The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)

Strength performance of Iowa soils stabilized with biofuel industry co-product

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Abstract

The increasing cost and depletion of fossil-based energy combined with the problems of global warming is driving the development of bio-based energy products from plant biomass as renewable energy. The utilization of biofuel co-product (BCP) in new industrial applications should be investigated to increase the profitability of bio-based products and the bio-energy business. One such area of high-impact application is the stabilization of low quality roadbed soils with sulfur-free lignins found in BCPs. Recently, researchers are taking interest in investigating the viability and use of biofuel derived sulfur-free lignins for soil stabilization. This study aims to investigate the utilization of biofuel co-products (BCPs) containing lignin in pavement geomaterials stabilization. Laboratory tests were conducted to evaluate the effect of BCP addition on strength performance for a wide range of soils encountered in Iowa. Two different sulfur-free lignins were investigated: Co-product A is a liquid material with higher lignin content and co-product B is a powder material with lower lignin content.

For all soil types, a significant increase in compressive strength was observed once 12% BCP B was added to pure soil. The compressive strength values were increased by up to two times for Soil 2 (CL-ML) and four times for Soil 4 (ML). The results of these study indicated that the BCP has excellent potential for stabilizing low quality materials for use in road construction.

Keywords: Renewable energy; Biofuel; Co-product; Soil stabilization; Lignin; Pavement.

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1. Introduction

The exhaustion of fossil fuel and environmental pollution impel human beings to use a sustainable and renewable energy source, and biofuel produced from biomass is one of the solutions to reduce environmental issues. [1]. The biomass of the world is synthesized via the photosynthetic process that converts atmospheric carbon dioxide to sugar. Plants use the sugar to synthesize the complex materials that are biomass. Bio refineries require a large and constant supply of biomass. Biomass for use in the bio refinery could include grains such as corn, wheat and barley, oils, agricultural residues, waste wood and forest trimmings and dedicated energy crops such as switchgrass (Panicum virgatum) or hybrid poplar [2]. Even though various natural resources (e.g., wind, sun, water, and biomass) can be recognized as alternative sustainable resources to fossil fuels, biofuel or ethanol derived from biomass is considered to be economical energy resources. [3]. BCP also coproduces products containing lignin, modified lignin, and lignin derivatives [1]. Corn stover is the leading candidate as a biomass source to support a lignocellulosic biorefinery because of large quantities available. It has been estimated that in the USA there is a potential supply of between 60 to 100 million tons per year [4,5]. The US Government has enunciated the goal of displacing 10% of the petroleum used in the USA with biomass derived fuel and products by 2020 [6].

Stabilization of soils is an effective method for improving soil properties and pavement system performance [7]. Soil stabilization refers to produce in which a special soil, a cementing material, or other chemical materials are added to the liquefiable sandy soils to improve one or more of their properties. There are two methods to enhance the properties of sandy soils, one of them is the mechanical stabilization which is mixed the natural soil and stabilizing material together for obtaining a homogeneous mixture and the second one is adding stabilizing material into undisturbed soils to obtain interaction by letting it permeate through soil voids [8,9].

Lignin has also been implicated as having a role in soil stabilization [10, 11]. The impact of lignin could be direct, or lignin may contribute to the formation of humic acid, which increases soil stability. It has been hypothesized that since the BCP is high in lignin, which is thought to play a role in stabilizing soil, incorporation of the co-product into soil may help maintain or improve soil structure and stability [12,13]. Johnson et al. (2004) evaluated the effects of BCP derived from corn stover on soil chemical, physical and biological properties [13]. The utilization of BCPs with lignin in pavement geo-material stabilization is hypothesized to be a good stabilization method. In addition, new use of lignin production can provide other revenue streams for bioenergy industry [1].

BCPs with lignin are hypothesized a possible additive for soil stabilization to provide stronger performance of pavement geomaterials. The objective of this study is to investigate the use of BCPs with sulfur-free lignin in pavement soil stabilization. The unconfined compressive strength (UCS) is the primary performance characterization to evaluate the effects of BCPs in soil stabilization.

2. Materials and Methods

The preparation of test specimen for UCS has five steps: (1) dry soil to remove initial moisture, and sieve soil by passing No.4 sieve (4.75 mm) to break down soil particle sizes; (2) mix dried and sieved soil with water and additive uniformly to achieve targeted water and additive contents; (3) mold mixture with calculated total weight of specimen; (4) compact soil-additive mixture into 2 in. diameter by 2 in. height cylinder specimen; (5) wrap and air-dry cure specimens at 25°C room temperature to avoid loss of moisture. The sample preparation with five steps produces a uniform, homogenous soil-additive mixture with maximum dry soil unit weight which is obtained from standard proctor compaction method.

