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This study explored the feasibility of lignin based biofuel co-product (BCP) for subgrade soil stabilization, and more specifically, its impact on Hot-Mix Asphalt (HMA) pavement performance using the Mechanistic-Empirical Pavement Design Guide (MEPDG). The HMA pavement systems with BCP stabilized subgrade under different traffic and climate conditions were modeled using mechanistic based damage analysis system. The performances of BCP stabilized subgrade and natural soil subgrade sections were compared in terms of fatigue (alligator) cracking and rutting predictions on HMA pavements. The results of this study indicate that BCP stabilization of subgrade soil could achieve more sustainable HMA pavements under different traffic volumes and climate conditions.

Keywords
climate condition, flexible pavements, hot mix asphalt, mechanistic-empirical pavement design guides, pavement performance, pavement systems, rutting predictions, geotechnical engineering, soil mechanics

Disciplines
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Comments
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Impact of Bio-fuel Co-Product Modified Subgrade on Flexible Pavement Performance

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Abstract

This study explored the feasibility of lignin based biofuel co-product (BCP) for subgrade soil stabilization, and more specifically, its impact on Hot-Mix Asphalt (HMA) pavement performance using the Mechanistic-Empirical Pavement Design Guide (MEPDG). The HMA pavement systems with BCP stabilized subgrade under different traffic and climate conditions were modeled using mechanistic based damage analysis system. The performances of BCP stabilized subgrade and natural soil subgrade sections were compared in terms of fatigue (alligator) cracking and rutting predictions on HMA pavements. The results of this study indicate that BCP stabilization of subgrade soil could achieve more sustainable HMA pavements under different traffic volumes and climate conditions.

Introduction

Roadway can be strong when it is supported by strong soil foundation. The subgrade soil-stabilization with additives or admixtures provide a working platform during construction and improves subgrade structural stability. The most widely used additives include hydrated lime, portland cement, and fly ash. However, the use of waste materials and by-products as an alternative to these materials continues to gain attention in the context of sustainable construction development.

Lignocellulosic biomass such as agri-residues, agri-processing by-products, and energy crops is abundantly available all around world. Lignocellulosic biomass is the only renewable source of carbon for the manufacture of carbon-based fuels. Lignocellulosic biomass in the transportation fuel conversion procedure produces not only bio-based energy but also co-products containing lignin, modified lignin, and lignin derivatives. The use of sulfur lignin (lignosulfonates) based product derived from paper industry in subgrade soil stabilization has been studied previously

(Nicholls and Davidson 1958). However, the sulfur-free lignins based biofuel co-product (BCP) has not been practically documented so far in literature with regard to their use in highway geomaterial stabilization until recently when the researchers at Iowa State University (ISU) started exploring this novel idea. Recent studies at ISU on the effectiveness of BCP as a soil stabilizer showed promising results in terms of substantially increased compressive strengths compared to those of their untreated soils counterparts (Ceylan et al. 2009, Ceylan et al. 2010, Gopalakrishnan et al. 2010).

In continuation of ongoing studies at ISU, this research investigated the impact of BCP stabilized subgrade on Hot Mix Asphalt (HMA) pavement performances. For this purpose, Mechanistic-Empirical Pavement Design Guide (MEPDG) was utilized as the mechanistic based damage analysis system to predict HMA pavement performances during pavement service life. The HMA pavement systems with BCP stabilized subgrade was modeled under different traffic and climatic conditions. The HMA pavement systems with natural soil subgrade were also modeled for each case. The performances of BCP stabilized subgrade and natural soil subgrade sections were compared in terms of fatigue (alligator) cracking and rutting in HMA pavements. The procedure and the results of data analysis are discussed in this paper highlighting the important findings regarding the impact of BCP stabilized subgrade on HMA pavement performance during service life.

Bio-fuel Co-Product (BCP) Containing Lignin

Lignocellulosic biomass consists of cellulose, hemicellulose and lignin. During biochemical conversion process from lignocellulosic biomass to bio-based energy, only cellulosic and hemicellulosic fractions can be utilized for ethanol production through transformation of fermentable sugar. The other fiber fractions including lignin has been considered as by product of this conversion process with its utilization predominantly limited to use as a fuel in the production of octane boosters, and in bio-based products and chemical productions.

