Management of Mud and DGS during Highway Construction and Maintenance

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Management of Mud and DGS During Highway Construction and Maintenance

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16. Abstract

The dramatic rise in the population of North Carolina over the past several decades has led to an increased need for infrastructure such as roads. This research addresses two distinct issues that emerge during road construction. First, we investigated the management and disposal of concrete grinding wastes generated during road construction and renovation. De-watered concrete grinding waste, referred to as diamond grinding slurry (DGS), has an alkaline pH, which makes disposal challenging. DGS settling in a sediment basin could be improved using polyacrylamide (PAM), following practices similar to those typically used to reduce sediment loads and turbidity. DGS from three road grinding projects were tested. In all three cases, PAM reduced the supernatant turbidity, decreased the volume of settled solids, or both. To expand DGS disposal options, we investigated using DGS solids as a lime replacement during revegetation. Sandy loam and clay loam soils amended with DGS rates up to 260 Mg ha^{-1} did not increase the electrical conductivity (EC) value above the salinity threshold of 4 dS/m. While not directly proportional to application rates, increasing DGS rates did raise pH of both soils beyond the tolerance range for some grasses used in roadside revegetation. However, in a germination study, Bermuda grass, centipede grass, Kentucky bluegrass, and rye grain had no significant changes in seed germination rates with DGS rates up to 260 Mg ha^{-1}. Overall, using DGS solids as a soil amendment for vegetation establishment is a viable option, and the limiting factor to the application rate is likely pH. The second construction-related issue investigated was the efficacy of the traditional stone exit and commercially available products for limiting sediment transport onto adjacent roads by vehicles exiting the construction area (termed "track-out"). Stone-lined exits are required as a part of sediment and erosion control plans, but no specialized guidance exists to inform contractors how soil properties may influence the effectiveness of this track-out prevention measure. Three track-out prevention methods approved by the North Carolina Department of Transportation (NCDOT); the stone exit, FODS Trackout Control Mat, and RubberForm Trackout Control Mat were tested using three soils: sandy loam, silty clay, and sandy clay loam. Atterberg limits of the soils were measured, and a mixing test was conducted to determine the water contents at which the soils were stickiest. The combination of these two tests allowed for inferences regarding the predominant clay mineralogy and at which water contents mud removal would be most difficult. Field testing determined the amount of mud each device could remove from tires after four device contacts. No single prevention method was most effective under all conditions, and differences emerged in the mud removal efficiencies for individual devices across the varying soil conditions when texture, mineralogy, and water content changed. Mud removal ranged from 3-58% (stone exit), 13-49% (RubberForm Trackout Control Mat, and 10-28% (FODS). When the number of contacts doubled to eight, there were limited gains for improving mud removal. Soil properties of texture, mineralogy, and water content impact the efficacy of track-out devices and reinforces the need for guidance in the sediment and erosion control plan based on site-specific soil conditions. Overall, our results will help inform the practices used for concrete highway management, and sediment and erosion control on road construction in North Carolina.

17. Key Words
Diamond grinding slurry (DGS), mud removal, construction exit pad, polyacrylamide (PAM), turbidity, track-out, concrete grinding residue (CGR)

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EXECUTIVE SUMMARY

Diamond Grinding Slurry

Diamond grinding is a standard concrete road maintenance technique in which diamond-toothed saw blades grind off the top layer of the road's surface to provide a smoother surface. Behind the blades, the mixture of concrete and water, called diamond grinding slurry (DGS), is collected. The simplest method for managing and disposing of DGS is to apply the slurry on the roadside as it is generated. Roadside application of DGS is not suited to the narrow shoulders and high moisture regimes of North Carolina. Instead, the slurry is typically hauled off-site to be separated, after which the water is recycled back into the grinding operation, and the solids become backfill or are taken to a landfill. We tested two possible methods for increasing the economic and environmental sustainability of DGS management: (1) the use of flocculation to improve DGS settling efficiency and (2) using the solid DGS fraction as a lime alterative during vegetation establishment on construction projects. In this study, polyacrylamide (PAM) was used to treat DGS from three road grinding projects to determine if the settling efficiency of the basins could be enhanced via flocculation. Additionally, soil incubations and seed germination assays were conducted using two North Carolina soils and DGS rates of 0, 22.4, 44.8, 89.6, and 260 Mg ha^{-1} to determine the potential impact of DGS additions on soil pH, salinity, and the germination of grass. Flocculation was successful in all DGS used. While previous DGS basins in North Carolina have not used PAM, this research establishes their potential for use in this setting. Neither soil became saline with DGS addition at any of the treatment rates. The pH increase was significant ($p<0.05$) with the addition of high pH DGS to soil, and it was determined to be the limiting factor for DGS potential as a liming material. None of the seeds used in the germination assay (rye grain, Bermudagrass, centipede grass, and Kentucky bluegrass) displayed significantly diminished germination ($\alpha = 0.05$) with any rate of DGS in either soil. When applied at the required lime rate for a given soil, DGS is unlikely to have a negative effect on the establishment of grass and could be a suitable replacement for lime on construction projects.