The mold apparatuses were designed and fabricated to produce specimen by static compaction and shown in Fig. 1. The apparatuses can be assembled to insert the 1 in. high spacer plug into the mold with removable collar. Loose mixture materials were placed in the mold and a 4 in. high spacer plug was also insert on the loose materials. The loose materials then can be compacted into 2 in. diameter and 2 in. height specimen by applying a static load on the 4 in. high spacer plug. This sample preparation method followed the Iowa State University 2 in. by 2 in. specimen preparation method modified with static loading instead of dynamic loading.
2.1. Properties of Soil

In this study, four types of soils representing common soil types in Iowa, USA were used. The engineering properties of the soil samples are shown in Table 1.

| Property | Soil 1 | Soil 2 | Soil 3 | Soil 4 |
|----------|--------|--------|--------|--------|
| Classification | A-6(2) | A-4(2) | A-4(1) | A-4(0) |
| USCS group symbol | SC | CL-ML | CL-ML | ML |
| USCS group name | Clayed sand | Sandy Silty with clay | Sandy Silty with clay | Sandy Silty |
| Grain size distribution | | | | |
| Gravel (> 4.75 mm), % | 7.1 | 0.1 | 5.2 | 3.8 |
| Sand (0.075–4.75 mm), % | 54.9 | 37.2 | 41.7 | 45.3 |
| Silt and clay (< 0.075mm), % | 38.0 | 62.7 | 53.1 | 50.9 |
| Atterberg limits | | | | |
| Liquid limit (LL), % | 32.8 | 29.1 | 27.5 | 17.2 |
| Plasticity limit (PL), % | 17.4 | 22.9 | 22.2 | 15.1 |
| Plasticity index (PI), % | 15.4 | 6.2 | 5.3 | 2.1 |
| Proctor test | | | | |
| Optimum moisture content (OMC), % | 14.4 | 18.2 | 13.5 | 12.0 |
| Maximum dry unit weight (γd,max), kg/m³ (pcf) | 1,728 (107.9) | 1,631 (101.8) | 1,818 (113.5) | 1,839 (114.8) |

Atterberg limits and compaction characteristics are important engineering properties. The influence of engineering properties of adding selected additive content into soil sample were evaluated. The selected percentage of co-products was the one in which the values of compression strength were at maximum. Atterberg limit test (LL, PL, and PI), Standard proctor test (optimum moisture content (OMC), maximum dry unit weight) for pure soil (control group) and soil-additive mixture were evaluated. Table 2. shows that the Atterberg limits [14] and proctor compaction test results [15].
Table 2. Atterberg limits and proctor compaction test results for four type’s soil.

| Soil Type            | Atterberg Limits of Soils | Optimum Moisture Content | Max. Dry Unit Weight |
|----------------------|---------------------------|--------------------------|----------------------|
|                      | LL | PL | PI | OMC, % | pcf | kg/m³ |
| Pure Soil 1          | 32.8 | 17.4 | 15.4 | 14.4 | 107.9 | 1728.0 |
| Soil 1+12% Cement    | 36.0 | 11.1 | 24.9 | 17.5 | 108.4 | 1736.0 |
| Soil 1+12% BCP B     | 76.0 | 39.0 | 37.0 | 16.3 | 91.1 | 1459.0 |
| Pure Soil 2          | 29.1 | 22.9 | 6.2 | 18.2 | 101.8 | 1631.0 |
| Soil 2+12% Cement    | 31.5 | 25.1 | 6.4 | 18.0 | 102.0 | 1634.0 |
| Soil 2+12% BCP B     | 67.8 | 39.4 | 28.4 | 18.9 | 90.6 | 1451.0 |
| Pure Soil 3          | 27.5 | 22.2 | 5.3 | 13.5 | 113.5 | 1818.0 |
| Soil 3+12% Cement    | 32.7 | 27.0 | 5.7 | 14.5 | 115.8 | 1855.0 |
| Soil 3+12% BCP B     | 72.7 | 36.4 | 36.3 | 15.8 | 90.1 | 1443.0 |
| Pure Soil 4          | 17.2 | 15.1 | 2.1 | 12.0 | 114.8 | 1839.0 |
| Soil 4+12% Cement    | 19.8 | 18.6 | 1.2 | 14.0 | 114.5 | 1834.0 |
| Soil 4+12% BCP B     | 58.3 | 44.3 | 14.0 | 18.8 | 36.2 | 1541.0 |

