Landon and Williamson 1983). Nicholls and Davidson (Puppala and Hanchanloet 1999) confirmed that lignin admixtures indeed do improve some engineering properties related to stability of soils. They also reported that the strength of lignin-treated soil increases rapidly with an increase in the length of air curing.

Ligninsulfonates were first utilized to control duct on unpaved roads in Sweden in the 1910s (Arnfelt 1939). The Institute of Road Research in Sweden in their dust control experiment with ligninsulfonate reported that it reacted well with dust and bound particles together if the road surface was rich in clay. Several states in the U.S also made much use of ligninsulfonate as a dust suppressant on road surface with impervious wearing courses in 1930s (Sinha et al. 1957). Field observation of the lignin-treated test sections indicated that the lignin acted like cement, binding the soil particles together into a hard surface that show strength gains over time (Addo et al. 2004).

Lignin has been used as an emulsifier in asphalt emulsions due to its sequestering and dispersing properties (ILI 1991). Several laboratory experiments have been conducted to examine the use of lignin from wood pulping as a substitute or an extender for asphalt in paving mixtures (Terrel and Rimstritong 1979, Sundstrom et al. 1983, Kandhal 1992). Recently, attempts have been made to investigate the use of lignin from wood pulping as an antioxidant in asphalt (Bishara et al. 2005, Guffey et al. 2005a, Guffey et al. 2005b). These studies imply that lignin-modified asphalt can decrease the rate of oxidation without adverse effects on the other asphalt performance properties.

The use of ligninsulfonate as an admixture in concrete has been known for more than 60 years (Zhor and Bremner 1999). Ligninsulfonate has been used as a water reducing and a set-retarding admixture to reduce water and offset the effects of high temperature without losing workability (Mindess et al. 2002). The hydrophilic modified aromatic structures of lignin can reduce the amount of water necessary in a concrete to reach a certain fluidity resulting in the improvement of the concrete's final strength (Nadif et al. 2002). However, the dosage of ligninsulfonate should be controlled to prevent retarding the development of strength. Zhor and Bremner (Zhor and Bremner 1999) investigated the effect of ligninsulfonate dosage rate on fresh concrete properties and concluded that the highest dosage rates will always cause set retardation. Ligninsulfonate has also been used in ready-mix concrete and pre-cast concrete to produce concrete with an improved rheology at the job-site and to obtain high-strength concrete (Plank 2004).

3. Materials

3.1. Soils

The natural soil used in this study conformed to class 10 soil as described in the Iowa Department of Transportation (DOT) specification (Iowa DOT 2008). The class 10 soil was obtained from a new construction site prepared for Highway US-20 in Calhoun County, Iowa (STA. 706 to STA.712, Project Number NHSX-20-3(102)- -3H-13). The class 10 soil is the typical excavated soil including all normal earth materials such as loam, silt, clay, sand, and gravel. Table 1 summarizes the engineering properties of Iowa class 10 soil used in this study. Based on characterized engineering properties, the soil could be classified to CL and A-6(8) in accordance with the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) soil classification system, respectively.

Table 1. Summary of Iowa class 10 soil engineering properties.

Property	Class 10
Gravel, %	7.6
Sand, %	40.4
Silt and clay, %	51.9
Liquid Limit (LL) , %	39.3
Plasticity Limit (PL), %	16.0
Plasticity Index (PI), %	23.3
USCS group symbol	CL
USCS group name	Sandy lean clay
AASHTO (group index)	A-6(8)
Optimum moisture content, %	17.7
Maximum dry unit weight, kg/m^3(pcf)	1,693 (105.7)

3.2. BioOil

A commercially available BioOil was used as the experimental lignin-containing biofuel co-product for this study. BioOil is a dark brown, free-flowing liquid fuel with a smoky odor reminiscent of the plant from which it was derived. BioOil is formed in a process called pyrolysis wherein plant material (biomass) such as forest residues (bark, sawdust, etc.) and agricultural residues (sugar cane, cornhusks, bagasse, wheat straw, etc.), are exposed to 400-500°C in an oxygen free environment (Dynamotive Energy Systems Corporation 2007). Recently, several qualification trial tests were conducted for using this commercial BioOil to heat the Iowa Capitol Complex (Iowa DAS 2008).