Track-out

The tracking of soil, mud, or sediment onto roadways by vehicles exiting construction sites, termed track-out, is a common problem across the United States. While sediment and erosion control plans require the installation of track-out prevention measures, there is little existing research on how effective these methods are and how their efficacy varies under differing soil conditions. This research investigated three track-out prevention measures approved by the North Carolina Department of Transportation (NCDOT): a stone exit, a FODS Trackout Control Mat, and a RubberForm Trackout Control Mat. Using three soils, a sandy loam, a silty clay, and a sandy clay loam; each at two different water contents, the devices were tested to determine how much mud they were removing after four and eight contacts. The RubberForm Trackout Control Mat consistently removed the highest amount (13 – 49%) of mud. The FODS Trackout Control Mat had the narrowest range for average mud removal percentages (10 – 28%), and the stone exit had the widest range (4 – 58%). Testing with eight wheel-contacts was conducted for three of the initial six soil conditions, and the stone exit was the only prevention method that successfully doubled the amount of mud being removed from tires with double the number of contacts (3% and increasing to 8%). Overall, no single track-out prevention method proved the best under all the conditions tested. Soil texture, water content, and mineralogy influence how well these track-out prevention methods work. As such, it is important to consider soil properties, such as texture and Atterberg limits, when developing sediment and erosion control plans and making decisions about track-out prevention.

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INTRODUCTION

There is a great deal of highway construction in North Carolina, with 1,753 highway projects in the North Carolina Department of Transportation (NCDOT) 2024-2033 State Transportation Improvement Plan (NCDOT STIP, 2023). Concrete highways constructed in the state are subject to NCDOT specifications set out in the contracts (How a Road Gets Built - Step 6: Construction, 2020). One of the specifications in these contracts is the standard for surface smoothness of concrete pavements (Standard Specifications for Roads and Structures, 2024). Some contractors opt to resurface the road after the concrete has cured through diamond grinding to meet this standard. As the number of highways in the state increases, there will likely be an increase in the amount of diamond grinding used to resurface new concrete roads and maintain older roads. Diamond grinding of concrete roads generates large volumes of high pH waste slurry, comprised of the water used to cool the diamond cutting heads and the solids from the road surface. Improving the management and disposal of diamond grinding slurry (DGS) in an environmentally responsible and economically beneficial way is emerging as a concern for the NCDOT.

All land-disturbing activities in the state must have sediment and erosion control (S&EC) plans before breaking ground on the projects. In these plans, numerous measures are put in place to limit the erosion of on-site soils and their deposition off-site. One such measure is the stabilized construction exit, which is put in place to prevent track-out. Track-out is a generalized term that describes any type of soil, sediment, or mud deposited onto public roadways by vehicles leaving construction sites. The deposited material can create a safety hazard for vehicles and is often the source of complaints by the public. There is minimal published literature regarding track-out, and little investigation has been conducted into the effectiveness of track-out prevention measures or the influence of soil properties on these measures. Thus, there is a need to investigate the effectiveness of existing track-out prevention systems in order to specify the appropriate devices to minimize track-out issues.

Results of the Literature Review

Diamond Grinding Slurry

The resurfacing of concrete roadways using diamond grinding generates large volumes of a high pH waste slurry, approximately 19.6 L m^{-2}, although this can vary depending on several factors (Albergo, 2016). There are two primary options for managing and disposing of DGS in North Carolina. The first option is land application, where DGS is disposed of roadside as it is generated. Within North Carolina, land application is possible with the proper permits; however, it is not viable in all areas of the state due to narrow road shoulders and a high moisture regime, which can result in off-site runoff. As a result, land application is a less common disposal method for DGS in the state.

The second and most common option for DGS management and disposal is the press plate system. The press plate physically compresses the slurry, separating the liquid and solid fractions. The slurry is transported to the press plate, which can result in a significant travel time depending on where the press plate has been set up relative to the grinding operation. The liquid fraction is then pumped back into the tanker truck and taken back to the grinding site to be recycled into the operation. The solids are either used as backfill or taken to a landfill for disposal.

One emerging strategy that has been employed is the use of sediment basins to separate DGS. Sediment basins are a common sediment and erosion control measure on construction sites to manage sediment-laden water (USEPA, 2007; NCDEQ, 2013). By collecting this water and having it pass through porous baffles, the energy of the water is dissipated, and the suspended particles can settle out of suspension (Thaxton & McLaughlin, 2005; Thaxton, et al., 2004). Contractors can then discharge water skimmed from the outlet end of the basin. When grinding finishes and no new DGS is added to the basin, the next step is to dewater the solids to pass a paint filter liquids test (USEPA, 2004). This test is used to classify the waste material left in the basin. If no liquid passes through the filter during the five-minute testing period, the material is deemed to contain no free liquids. Once it is established that the waste remaining in the basin contains no free liquids, the basin can be closed, and the DGS solids will be buried or repurposed.

Another sediment and erosion control practice that may be employed to improve the efficiency of DGS separation via sediment basins is the use of polyacrylamide (PAM). Anionic forms of PAM are most commonly employed on construction sites in North Carolina to reduce turbidity, although the specific PAM molecule or blend used will vary, and soils must be matched to individual PAMs to ensure effectiveness (McLaughlin, 2015; McLaughlin & Bartholomew, 2007). While there are some indicators for the efficacy of different PAMs on reducing turbidity in sediment-laden water based on soil properties (McLaughlin & Bartholomew, 2007), there are no studies we are aware of that have tried flocculating DGS.