Lignin is the essential natural glue that holds all plants together. It is a large complex polymer of phenylpropane and methoxy groups, a non-carbohydrate polyphenolic substance that encrusts the plant cell walls and cements the plant cells together. It is important to recognize that the native lignin undergoes profound structural changes and dramatic modification of molecular weight profiles depending on the recovery technology employed. The lignin modified by various recovery technologies can be divided into two principal categories: the sulfur lignin and the sulfur-free lignin (ILI. 2008). Most of sulfite lignins (lignosulfonates) are derived from paper industry while the lignins obtained from bio-based energy production are sulfur-free.

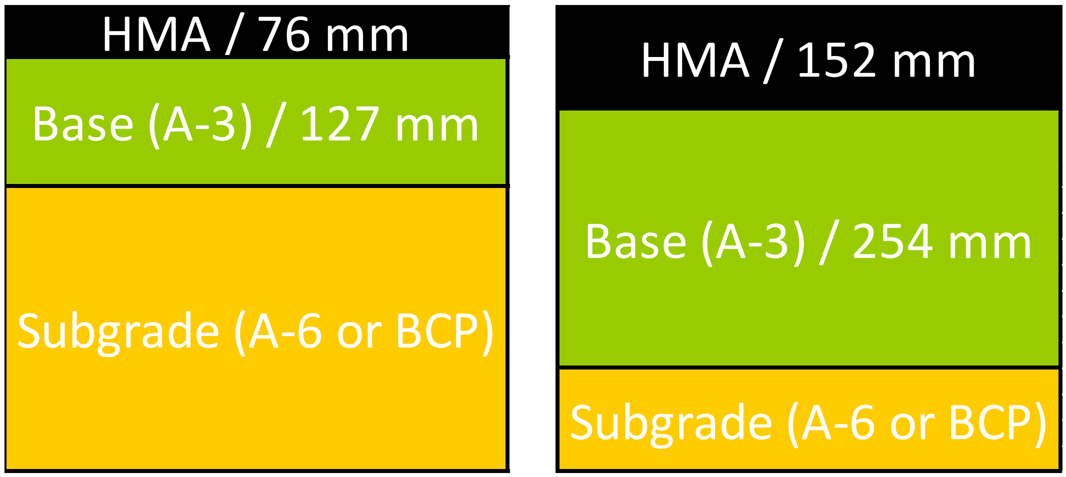
The use of sulfite lignins in soil stabilization has been studied over the past decade (Nicholls and Davidson 1958). Adding sulfite lignin to clayey soils increases the soil stability by causing dispersion of the clay fraction (Gow et al. 1961). Recent studies at ISU (Ceylan et al. 2009, Ceylan et al 2010) focused on the utilization of BCP containing sulfur-free lignin in pavement soil stabilization. Laboratory tests were conducted to compare the strength property of BCP treated soil samples with untreated and traditional stabilizer (fly ash) treated soil samples. Preliminary study results demonstrated that BCP can improve subgrade soil strength (Gopalakrishnan et al., 2010). It was also demonstrated that BCP is more effective in providing moisture resistance of soil rather than traditional stabilizer (fly ash). The results of these tests indicated that the BCP has excellent potential for stabilizing low quality materials for use in road construction.

Mechanistic Based Damage Analysis Modeling

The MEPDG and its software were developed to provide more rational methodologies in pavement thickness design through National Cooperative Highway Research Program (NCHRP) 1-37A project (NCHRP 2004). The MEPDG has adopted as the new AASHTO pavement design guide after the final refinement by the AASHTO DarWin Task Force (Hall et al. 2010). The MEPDG employs the application of the principles of engineering mechanics to calculate pavement responses (stresses, strains, and deflection) under loads for the predicting the pavement performance history.
The general design approach featured in the MEPDG is an iterative process in which the designer first selects a trial design scenario and subsequently analyzes the predicted performance. The designer then changes the trial design scenario until the predicted performances meet some predetermined design criteria (NCHRP 2004). Strictly speaking, the MEPDG is a pavement analysis system rather than a pavement decision tool providing a design thickness as the end product. In this paper, MEPDG was utilized to predict distress measurements of HMA pavement with BCP stabilized subgrade against natural subgrade performance during pavement service life. The latest version of MEPDG (Version 1.1) was used in this study.