The raw BioOil contains about 25 percent lignin and up to 25 percent water with a pH of 2.2. Table 2 presents a summary of constituent materials present in raw BioOil. The water component in raw BioOil for use of liquid fuel is not a separate phase because it lowers the viscosity of the fuel. However, the water content is significantly removed by heating the raw BioOil in the oven for a specified period of time. This water removed BioOil is defined as the evaporated BioOil in this study.

Table 2. Component materials in BioOil.

Components	Percent by weight
Gases	5 to10
Water	Up to 25
Lignin	25
Char	4
Aldehydes	35 to 41

This study used raw BioOil as well as evaporated BioOil. Since raw BioOil already contains water in it, it was directly mixed with soil during compaction without the addition of further water. With evaporated BioOil, water was added while mixing it with soil to investigate the effect of different moisture contents on strength properties.

3.3. Fly ash

The relative performance of biofuel co-product was assessed with respect to a traditional soil stabilizing agent, Ottumwa class C fly ash. Ottumwa class C fly ash is a coal combustion by-product from Ottumwa Generating Station (OGS) located near Chillicothe, Iowa. This fly ash is commonly used in soil treatment in Iowa. The chemical composition of Ottumwa fly ash is presented in Table 3.

Table 3. Chemical composition of Ottumwa fly ash.

Components	Percent by weight
Na_2O	3.21
MgO	6.81
Al_2O_3	16.2
SiO_2	31.6
P_2O_5	1.02
SO_3	3.13
K_2O	0.32
CaO	28.8
TiO_2	1.24
Fe_2O_3	6.03
SrO	0.51
Mn_2O_3	0.02
BaO	0.89
LOI	0.30

4. Experimental plan

For comparison purposes, the primary experimental plan encompassed preparation and testing of three broad categories of treatment types: (1) untreated soil sample (control), (2) soil sample treated with the biofuel co-product, and (3) soil sample treated with fly ash. Soil was mixed with each additive (biofuel co-product or fly ash) at varying amounts to identify the optimal additive content. The BioOil and fly ash contents evaluated are 1, 3, 6, 12, and 15 percent by dry soil weight. The untreated soil samples were also tested without any additive.

Similarly, variable moisture contents and curing periods were incorporated into the test factorial. All soil specimens were tested at three different moisture contents: untreated soil optimum moisture content (OMC), OMC+4 percent, and OMC-4 percent. For soils mixed with the raw BioOil, the additive concentration levels were adjusted to achieve the same water contents corresponding to OMC, OMC+4, and OMC-4 percent. The curing periods primarily investigated were 1 and 7days after sample fabrication for strength tests.

Table 4 lists the primary treatment group combinations evaluated during the study. Specimens incorporating seventy-eight (78) different treatment combinations were fabricated in the laboratory that underwent unconfined compression strength (UCS) test programme. In order to obtain quality test results, two specimens were prepared for each treatment which resulted in a total of 156 specimens.

Table 4. Primary treatment group combinations.

Moisture content level	Curing period	Additives, %	
		BioOil	Fly ash
Without water	1 day	13.7 [b], 17.7 [b], 21.7 [b]	N/A [c]
	7 days	13.7 [b], 17.7 [b], 21.7 [b]	N/A [c]
OMC-4	1 day	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15
	7 days	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15
OMC	1 day	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15
	7 days	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15
OMC+4	1 day	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15
	7 days	0, 1, 3, 6, 12, 15	0, 1, 3, 6, 12, 15

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

b. Same water contents as OMC, OMC+4, and OMC-4 of untreated soil

c. Not available

Apart from the primary treatment group combinations listed in Table 4, several other treatment group combinations were also considered to evaluate the effect of variability in specimen preparation methodology on the strength testing results. Also, soils were mixed with water before and after the addition of biofuel co-product to identify the effect of mixing procedure on strength.