The DGS solids that are currently being treated as waste have the potential to serve as recycled lime due to their high pH. Using DGS as a recycled liming agent would enhance the sustainability of grinding operations and reduce the costs associated with disposal. Numerous research studies have been conducted to quantify the effect of roadside DGS application on soil properties and vegetation (Desutter, et al., 2011; Luo et al., 2019; Mamo et al., 2015; Wingeyer et al., 2018; Yang, et al., 2019). Overall, it appears that the primary way in which DGS affects soils is its influence on soil pH and salinity, measured by electrical conductivity (EC). DGS did not change the infiltration rate of soils (DeSutter et al. 2011). Only one other NCDOT project has looked at the effects of DGS on soil properties and vegetation. Line & Smyth (2015) found that there was lead in the DGS, and it was higher than regulatory limits. However, they determined the lead to be closely associated with the solids and unlikely to leach if applied to soil. They also found that using DGS as a liming alterative did not result in detrimental effects on grass growth over a 6-week period using 3,920 gal ac^{-1}.

The NCDOT has a variety of species in their pre-approved seed mixes for vegetation establishment in both the state's eastern and western regions. The tolerance of these species to salinity and pH varies. For example, rye grain and Kentucky bluegrass appear in the NCDOT-approved vegetation for resurfacing projects' west seed mix. The optimal soil pH range for rye grain is 5-7, but it can tolerate a pH anywhere from 4.5-8 (Cereal Rye, 2021). Kentucky bluegrass has a narrower optimal soil pH range, 5.5-6.5 (Waltz, 2020). While rye grain has a moderate salinity tolerance, the tolerance of Kentucky bluegrass to salinity is poor (Cereal Rye, 2021; Waltz, 2020). Bermudagrass and centipede grass are two seed types that appear in the approved vegetation for resurfacing projects' east seed mix. The optimal soil pH ranges for the two seed types are 5.5-6.5 for Bermudagrass and 5-6 for centipede grass (Waltz, 2020). Bermudagrass has good salinity tolerance, while the tolerance of centipede grass to salinity is poor (Waltz, 2020). There are no studies optimizing DGS application rate as a liming alternative and for vegetation establishment.

Track-out

The deposition of mud and debris creates several distinct issues. Firstly, the presence of track-out may indicate a failure to maintain the installed track-out prevention method (Burby et al., 1990). Secondly, track-out onto public roadways creates hazards for drivers. The presence of debris on the road can limit the traction of vehicles passing over those areas, which creates dangerous conditions for drivers. Additionally, debris with sizeable soil aggregates or rock fragments creates the risk of following vehicles being damaged, and individuals who suffer injuries or incur property damage may file a damage claim with the NCDOT (NCDOT, 2022). Finally, the aesthetic appearance of track-out is undesirable, and the perception of construction can become increasingly poor when track-out is not prevented. Track-out is a major cause of public complaints about construction in North Carolina (NCDOT, personal communication, August 17, 2022).

Stabilized construction exits are the most common best management practice to prevent track-out. All stone exits must meet the same minimum specifications as set out in the North Carolina Erosion and Sediment Control Planning and Design Manual (NCDEQ, 2013). Exits must be 50 feet long, 12 feet wide, excavated to 8 inches deep, and filled with Class A stone. If the stone exit is not sufficiently preventing track-out, then wheel washing is the next choice. While this would generally be considered the best option for consistently preventing track-out, the cost of using a wheel washing system and the intensive water use make it less favorable than the passive stone exit.

In addition to the stone exit and wheel washing, several other track-out prevention devices are commercially available. The NCDOT has approved several commercial products to replace the stone exit. These approved products include the FODS LLC Trackout Control Mat, the Rumble Grate LLC Grizzly Rumble Grate®, and the RubberForm LLC Trackout Control Mat. The products are a one-time investment with substantial lifespans that enable contractors to use and reuse them, whereas stone exits require additional aggregate throughout the life of a project, and the aggregate is not reused.

Regardless of the track-out prevention method, limited research exists on how effective these methods are at removing mud from vehicle tires or how soil properties may influence this effectiveness. The regulations in North Carolina surrounding track-out prevention do not offer site-specific guidance on how management may need to change under differing soil conditions. Several soil properties, including texture, clay mineralogy, and water content, may influence mud adhesion to a vehicle's tires (Bleam, 2012; Das, 2002, and therefore, its potential for track-out. This is the first study we are aware of that scientifically compares mud removal by track-out devices with a range of soil textures and moisture contents.

Report Organization

The main body of this report includes a summary of the methods and results for the experiments. Advanced settling of DGS using PAM consisted of three different experiments: (1) PAM screening to find which PAMs work with DGS, (2) dose-response testing to find the best rate of PAM, and (3) settleable solids testing to see which PAM settled the solid portion of DGS the most. The use of DGS as a liming alterative had two different experiments. The first was a soil incubation, where pH and EC were monitored at different application rates of DGS. The second experiment consisted of a seed germination assay on grasses used on NCDOT projects. Next, there was a laboratory and field component to the track-out testing. In the laboratory experiments, the Atterberg limits and soil mixing test (empirical stickiness ratio) allowed the stickiness of different soils to be assessed. In the field experiments, mud with different stickiness was adhered to vehicle tires and driven over different track-out devices to monitor the amount of mud removed from the tires. Following the description of research activities, we include a summary of the main findings and associated recommendations. In addition to these main sections of the report, we have included an appendix that has additional information on the basin used to separate DGS, including sampling design and water quality data (pH, EC, and turbidity).