Four sites representing different climate extremes in the U.S. were considered: Des Moines in Iowa (wet - freezing and thaw zone), Orlando in Florida (wet - no freeze zone), Billings in Montana (dry - freezing and thaw zone), and San Antonio in Texas (dry - No freeze). Typical asphalt performance grade utilized in each site was assigned corresponding HMA material property inputs: PG 58-28 for Des Moines in Iowa, PG 67-22 for Orlando in Florida, PG 64-28 for Billings in Montana, and PG 70-16 for San Antonio in Texas. Two levels of initial Average Annual Daily Truck Traffic (AADTT) considered were 100 and 12,000 vehicles per day representing low and high traffic levels. A 5% of compound traffic growth rate was set up over a 20-year design life. Two typical HMA pavement structures, shown in FIG 1, were modeled for low and high traffic level cases.

MEPDG requires the resilient modulus value as subgrade material characterization input. For this study, the resilient moduli of BCP stabilized subgrade material and natural subgrade material were interpreted from measured average compressive strength of 580 kPa for BCP stabilized subgrade material and of 240 kPa for natural subgrade material. The correlations between compressive strength and resilient modulus reported by previous studies (Heukelom and Klomp 1962, Thompson and Robnett 1979, Bejarano and Thompson 1999, Gopalakrishnan and Thompson 2007) were utilized for interpretation. Average correlated values of 4,544 kPa for BCP stabilized subgrade material resilient modulus and 1,642 kPa for natural subgrade material resilient modulus were set up for MEPDG modeling. All other reference inputs were set equal to the MEPDG Level 3 defaults. The performance measures investigated were alligator cracking and rutting. Design reliability was set at 50% for both distresses.



(a) **(b)**

FIG. 1. Pavement structure modeled; (a) low traffic, (b) high traffic.

Results and Discussions

FIGS 2 and 3 illustrate the predicted alligator cracking and rutting with service times of the modeled high traffic volume HMA pavements in Iowa (wet - freezing and thaw zone) to disuses the impact of BCP stabilized subgrade on HMA pavement performance measures. As seen in these figures, the HMA pavement with BCP treated subgarde had much lower alligator cracking and rutting predictions than one with natural subgarde. This behavior could be explained by the higher resilient modulus of BCP stabilized soil materials, i.e., soil strength and stiffness improvement caused by BCP could contribute to prevent pavement distress during service life.