5. Strength property testing

The UCS test result was used as an index of specimen performance. The performance of test specimens relative to control specimen performance provided a means of evaluating the effects of specimen preparation methods, and the additive types and concentration levels. The control specimens consisted of untreated soil prepared at the desired moisture contents without any stabilizer.

The ASTM D2166 (ASTM International 2006) specification describes general test procedure for determining the UCS of soil samples, but does not specify the sample geometry. Portland Cement Association (PCA) recommends three types of sample geometry for compression test of soil-cement mixture: 102-mm (4-inch) in diameter by 117-mm (4.6-inch) in height, 51-mm x 51-mm (2-inch x 2-inch), and 71-mm x 142-mm (2.8-inch x 5.6 inch) (PCA 1971). The compaction method for producing 51-mm x 51-mm specimens was developed by previous researchers at Iowa State University (ISU) (Chu and Davidson 1960). The compression strengths of 51-mm x 51-mm specimens have been correlated to that of the other geometry specimens for the soil and the soil–fly ash mixtures (White et al. 2005, ASTM International 2005). The use of 51-mm x 51-mm specimens can save time and materials. Because of these and other advantages reported in the literature (White et al. 2005) specimens of these dimensions were prepared in this study for UCS testing.

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5.1. Sample preparation

Each sample for UCS testing was prepared following 5 steps: soil preparation, soil-water-additive mixing, molding, compaction, and curing. The soil was dried in an oven at 60°C before mixing with water and additives. Fly ash was dried in air before mixing with soil and water. As mentioned previously, both raw BioOil (which contains moisture) as well as evaporated BioOil were used in the preparation of soil samples.

Once the soil and additive were prepared, soil was mixed with water and additives to obtain the desired moisture content and additive content. The materials were mixed together to produce a uniform, homogenous mixture. A sample of the mixture was used to determine the initial moisture content of the soils according to ASTM D2216 (ASTM International 2005).

The effect of mixing procedures on compression strength was evaluated by testing samples mixed through two types of mixing method. Type I method involves mixing soil with water before the addition of biofuel co-product and in type II method, the soil was mixed with water after the addition of biofuel co-product. Figure 1 compares the strengths of soil prepared by these two methods with 6 % BioOil. No significant difference can be observed between these two methods. However, all samples in primary treatment group combinations (See Table 4) were prepared by the Type I method for further investigation, since this method better represents actual field practice of soil stabilization.