IMPROVING DIAMOND GRINDING SLURRY MANAGEMENT IN NORTH CAROLINA

This research addressed the current issues with managing and disposing of DGS. The objectives of this study were to determine the potential for recycling DGS solids (as a liming material) on a construction site and the potential of using a sediment basin with PAM to enhance settling of DGS. The effects of DGS on soil pH, soil EC and seedling germination were monitored in lab bench-scale experiments. Settleable solids were measured to determine the effectiveness of PAM with different DGS samples. Water samples from a DGS basin in Statesville, NC were additionally analyzed.

Materials and Methods

Diamond Grinding Slurry Collection and Preparation

DGS was collected from three road grinding projects in North Carolina (Table 1). The section of I77 where samples were collected was from grinding an old section of the highway. The samples collected from I4400 and I77/40 were from grinding of new construction. The I77/40 interchange project utilized a sediment basin for DGS separation, and water quality samples were taken, the results of which are presented in Appendix 1. The average concentration of the three DGS samples is presented in Table 1. The DGS samples were dried in an oven at 105 C for 24 hours before testing.

Advanced Settling of Diamond Grinding Slurry Using Polyacrylamide

PAMs with different properties were selected to encompass a variety of charges and molecular weights: (1) anionic (FloPAMs AN 913 VHM, AN 956 VHM), (2) non-ionic (FloPAMs FA 920, FA 920 SH, FA 920VHM), (3) cationic (FloPAM FO 4400 SSH), and (4) blends (APS 705, 710, and 740, and NALCO Optimer 8110 PULV, 9907, and 9913). All PAMs were made into stock solutions at a concentration of 0.5 g/L.

Dry DGS was weighed into the sample cups, and deionized water was added to the cups to rehydrate the DGS. The dry weight was 25% of the actual DGS concentration (Table 1). The sample cups were shaken for 10 seconds for each test and then allowed to settle for 30 seconds before the supernatant depth was measured. PAM was added, and these steps were repeated. The difference in depth of supernatant before and after PAM addition was used to quantify the effectiveness of a given PAM at flocculating the DGS.

The four PAMs that produced the highest relative increase in supernatant depth for each DGS in screening were used in dose-response testing. Dose response testing followed the same time and depth measurement procedures outlined above. Additionally, the turbidity of the supernatant after PAM addition was measured using a turbidity meter (LaMotte 2020e Turbidimeters, Chestertown, MD, USA). The dosages of PAM used to establish dose-response curves were 0.1, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, and 2 mL, yielding concentrations in the DGS solution of 0.5, 1.25, 2.5, 3.75, 5, 6.25, 7.5, and 10 mg L^{-1}.

For each of the three DGS samples, the four most effective PAM varieties used in their respective dose-response testing were used in settleable solids testing. This testing was conducted using DGS at its actual concentration (Table 1), and the PAM dose volume was calculated using the ratio of PAM to DGS concentration in the dose-response testing that was most effective in reducing turbidity and scaling it to match the increased DGS concentration. The DGS slurry was then poured into an Imhoff cone and stirred to suspend particles before adding PAM. The volume of settleable solids was measured using the Procedure and Method Detection Limit for Measurement of Settleable Solids (Protection of Environment, 1985).

Potential for Recycling Diamond Grinding Slurry Solids as Lime

Two North Carolina soils with different textures (clay loam and sandy loam) were collected to determine the potential for recycling DGS solids as a liming material in an incubation experiment and a seed germination experiment. Particle size analysis was conducted by the hydrometer method (Gee & Or, 2002) (Table 2).

Soil Incubation Study. The application rates of DGS used were 0, 22.4, 44.8, 89.6, and 260 Mg/ha based on previous research (Luo et al., 2019; Mamo et al., 2015; Wingeyer et al., 2018; Yang, et al., 2019). For the soil incubation, DGS and soil for each treatment were homogenized by hand, then hydrated with water to field capacity. The DGS mixture was placed in a sealed container and incubated at room temperature for 2, 4, 8, or 16 weeks. At each time interval, soil pH and EC measurements were conducted using a 2:1 water-to-soil ratio (Mylavarapu et al., 1993).

Seed Germination. The soil and DGS mixture preparation process followed the procedure outlined for the incubation above. Each Petri dish received 30-36 seeds. Kentucky bluegrass, centipede grass, and Bermuda grass seeds all germinated in the same Petri dish. Due to their allelopathy, the rye grain seeds were germinated in separate Petri dishes (Putnam et al., 1983). The Petri dishes were placed on a windowsill to germinate over fourteen days. The total germination count was measured daily.

Data Analysis

All statistical analysis was performed in R version 4.3.1 (R, 2023). An ANOVA was performed on all the data sets. A Fisher's Least Significant Differences (LSD) test ($\alpha = 0.05$) was conducted to determine which means differed significantly.