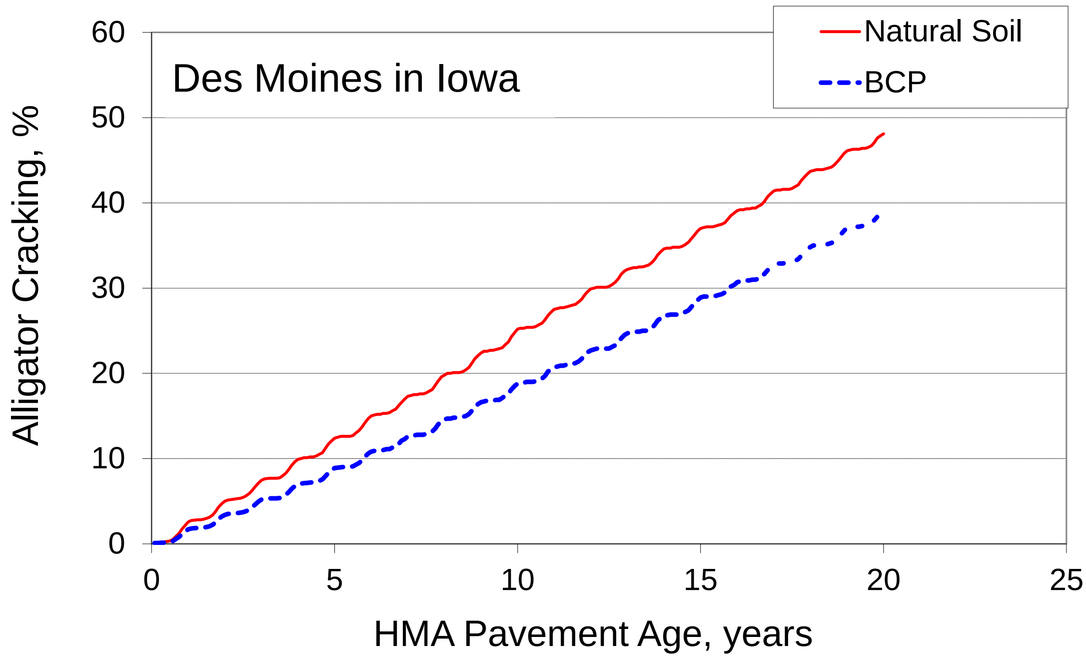


FIG. 2. Alligator cracking predictions with age of modeled high traffic volume HMA pavements in Iowa.

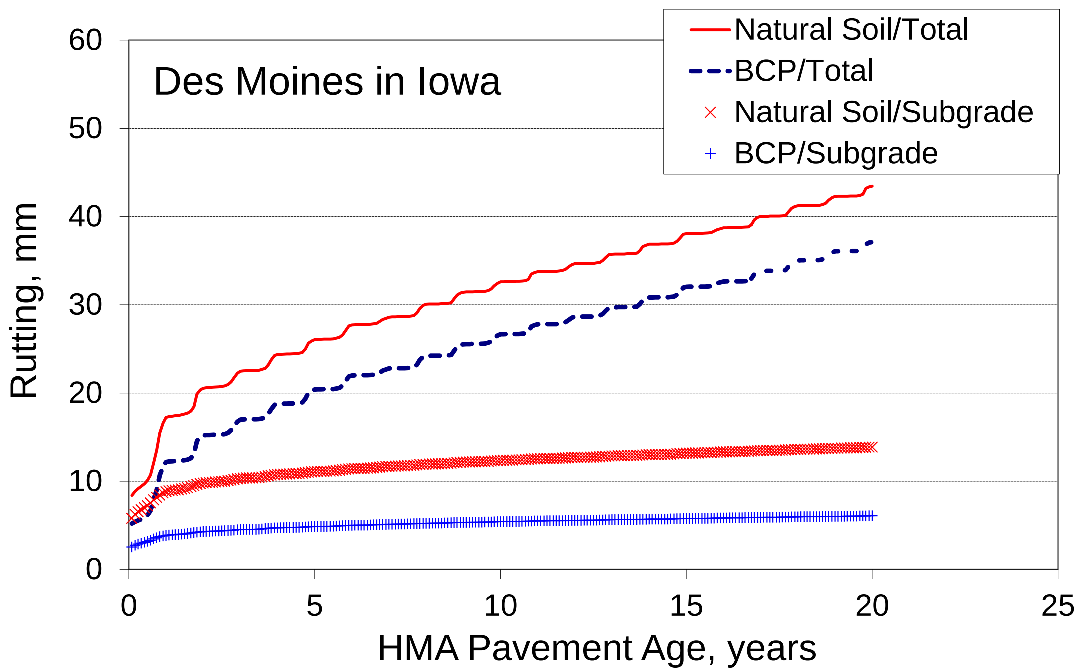


FIG. 3. Rutting predictions with age of modeled high traffic volume HMA pavements in Iowa.

FIGS. 4 and 5 summarize the predicted alligator cracking and subgrade rutting for low and high traffic volume HMA pavements at each of the four climate locations.