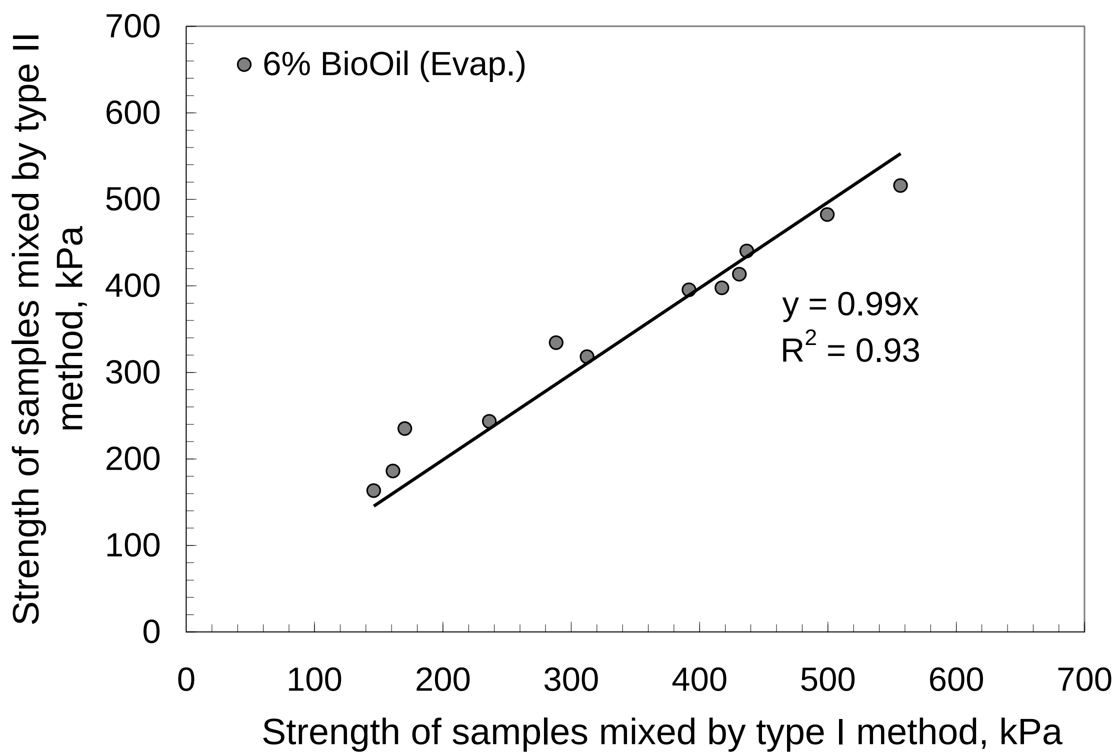

Fig. 1. Effect of mixing procedures on unconfined compressive strength.

A quantity of loose material was measured for each sample that would produce a 51-mm (2-inch) high compacted sample. The ISU 51-mm (2-inch) by 51-mm (2-inch) specimen preparation method specifies that loose materials are compacted in 51-mm (2-inch) diameter mold with removable collar by dynamic loading. The term 'dynamic loading' herein refers to five blows of 22-N (5-lb) hammer falling from a height of 305-mm (12 inch) on each end of the single layer of material (White et al. 2005). However, it was found that this compaction approach produce compacted samples with higher variations of density and strength. To reduce these variations of samples, a static compaction approach was employed which is similar to the approach used in soil specimen preparation for resilient modulus test in accordance with AASHTO T307 (AASHTO 1999).

Specially designed mold apparatus was fabricated and used to compact loose materials by static compaction. A 25-mm (1-inch) high spacer plug was inserted into the specimen mold with removable collar. Measured amounts of loose material were placed in the specimen mold and then the 102-mm (4-inch) high spacer plugs were inserted on loose materials in the specimen mold. A static load was applied to 102-mm (4-inch) high spacer plugs until the plug rested firmly against the mold end. After compaction was completed, the compacted specimen, as shown in Figure 2, was extracted from the mold using an extrusion ram. Table 5 and Table 6 list the average of dry density and wet density for the compacted samples, respectively.

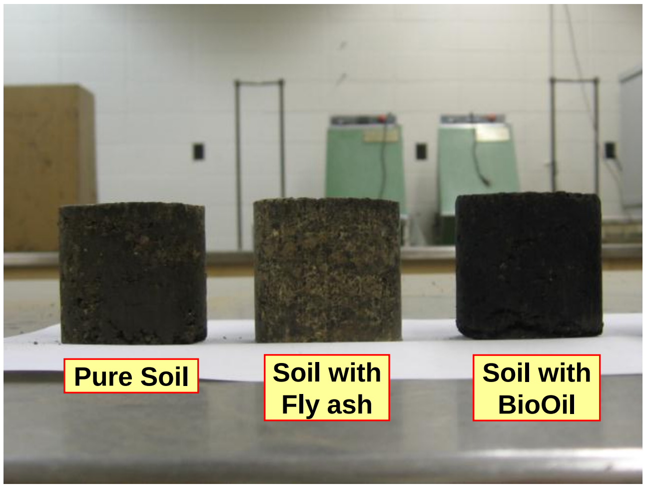

Fig. 2. Prepared samples for USC test.

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Table 5. Average dry density of compacted samples (unit: kg/m^3).