Results and Discussion

Advanced Setting of Diamond Grinding Slurry Using Polyacrylamide

PAM was found to be effective in flocculating all three DGS samples. In the I77 DGS screening, the four PAMs with the most success in increasing the relative supernatant depth across all doses were APS 705, FA 920 VHM, APS 740, and AN 913 VHM (Figure 1). No significant differences existed between the four most successful PAMs. The dose-response testing in the I77 DGS had the highest supernatant turbidity values of the three DGS samples tested (Figure 2). For APS 705, the PAM concentration that produced the lowest turbidity was 6.25 mg L^{-1}, with a turbidity of 341 NTU. Similarly, FA 920 VHM at a concentration of 6.25 mg L^{-1} produced the lowest turbidity value for that treatment with 656 NTU. The lowest turbidity was produced by APS 740 was 730 NTU, and for AN 913 VHM, the lowest value was 153 NTU, both with a 10 mg L^{-1} dose. In the settleable solids test, AN 913 VHM and APS 740 reduced the turbidity of the supernatant relative to the control the most, 74% and 85% reduction, respectively. However, the volume of solids in one liter of the slurry material treated with AN 913 VHM or APS 740 increased compared to the control by 10% and 13% increase, respectively. FA 920 VHM and APS 705 were effective in both reducing the turbidity (20% reduction for both) and settled solids volume (5% and 7% reduction, respectively) relative to the control (Figure 3).

Screening results in the I4400 DGS varied among the PAM types used. The four most successful PAMs were APS 740, APS 705, FA 920 VHM, and FA 920 SH, and there were statistically significant differences ($p <0. 05$) (Figure 4). For the dose-response testing, APS 740 at 10 mg L^{-1} was the most successful at lowering the turbidity with a value of 26.3 NTU (Figure 5). The doses of APS 705 from 0.5 to 7.5 mg L^{-1} were not significantly different; however, the lowest absolute turbidity was 771 NTU for the 1.25 mg L^{-1} dose. For FA 920 VHM and FA 920 SH, the dose yielding the lowest turbidity was 1.25 mg/L, yielding 871 and 958 NTU turbidities, respectively. Like the trend for APS 705, doses of FA 920 VHM and FA 920 SH from 0.5 to 7.5 mg L^{-1} did not significantly. The turbidity of the control in the settleable solids test was 25.4 NTU, less than that of slurry treated with FA 920 SH and FA 920 VHM, 28.6 and 34.7 NTU, respectively. The supernatant turbidity of I4400 DGS treated with APS 705 and 740 was 9.91 and 11.5 NTU, respectively. The volume of settled solids in I4400 DGS treated with APS 740 was increased by 11% (Figure 6). DGS treated with FA 920 SH, APS 705, and FA 920 VHM had settled solids volume reductions of 6%, 4%, and 2%, respectively.

PAM screened in I77/I40 DGS had variable success. The differences in relative supernatant depth increase across doses were not significant for the four most successful PAM types, AN 956 VHM, AN 913 VHM, FO 4400 SSH, and APS 740 (Figure 7). In dose-response testing (Figure 8), the effect on turbidity was not significantly different for any of the four PAMs for doses from 1.25 to 10 mg L^{-1}. In AN 956 VHM, the 10 mg L^{-1} concentration yielded the lowest turbidity value, 23.5 NTU. The lowest turbidity value for AN 913 VHM was 76.8 NTU for the 5 mg L^{-1} dose. For APS 740, the lowest turbidity value, 70.3 NTU, resulted from the 10 mg L^{-1} dose. Two doses, 7.5 and 10 mg L^{-1}, yielded a turbidity value of 137 NTU for FO 4400 SSH. All four PAM treatments decreased the supernatant turbidity relative to the control during the settleable solids testing (Figure 9). The PAM types reduced the turbidity by 77-99%. While the treatments demonstrated an apparent effect on turbidity, all four PAM treatments increased the volume of settleable solids relative to the control by 3-15%.

Treating DGS with PAM did not have a significant effect on EC (Table 3). If DGS treated with PAM is to be used as a liming material, then the pH and EC of the treated DGS should be measured. pH changes may impact the material's calcium carbonate equivalency. Additionally, it may be beneficial to determine if DGS treated with PAM behaves the same in soil incubation and seed germination as the untreated DGS.

Overall, PAM is effective in flocculating DGS. Using PAM in DGS basins would enhance the efficiency of these basins in settling the solids and reduce the turbidity in the water being reused in the grinding operations. Appendix 1 shows the results of water quality testing from the DGS basin present at the I77/40 interchange project. Water quality testing was conducted using three sampling points, and samples were taken both during active grinding while slurry was being inputted into the basin and after the grinding ceased. The turbidity of water samples varied across sampling points and times. The highest measured value was 26,188 NTU, and the lowest was 0 NTU. Samples taken from the second evaporation basin had the lowest average turbidity, 16.8 NTU. The use of PAM in a basin could offer consistent turbidity reduction in the reclaimed water, allowing for easier management. Changes in concrete mixes would lead to changes in DGS chemistry. Therefore, a single PAM chemistry may not effectively flocculate DGS from different roads. Instead, a screening process like the one used here would be needed to match the individual slurry to the most effective PAM.

Potential for Recycling Diamond Grinding Slurry Solids as Liming Material

Soil Incubation Study. The results of the soil incubation study show an increase in pH and EC with increasing DGS application rate across all four sampling intervals (Figures 10 & 11). The pH increased significantly with increasing DGS rates at the week two sampling interval up to the 89.6 Mg ha^{-1} application rate. At both the four and sixteen-week sampling intervals, the pH of the clay loam increased significantly with treatment rate. The EC values increased significantly with increasing treatment rates at every sampling interval for the clay loam soil. The highest EC value was 0.96 dS m^{-1} for the clay loam soil at the sixteen-week interval with a 260 Mg ha^{-1} DGS treatment rate.