2.2. Additives

This study investigated the performance of utilization of two types of co-products as stabilizers, A and B, which containing sulfur-free lignin. BCP A looks like bitumen, a liquid fuel with dark brown color and choking odor. This liquid co-product was produced from the process of biomass pyrolysis in Canada. The plant residues (bark, sawdust, shavings, sugarcane, cornhusks, bagasse, wheat straw, etc.) can be used as abundant biomass resource and exposed in an oxygen-free and high temperature environment (400°C to 500°C) to produce this BCP oil. The ingredient of BCP A is shown in Table 3. It has 25% sulfur-free lignin and up to 25% water with a pH value of 2.2.

BCP B is a fine yellow powder was obtained from a corn-based plant for ethanol production of Grain Processing Corporation (GPC) of Muscatine, Iowa. This type of BCP contains about 5% lignin, 50% hemicellulose, 20% cellulose, and 25% other components. Its ingredients are also shown in Table 3. It is similar with corn ash, and has a specific gravity of 2.

Table 3. Component materials in BCP A and BCP B.

| Components | % by weight   |
|------------|--------------|
|            | BCP A        |
| Gases      | 5 to 10%     |
| Water      | Up to 25%    |
| Lignin     | 25%          |
| Char       | 4%           |
| Aldehydes  | 35% to 41%   |
|            | BCP B        |
| Lignin     | 5%           |
| Hemicellulose | 50%     |
| Cellulose  | 20%          |
| Other      | 25%          |

2.3. Experimental Program

The laboratory experimental program was conducted UCS test following ASTM D 2166 [16] with three different moisture levels, OMC-4%, OMC, and OMC+4% after various curing time, 1-day, 7-day and 28-day curing conditioning. OMC is the moisture content which soil can achieve the maximum dry density [17]. OMC-4% represents dry side of soil condition, and OMC+4% represents wet side of soil condition. The effect of stabilizer for soil treatment is measured in terms of the improvement in loadbearing capacity as indicated by UCS [18, 19, 20]. Three repetitions were conducted to decrease the test errors.
3. UCS Test Results

The four types of soils were mixed with different percentages of cement (3%, 6%, 12%) and 12% of BCP B. Also, 12% BCP A was mixed with Soil 2. The test matrix and results are shown in Table 4.

Table 4. The unconfined compression strength (UCS) test results for all soil types.

| Soil Types | Sample Type       | UCS Peak Stress (psi) | OMC 28-Day |
|------------|-------------------|-----------------------|------------|
|            | OMC-4             | OMC                   | OMC+4      |
|            | 1-Day 7-Day 28-Day | 1-Day 7-Day 28-Day    | 1-Day 7-Day 28-Day |
| Pure Soil 1| 84 89 93          | 42 37 41             | 22 28 24   |
| Soil 1     | 113 136 103       | 71 110 102           | 57 57 60   |
| Soil 1+4%  | 122 156 234       | 148 228 311          | 136 228 323|
| Soil 1+6%  | 203 272 320       | 262 369 648          | 226 341 698|
| Soil 1+12% | 281 447 747       | 400 664 955          | 379 613 1057|
| Soil 2     | 20 21 19          | 13 16 12             | 11 12 10   |
| Soil 2+4%  | 51 44 28          | 29 31 23             | 19 22 16   |
| Soil 2+6%  | 28 58 84          | 18 28 40             | 9 19 39    |
| Soil 2+12% | 69 114 201        | 87 122 238           | 58 112 195|
| Soil 3     | 159 225 357       | 145 212 384          | 129 188 256|
| Soil 3+6%  | 243 294 435       | 282 336 456          | 204 274 313|
| Pure Soil 2| 68 67 66          | 33 30 30             | 26 23 24   |
| Soil 2+4%  | 115 94 81         | 73 57 51             | 64 46 28   |
| Soil 2+6%  | 128 155 214       | 123 140 174          | 111 135 158|
| Soil 3+6%  | 222 277 355       | 200 274 306          | 170 245 301|
| Soil 3+12% | 324 442 538       | 334 474 607          | 299 370 556|
| Pure Soil 3| 27 27 35          | 12 14 15             | 9 11 11    |
| Soil 3+4%  | 115 112 87        | 71 55 33             | 34 34 25   |
| Soil 3+6%  | 72 147 181        | 45 131 194           | 28 96 139  |
| Soil 3+12% | 117 225 255       | 77 255 291           | 57 208 223|
| Pure Soil 4| 197 366 510       | 136 438 597          | 119 406 452|
| Soil 4     | 115 112 87        | 71 55 33             | 34 34 25   |
| Soil 4+4%  | 72 147 181        | 45 131 194           | 28 96 139  |
| Soil 4+12% | 117 225 255       | 77 255 291           | 57 208 223|