Moisture content level			OMC-4		OMC		OMC+4	
Curing period			1 day	7 days	1 day	7 days	1 day	7 days
Type	Untreated soil		1,625	1,628	1,627	1,636	1,653	1,642
	BioOil (Raw)		1,620	1,618	1,620	1,622	1,637	1,627
	BioOil (Evap.)	1%	1,630	1,630	1,624	1,631	1,641	1,645
		3%	1,615	1,621	1,629	1,627	1,629	1,633
		6%	1,622	1,617	1,623	1,615	1,606	1,611
		12%	1,613	1,621	1,574	1,604	1,549	1,571
		15%	1,614	1,625	1,529	1,576	1,538	1,549
	Fly Ash	1%	1,642	1,635	1,655	1,649	1,647	1,641
		3%	1,633	1,635	1,653	1,641	1,646	1,650
		6%	1,628	1,626	1,639	1,635	1,637	1,638
		12%	1,625	1,621	1,618	1,614	1,610	1,609
		15%	1,625	1,627	1,618	1,625	1,611	1,611

Table 6. Average wet density of compacted samples (unit: kg/m^3).

Moisture content level			OMC-4		OMC		OMC+4	
Curing period			1 day	7 days	1 day	7 days	1 day	7 days
Type	Untreated soil		1,831	1,831	1,898	1,904	1,972	1,967
	BioOil (Raw)		1,829	2,147	1,897	1,890	1,981	1,963
	BioOil (Evap.)	1%	1,848	1,837	1,905	1,929	1,975	1,982
		3%	1,854	1,860	1,931	1,928	1,997	1,996
		6%	1,900	1,892	1,965	1,955	1,985	1,986
		12%	1,954	1,957	1,961	1,999	1,933	1,964
		15%	1,942	1,974	1,905	1,977	1,912	1,938
	Fly Ash	1%	1,864	1,933	1,940	1,883	1,997	2,055
		3%	1,881	1,874	1,959	1,935	2,036	2,027
		6%	1,826	1,810	1,905	1,898	1,964	1,968
		12%	2,040	2,002	2,050	2,027	2,076	2,093
		15%	2,064	2,039	2,110	2,105	2,107	2,095

The compacted sample was sealed in plastic wrap and then placed in a temperature-controlled room where it was allowed to cure at 25°C and 40 percent relative humidity for various cure times. The curing process could be considered as the hardening or cementation of the additive-soil matrix. The air-curing process was selected to represent field condition.

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5.2. Unconfined compression strength (UCS) test

The UCS test was conducted following ASTM D2166 (ASTM International 2006). The cured sample was positioned in the test equipment and a compression load was applied at a constant rate of 1.3-mm per minute (0.05-in. per minute). The magnitude of compression load and the corresponding sample deformation were monitored and recorded. Each sample was compressed until a peak load was reached and either decreased or remained constant, or until deformation of sample exceeded past 20 percent strain before reaching the peak. A sample of the broken material was taken to determine the moisture content of the materials according to ASTM D2216 (ASTM International 2005).

6. Results and discussion

The effect of additive types and contents on strength was evaluated under different moisture conditions: OMC representing moisture condition providing maximum dry density of soil and used for construction quality control, OMC-4 representing more dry side of soil condition, and OMC+4 representing more wet side of soil condition. The evaluations were also made under different curing periods. The results are shown graphically in Figure 3 through Figure 5. The strength values at 0 % additive content on these figures indicate those corresponding to untreated soil. The strengths of the soil and raw BioOil samples without the addition of water are also depicted by dashed lines in these figures to provide comparisons.