The sandy loam soil pH values for two-, four-, and eight-week sampling intervals increased significantly with DGS treatment rates. The pH increased significantly from 0 to 44.8 Mg ha^{-1} treatment rates at the sixteen-week sampling interval. The EC values for sandy loam at two weeks increased as the DGS rate increased, except that the 44.8 and 89.6 Mg ha^{-1} treatments were not significantly different. At the four-week measurement interval, the 44.8, 89.6, and 260 Mg ha^{-1} treatment rates had significant EC increases with DGS increases. Similarly, at the sixteen-week measurements, EC values for 0 and 22.4 Mg ha^{-1}

treatments did not differ significantly, nor did those of 22.4 and 44.8 Mg ha^{-1} treatments. The 44.8, 89.6, and 260 Mg ha^{-1} treatment rates were the same at the sixteen-week measurements (Figure 11).

Across the five treatments, as the rate of DGS increased from 0 to 260 Mg ha^{-1}, there was a nearly twelve-fold increase in application rate between the 22.4 and 260 Mg ha^{-1} treatments. Despite this, there was not a proportional EC increase for either soil at any sampling time. At eight weeks, there was a 1.18-unit difference in the pH values of the clay loam soil between the 22.4 and 260 Mg ha^{-1} treatments, with values of 6.71 and 7.94, respectively. This was the largest difference between the two rates across sampling times. The sandy loam soil at two, eight, and sixteen weeks had a 1.11-unit increase in pH values between the 22.4 and 260 Mg ha^{-1} DGS rates. In this case, the increases in EC were slightly more proportional to DGS rate increases. The largest EC increase, from 22.4 to 260 Mg ha^{-1} for the clay loam soil, was a 3.06-fold increase from 0.25 to 0.76 dS m^{-1} at the eight-week measurement interval. The largest EC increase for the sandy loam soil was a 3.50-fold increase at four weeks, from 0.17 to 0.59 dS m^{-1} for 22.4 and 260 Mg ha^{-1}, respectively.

In both soils, from the control to the 22.4 Mg ha^{-1} treatment, the pH increase exceeded the published pH tolerance for centipede, Bermuda, and Kentucky blue grasses. The pH exceeded the pH tolerance of rye grain for the highest treatment rates when pH exceeded 8 in the sandy loam soil. No treatment reached the EC threshold to be categorized as saline, 4 dS m^{-1} (Ogle & St. John, 2009). All measured EC values were below 1 dS m^{-1}, so the salinity is negligible (Belden & Panter, 2005). The increase in soil pH could be the limiting factor in determining the DGS application rate required to lime soil for vegetation establishment.

Seed Germination. Of the four seed types used, none were found to have significantly diminished germination with rates of DGS applied up to 260 Mg ha^{-1} (Figure 12 & 13). Bermuda grass (Figure 12A & 13A) had a significantly higher germination in the sandy loam soil compared to the clay loam soil. Kentucky bluegrass (Figure 12C &13C) and Bermuda grass share a pH tolerance range, but Kentucky bluegrass was more successful in germination. Growing conditions likely played a role in the success of Kentucky bluegrass, which is better adapted to growing in the shade than Bermuda grass (Waltz, 2020). The germination results of Bermuda grass under DGS treatments may improve with a modification to increase the sunlight the seeds receive. Centipede grass (Figure 12B & 13B) had the narrowest reported pH tolerance of the four seeds and a poor salinity tolerance. Despite this, it had the third most successful germination in both trials. While centipede grass prefers full sunlight, it can grow in intermittent or filtered sunlight, which is likely why it performed better than Bermuda grass (Waltz, 2020). Rye grain (Figure 12D & 13D) had the most success in germination for the first trial, and the second most successful germination in the second trial, likely due to its wide pH tolerance.

Tables and Figures

Table 1. Concentrations of DGS samples from various road grinding projects**.**

	Concentration	
Collection Site	g/g	g/L
I77	1.54	1537
I4400	0.30	296
I77/40	0.62	623

Note: Concentrations calculated initially on a mass per mass basis determined through oven drying, before being converted to g/L. Concentration in g/g represents the concentration as grams of solids per gram of water.

Table 2. Results of particle size analysis for selected soils to be used in soil incubation and germination studies.

Location	Sand (%)	Silt (%)	Clay (%)	USDA Classification
Hurdle Mills, NC	27.2	38.8	34.8	Clay Loam
Raleigh, NC	69.2	18.9	11.9	Sandy Loam

Table 3. pH and EC values for I77 DGS treated with PAM blends**.**

Treatment	**pH**	**EC (dS/m)**
Control	9.90 a	1.95 a
AN 913 VHM	9.69 b	1.68 a
APS 705	9.89 a	2.17 a
APS 740	9.91 a	2.29 a
FA 920 VHM	9.96 a	1.95 a

Note: Letters indicate a statistically significant difference using Fisher-LSD means with $\alpha = 0.05$.