The preliminary findings from UCS test results are as follows:

- Soil type based on fine content influences soil strength capacity. Soil 1 shows the highest strength capacity for all types of specimen results from its lowest clay content. Soil 2 shows the weakest strength results from its highest clay content. The previous literatures found that the clay content could influence soil strength significantly. Soil 3 and Soil 4 have similar fine contents, but Soil 3 has higher strength than soil 4 for pure soil samples. The BCP powder treated samples for Soil 3 and 4 don’t show significant difference, but the cement treated samples for Soil 3 and 4 show the significant difference. The different soil engineering properties and structures may contribute to this strength difference.

- As can be seen from Fig. 2, moisture content influences soil strength capacity significantly. The compressive strength results were compared and the highest value was obtained in OMC-4 for pure soil and BCPs treated soil. More flocculated structures exist in dry side condition and increase internal friction in soil. For cement treated samples, its highest strength is always achieved with OMC. Hydration process with water is important to explain this phenomenon.

- Fig. 2 shows that curing periods influence on strength of treated soil, but it doesn’t have effect on strength of pure soil. For cement treated soil, long curing time increases the strength because hydration process needs time to harden soil. For BCP powder (BCP B) treated soil, the increase of curing time doesn’t show significant effect on Soil 1 and Soil 2, but it decreases the strengths of Soil 3 and 4. The BCP oil (BCP A) treatment shows a low peak strength in early age, but it will increase with the increase of curing time.
The additions of stabilizers improve soil strength capacity significantly. For BCP B treated sample, its strength generally shows 2 to 6 times higher than pure soil, for cement mixed samples generally show more than 10 times higher. BCP A is similar with asphalt binder, and its trial UCS test results show that BCP oil treatment has lower strength than other two additives (BCP B and cement) with 1-day curing (Table 4.). However, the long term curing period (28-day) made BCP oil treated samples have two to three times higher strength than BCP powder treated samples at all three moisture levels. 28 days compressive strength of pure Soil-2 was compared with the compressive strength of Soil 2+BCP A and Soil 2+BCP B mixtures at OMC-4, OMC, OMC+4 (Table 4.). The pure Soil 2 was also mixed with 3%, 6% and 12% cement and the compressive strength results were compared. As can be seen from Table 4., in each moisture content, the compressive strength values increased consistently. The increase of cement content improved soil strength significantly. Compared to pure soil, BCP A gave 4 times and BCP B two times higher compressive strength. The results show that BCP A and BCP B are promising additives for soil stabilization. For BCP mixtures, the highest compressive strength value was obtained at early age (OMC-4) as parallel to the previous studies [21].

4. Conclusion and Discussion

The increasing cost and depletion of fossil-based energy combined with the problems of global warming is driving the development of bio-based energy products from plant biomass as renewable energy. The utilization of biofuel co-product (BCP) in new industrial applications should be investigated to increase the profitability of bio-based products and the bio-energy business.

BCPs could be effective additives to stabilize pavement subgrade soil and improve bearing capacity of soil layer within pavement system. In addition, these biofuel co-products containing sulfur-free lignin are considered biodegradable and moisture resistant result from the sulfur-free lignin is insoluble in water.
This study investigated the compressive strength of soils stabilized by a bio-based energy co-product containing lignin. A laboratory experimental test program was conducted to compare the compressive strength of two types of biofuel co-product treated four different soils type. The final concluding statements of this study are as follows:

- BCP A treatment has an increase of strength with curing time increasing, however, BCP B treatment has a decrease of strength with long term curing period. After BCP treatment, compressive strength values of soil were increase up to two times for Soil 2 and four times for Soil 4.
- Generally, for pure soil and BCP treated soil, lower moisture content contributes to higher strength. The highest compressive strength value of cement treated samples was observed at OMC.
- The results of these study indicated that BCP A and BCP B are promising additives for soil stabilization.

Acknowledgements

The authors gratefully acknowledge the Iowa Highway Research Board and Iowa State University (ISU) for supporting this study. This study also was supported by The Scientific and Technological Research Council of Turkey (TUBITAK-1059B191301249) and Research Foundation of Selcuk University.

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