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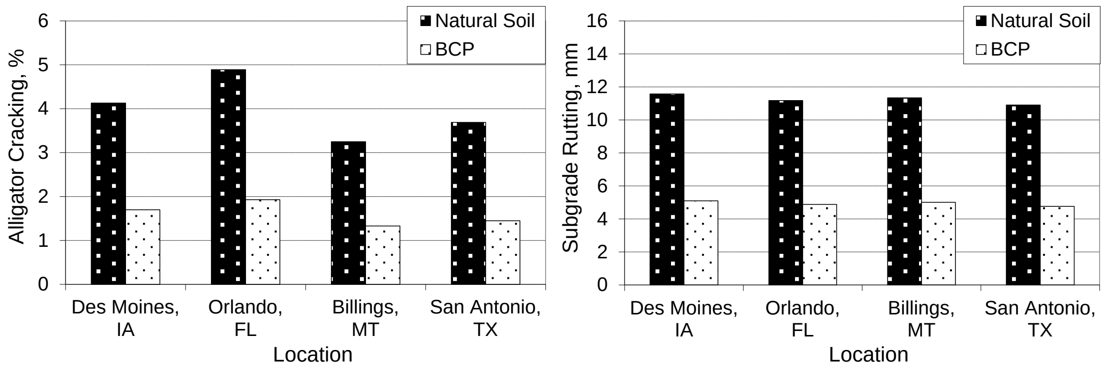
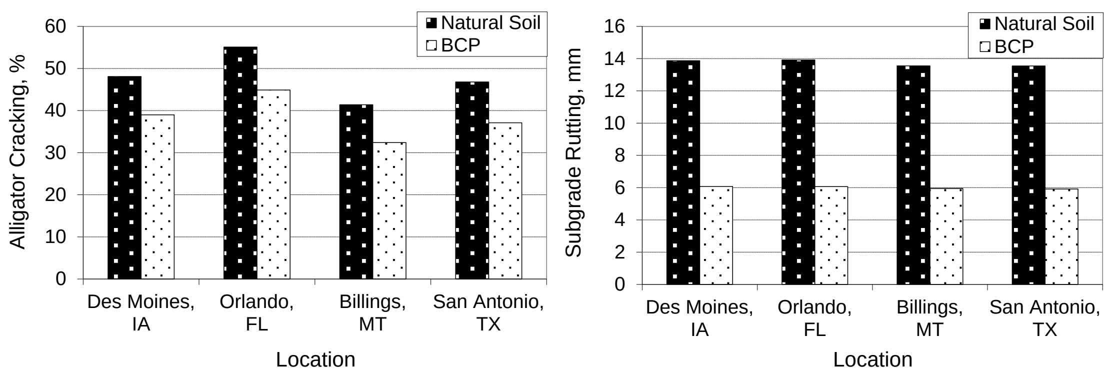
It is clear, according to these figures, that all of traffic levels and climate locations investigated have lower alligator cracking and subgrade rutting of BCP treated pavement rather than untreated pavement. The MEPDG performance predictions of these figures suggest that BCP stabilization of subgrade soil could achieve more sustainable HMA pavements under different traffic volume and climate conditions.



(a) **(b)**

FIG. 4. Low traffic volume HMA pavement performance predictions after 20 years service life: (a) alligator cracking, (b) subgrade rutting.



(a) **(b)**

FIG. 5. High traffic volume HMA pavement performance predictions after 20 years service life: (a) alligator cracking, (b) subgrade rutting.

Conclusions

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 Bio-fuel Co- Product (BCP) in new industrial applications should be investigated to increase the profitability of bio-based products and the bio-energy business. This study explored the feasibility of utilizing BCP for subgrade soil-stabilization to provide more strong foundation for pavement systems. The Hot-Mix Asphalt (HMA) pavement systems with BCP stabilized subgrade under different traffic and climate conditions were modeled using the Mechanistic Empirical Pavement Design Guide (MEPDG). The performance of BCP stabilized subgrade and natural soil subgrade sections were compared in terms of fatigue (alligator) cracking and rutting predictions for HMA pavements. The much lower alligator cracking and rutting predictions of HMA pavements with BCP treated subgarde were observed under different traffic volume and climate conditions. These results indicate that BCP stabilization of subgrade soil could achieve more sustainable HMA pavements.

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