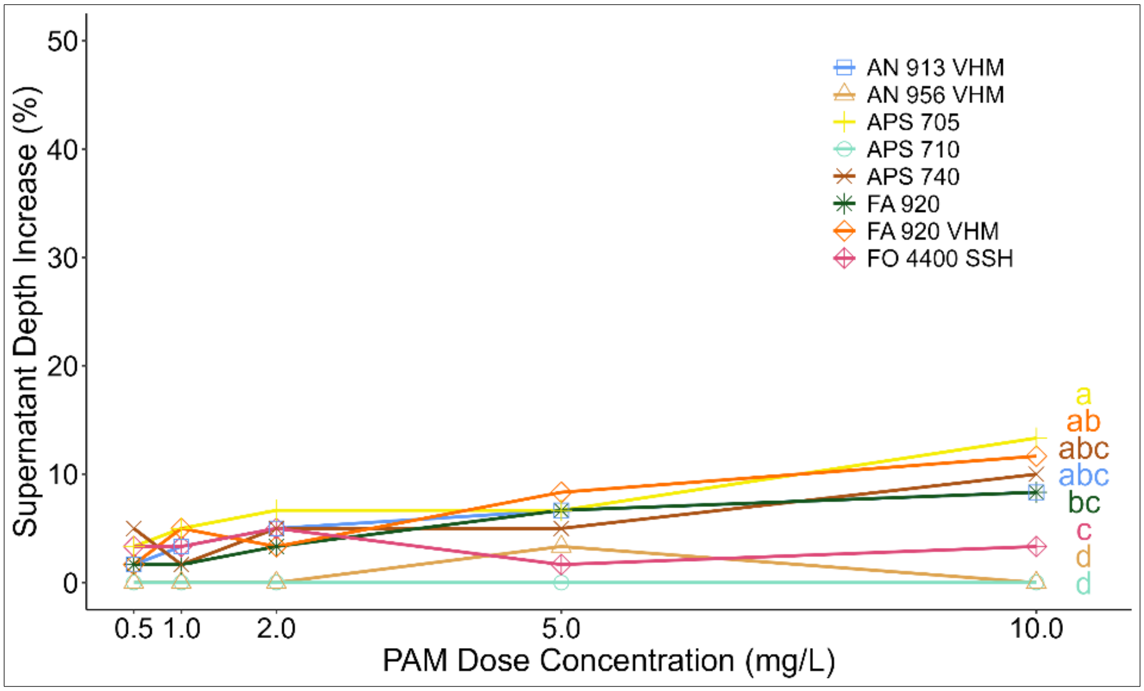

Figure 1. Flocculation Testing of I77 DGS. PAM screening: relative supernatant depth increase (%) after PAM addition displayed as a function of PAM dose concentration in solution (mg/L). Letters indicate significant differences ($p<0.05$) in average supernatant depth increase between PAM chemistries.

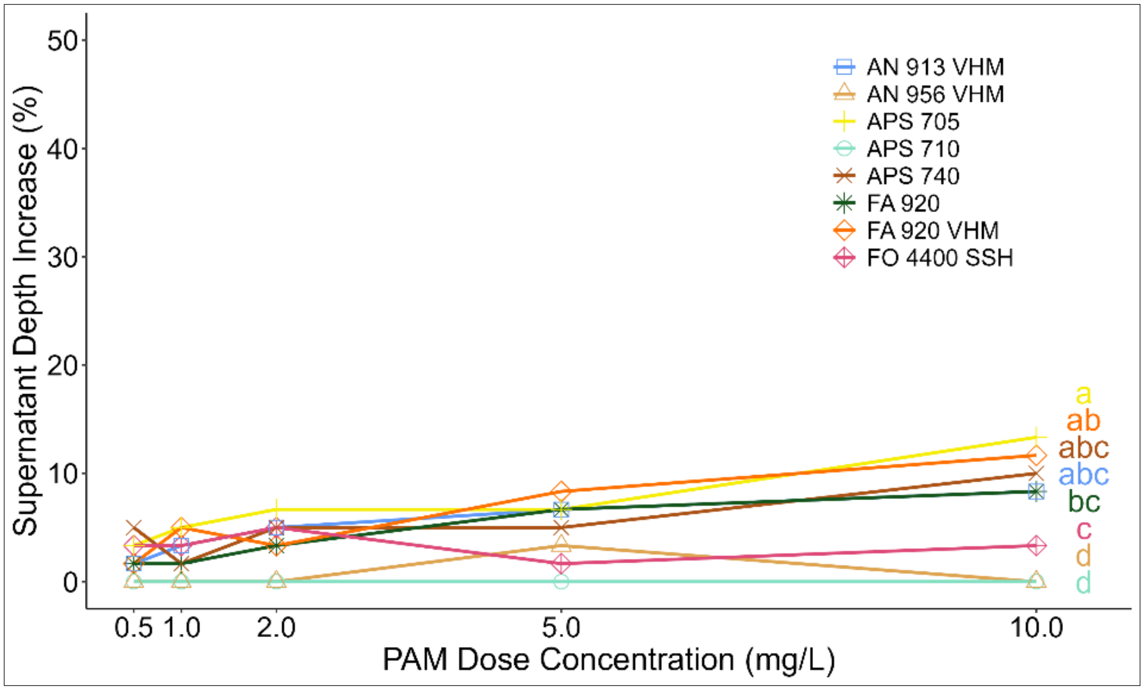

Figure 2. Flocculation Testing of I77 DGS. Dose-response curve: supernatant turbidity (NTU) after PAM addition, the absence of a point for a PAM dose indicates turbidity greater than 4000 NTU. Letters indicate significant differences ($p<0.05$) between the turbidity of the supernatant for different doses of PAM chemistry.