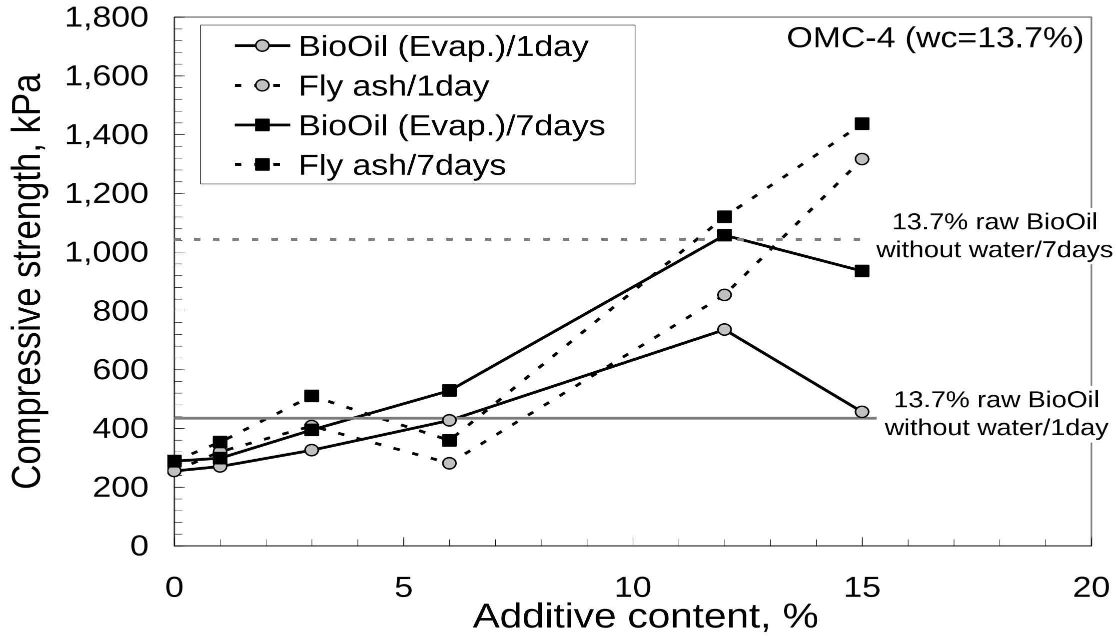

Fig. 3. Effect of additive types and contents on unconfined compressive strength under OMC-4 condition.

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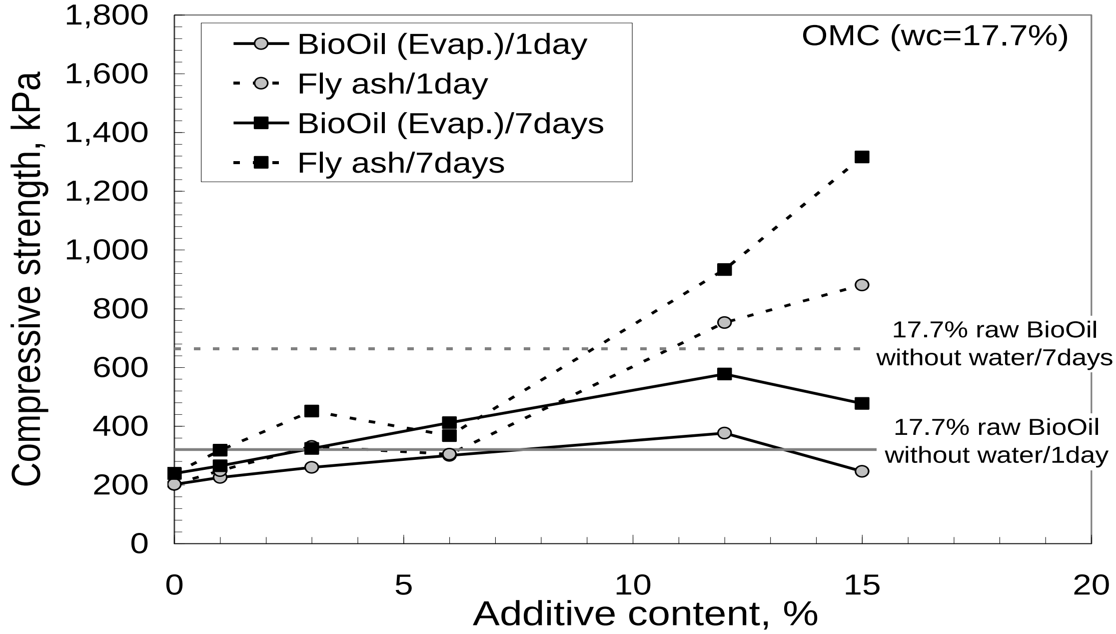

Fig. 4. Effect of additive types and contents on unconfined compressive strength under OMC condition.

