Use of Iowa Eggshell Waste as Bio-Cement Materials in Pavement and Gravel Road Geo-Material Stabilization

tech transfer summary

The use of eggshell powder to enhance the properties of geo-materials such as soil and gravel is a promising application for the large amount of eggshell waste produced in Iowa.

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RESEARCH PROJECT TITLE
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The Program for Sustainable Pavement Engineering and Research (PROSPER) is part of the Institute for Transportation (InTrans) at Iowa State University. The overall goal of PROSPER is to advance research, education, and technology transfer in the area of sustainable highway and airport pavement infrastructure systems.

Objective

This study aimed to evaluate the performance of Iowa eggshell waste in improving the engineering properties of Iowa geo-materials and to establish recommendations for the use of Iowa eggshell powder (ESP).

Background

The Iowa Egg Council reports that between September 2019 and August 2020, nearly 16 billion eggs were produced in Iowa, resulting in more than $2 billion in total sales. Approximately 70% of the eggs produced in the state are delivered in liquid or dried form, a production strategy that generates a large amount of eggshell waste. This waste is typically disposed of in landfills or used in limited agricultural applications.

A potential application for eggshell waste in a value-added product involves the use of ESP as a soil stabilizer. Soil stabilization is a critical process in construction and civil engineering that aims to enhance the physical properties of soil to meet specific engineering requirements. Traditional methods of soil stabilization involve the use of materials such as lime and cement that, while effective, pose environmental concerns.

The exploration of sustainable alternatives has led researchers to investigate the use of ESP as a bio-based cementitious material. Eggshells consist of up to 94% calcium carbonate ($CaCO_3$), the primary element of calcium-based stabilizer materials (CSMs) that bind soil and aggregates through hydration, cation exchange, flocculation, and carbonation.

Raw eggshells

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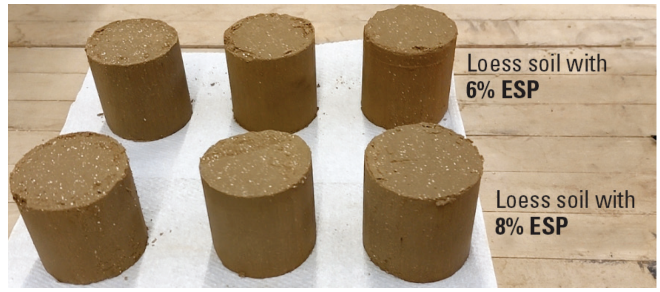
Problem Statement

The use of eggshells as bio-based cementing materials in various value-added products (e.g., cement replacement materials, soil stabilizers, masonry blocks) has been successfully demonstrated in other countries. This success suggests that Iowa eggshell waste can be used to improve the engineering properties of Iowa geo-materials (e.g., frost-susceptible soils and low-quality local aggregates) used in either pavement or gravel road systems.



Soil samples with ESP

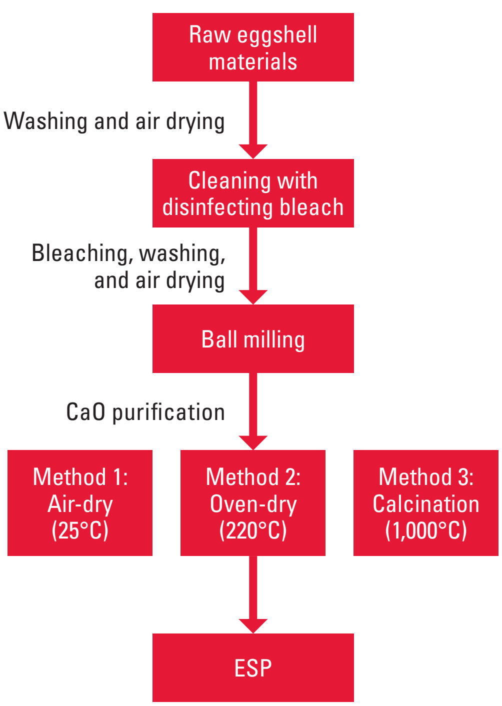
Research Description

A comprehensive laboratory testing program was undertaken to evaluate the effects of ESP on the engineering properties of two types of Iowa soils: silty soil (Soil A) and clayey soil (Soil B). Three processing methods for ESP were investigated to determine their impact on soil stabilization: air drying, oven drying, and calcination.

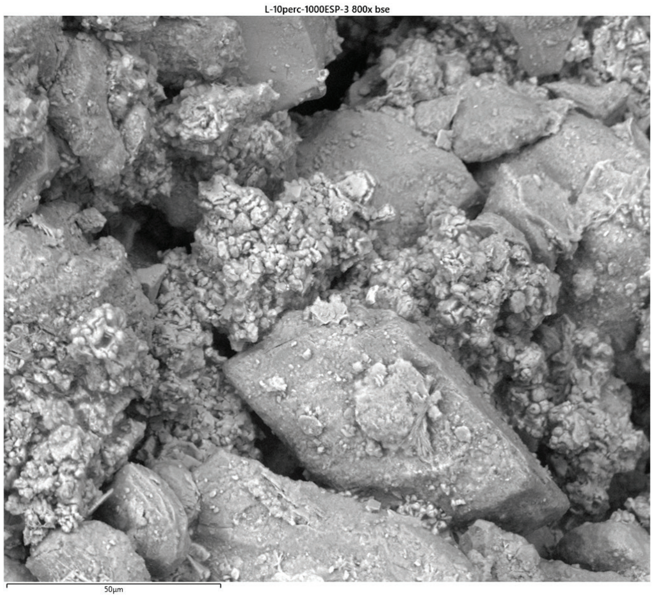
Atterberg limit tests, standard Proctor compaction tests, and unconfined compressive strength (UCS) tests were used to assess the consistency and compaction characteristics of soil samples mixed with varying percentages of ESP up to 12% at different moisture levels and under different curing conditions.

The effects of air-dried, oven-dried, and calcined ESP on soil were analyzed to determine changes in soil plasticity, maximum dry unit weight, optimum moisture content (OMC), and soil strength. Additionally, the California bearing ratio (CBR) values for ESP-treated specimens were evaluated in accordance with ASTM D1883-21.

Laboratory testing



Production of ESP



SEM image of soil stabilized with ESP

An innovative method was developed to translate laboratory findings into practical and scalable applications. Laboratory-controlled dynamic cone penetration (DCP) testing was implemented to simulate field evaluations of soils stabilized with ESP. X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS) were employed to characterize the microstructure of ESP, ESP-treated soil, and untreated soil.

Key Findings

- Eggshell waste should be properly cleaned and ground into ESP before use in geo-material stabilization.
- The use of untreated and oven-dried ESP could slightly increase the liquid limit (LL) and plastic limit (PL) of soils, leading to a minor increase in soil plasticity index (PI).
- The use of calcined ESP resulted in a significant decrease in LL and PI and an increase in PL, indicating a reduction in soil plasticity due to active chemical reactions involving the CaO present in calcined ESP.
- All ESP types showed a strong correlation between ESP content and maximum dry unit weight for Soil A (silty soil), indicating densification effects.
- Untreated and oven-dried ESP acted as filler material, improving maximum dry density without significant chemical interaction.
- The use of calcined ESP resulted in a limited increase in maximum dry unit weight because the hydration reactions resisted the compaction efforts, especially at higher moisture levels.
- The use of untreated and oven-dried ESP resulted in a limited strength improvement of less than 20%; extending the curing period or raising the temperature did not significantly affect performance because the ESP acted as a physical filler.
- The use of calcined ESP resulted in a strength improvement of 5 to 8 times when an additional 3% moisture above the OMC was applied and when the soil was cured at room temperature for up to 28 days.
- Elevated curing temperatures significantly increased the strength of Soil B (clayey soil) by over 20 times, indicating enhanced hydration of lime to hydroxide.
- The optimum calcined ESP application rate was identified as 8%, with higher moisture levels (OMC+6%) leading to decreased strength compared to lower moisture levels (OMC+3%). However, since 6% calcined ESP showed the second-highest strength gain and performed similarly to 8% ESP, 6% calcined ESP is recommended for field application.
- Based on the laboratory CBR testing, the optimal content of untreated ESP for improving soil strength is 10% for both Soil A and Soil B, and both OMC and curing duration are critical factors in the effectiveness of ESP in enhancing soil strength. Soils with high expansive silt and clay content, like Soil B, could attain more benefits when blended with calcined ESP.
- Based on the results of UCS and CBR testing, the use of 6% calcined ESP at OMC+3% can achieve similarly high strength to the use of 8% and 10% calcined ESP. However, since 6% calcined ESP at OMC+3% requires less material, it could be regarded as the optimum rate for soil stabilization.
- The laboratory-based DCP simulations demonstrated that calcined soil can triple CBR values compared to untreated soil. This finding aligns with UCS test results from this study.
- The XRD and SEM analyses demonstrated that when calcined ESP (1,000°C) is added to soil, the soil structure becomes more solid and dense due to the interfacial bonds between the soil particles and the calcined ESP (1,000°C). These effects are visible in the microstructure of the treated soil samples.
- Calcined ESP reacts with moisture in the soil mixture to form hydration products, specifically portlandite ($Ca(OH)_2$). Notably, portlandite was detected in the soils with calcined ESP, likely due to the absorption of moisture from the air by the primary component, CaO, in the calcined ESP.

- The XRD results validated the hypothesis that the improved soil strength from calcined ESP treatment is primarily due to chemical reactions such as hydration. The SEM images revealed that the treated soils exhibited reduced particle spacing and increased calcium distribution, confirming the stabilizing effects of calcined ESP.

Recommendations for Implementation

- It is essential to thoroughly wash and calcine Iowa eggshell materials at 1,000°C for a minimum of five hours before field application to ensure the removal of any residual matter from the eggshells before they are finely ground into powder for use.

- The detailed illustration of ESP production in this study serves as a guide for replicating the study's findings, suggests the potential for this process to be adapted and scaled up for larger field applications, and provides valuable insights that can be used to optimize the conversion of eggshell waste into high-quality ESP.

- ESP is highly recommended for stabilizing expansive soils such as loess. Treatment is particularly advantageous for soils that exhibit high moisture contents or acidity levels.

- The optimal ESP application rate for field use is between 6% and 8%. This range allows for adjustments based on soil characteristics, budget constraints, and local environmental conditions to achieve the best outcomes.

- To enhance the hydration of lime to hydroxide, a critical reaction for soil stabilization, the addition of moisture to reach OMC+3% during construction is advisable.

- The most effective time to employ calcined ESP in construction projects is during the hot summer months, preferably around noon. The elevated temperatures at this time can significantly boost the stabilizing effects of ESP, leading to greater strength gains in the treated soil.

Implementation Readiness and Benefits

The findings of this study indicate that calcined ESP is an effective and sustainable soil stabilizer that can be used to enhance the strength and structural integrity of soils. Detailed recommendations for implementation are presented in the final report for this study.

The use of eggshell waste as a soil stabilizer not only improves the engineering properties of local Iowa soils but also contributes to sustainable construction practices and waste management. This innovative and sustainable approach may lead to the achievement of stronger and more durable pavement foundations and gravel road systems in Iowa.