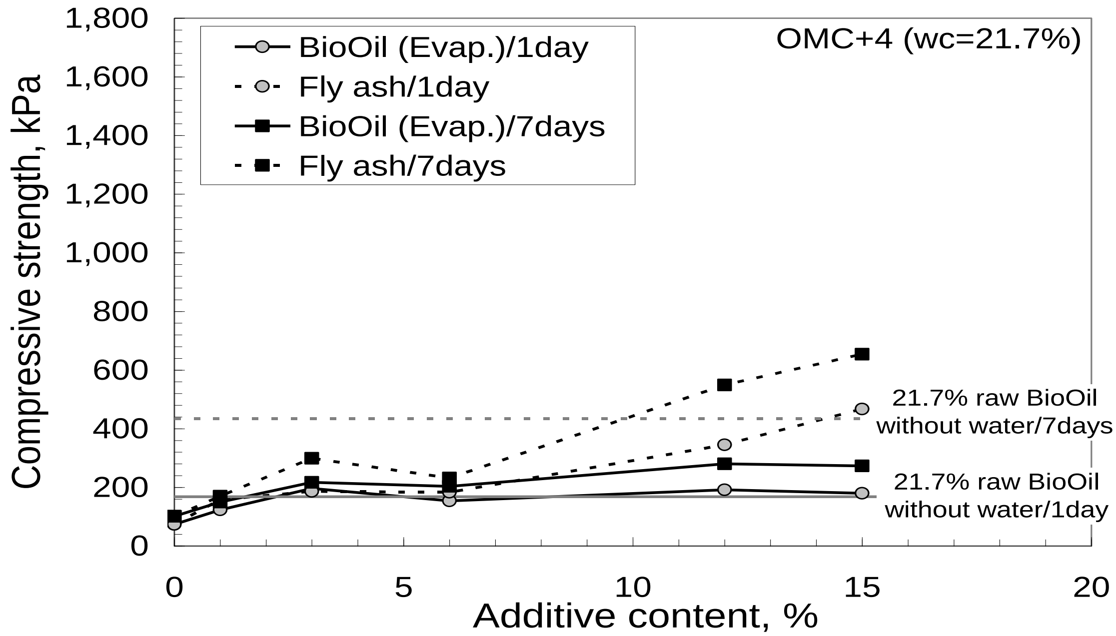

Fig. 5. Effect of additive types and contents on unconfined compressive strength under OMC+4 condition.

6. 1. OMC-4

As shown in Figure 3, fly ash (a traditional soil stabilizer) seems to be a very effective additive in enhancing the strength of tested soils under dry condition of soil (OMC-4). The BioOil-treated soil test results also show improved UCS similar to fly ash-treated soil. Under the dry condition of the soil, the increase in the amount of additives and the curing periods seem to improve the strength. Changes in the additive amount for BioOil revealed a definite optimum additive quantity near 12 %. These results indicate that BioOil can be as effective as fly ash in stabilizing the natural soil for strength improvement under dry condition.

6. 2. OMC

Similar to dry condition of soil (OMC-4), both the fly ash and the BioOil-treated soil test results in Figure 4 show improved strength at the OMC condition of soil. Overall, an increase in the amount of additives and the curing periods improves strength with 12 % as the optimum additive quantity for BioOil. These results indicate that BioOil can still be effective, but not better than fly ash, to stabilize pure soil with a target moisture condition for construction.

6.3. OMC+4

All additives-treated soil test results in Figure 5 also show improved strength under wet soil conditions (OMC+4). However, the fly ash provides more strength improvement with the increase in the amount of additive rather than the BioOil. These results indicate that BioOil cannot be used solely under wet soil conditions to achieve a given strength comparable to fly ash-treated soil. Further investigation is recommended to improve the strength of BioOil-treated soils in addition to fly ash under wet condition of soil. A lesser amount of fly ash might be required in this investigation since fly ash is costlier than BioOil.

6.4. Discussion

Multiple comparison tests were performed to see how the different treatments could be ranked. The Student-Newman-Keuls (SNK) test utilized in this study is one of multiple comparison tests that can be used to determine which means amongst a set of means differ from the rest. A SNK test result can be expressed in terms of a p-value, which represents the weight of evidence for rejecting the null hypothesis. The null hypothesis is the equality of mean between each pair of comparisons. The null hypothesis can be rejected, i.e. the mean between each pair of comparisons are significantly different, if the p-value is less than the selected significance level (α). A 0.05 of significance level (α) was used in this study.

Table 7 presents multiple comparison test results for the different treatments. Significant difference between each pair of comparisons was noted by p-value with less than 0.5 and levels not connected by same letter. Fly ash-treated soil has the highest strength, followed by raw BioOil-treated, evaporated BioOil-treated, and natural soil.

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Especially, raw BioOil-treated soil appears not to provide significant strength difference to fly ash.

Table 7. Multiple comparison test results.

Type	Mean	p-Value[1]				Level[2]
		Fly Ash	BioOil (Raw)	BioOil (Evap.)	Soil	
Fly Ash	536.8		0.9922	*0.0073*	*0.0017*	A
BioOil (Raw)	510.7	0.9922		0.3782	*0.0432*	A B
BioOil (Evap.)	362.0	*0.0073*	0.3782		0.267	B C
Soil	193.2	*0.0017*	*0.0432*	0.267		C

[1]p-value less than 0.5 indicate significant different in an pair of comparisons.
[2]Levels not connected by same letter are significantly different.

The strength gain mechanism from cellulosic biomass-derived lignin has not been identified. However, Gow et al. (Gow et al. 1961) addressed the soil stability increase from conventional sulfite lignin (lignosulfonates) by several explanations including a) plugging voids and consequently improving water tightness and reducing frost susceptibility, b) eliminating soft spots caused by local concentrations of binder soil, c) filling voids with fines thus increasing density, and d) increasing the effective surface area of the binder fraction which results in greater contribution to strength. It is speculated that some of these mechanisms could also contribute strength gain mechanism from cellulosic biomass-derived lignin.

Since industry supplied the experimental lignin-containing biofuel co-product investigated in this study, it is difficult to estimate the cost of these materials in construction in this study. However, it is obvious that sustainable development can drive more use of bio-based energy as alternative energy to fossil fuels. Considering the increase in biofuel production and limited commercial utilization of these materials, the cost of these materials would be comparable to or even less than traditional stabilizers such as fly ash which is by product of fossil fuels (coal) and might be less produced with decease of coal-fired power plants.

7. Conclusions

This study investigated the utilization of a lignin-containing biofuel co-product for roadway soil stabilization. Laboratory tests were conducted to determine strength properties of untreated soil samples, soil samples treated with biofuel co-product, and soil samples treated with a traditional soil stabilizing agent, fly ash. The analysis of the test data focused on identifying effects of additive types and contents. The following conclusions can be drawn on the basis of test results obtained from this study:

- Both biofuel co-product and fly ash were effective in stabilizing the Iowa class 10 soil classified to CL or A-6(8).
- The Unconfined Compressive Strength (UCS) of soils with Biofuel co-product is comparable to that of soils with fly ash under dry condition.
- A definite optimum additive quantity of Biofuel co-product is near 12 percent for

stabilizing soils underneath roadways in Iowa.

Utilization of biofuel co-product as a soil stabilization agent appears to be one of many viable answers to the profitability of the biobased products and the bioenergy business, especially in and around Iowa. Since there is much more biofuel co-product that is disposed of rather than utilized, making more productive use of biofuel co-product would have considerable benefits for sustainable development.

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