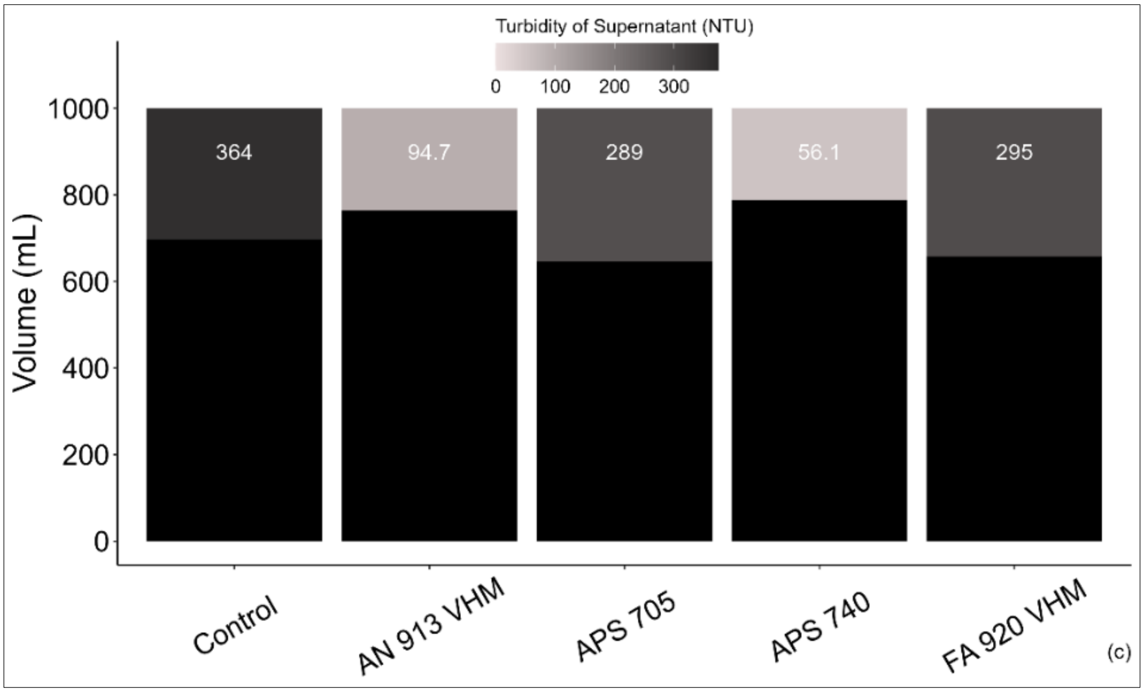

Figure 3. Flocculation Testing of I77 DGS. Settleable solids testing: the volume of solids settled in one liter of slurry in mL is denoted by the black bars on the bottom of each treatment category, greyscale bars on the top indicate the volume of supernatant, and color intensity corresponds to the turbidity value, listed within the bar.

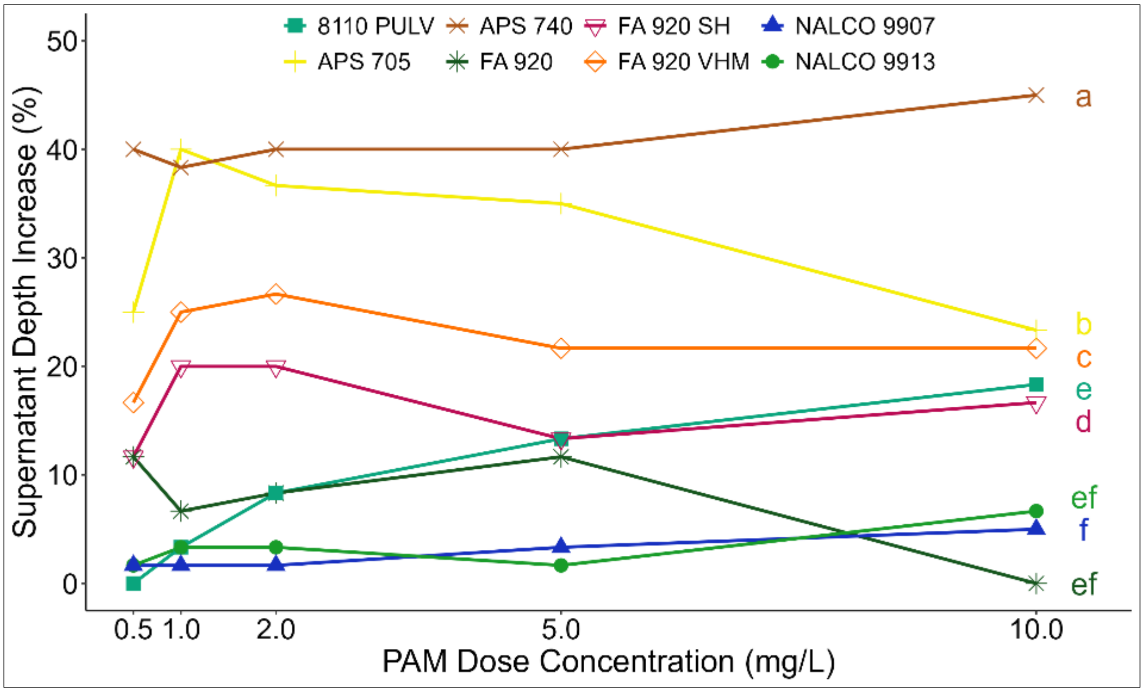

Figure 4. Flocculation Testing of I4400 DGS. PAM screening: relative supernatant depth increase (%) after PAM addition displayed as a function of PAM dose concentration in solution (mg/L). Letters indicate significant differences ($p<0.05$) in average supernatant depth increase between PAM chemistries.

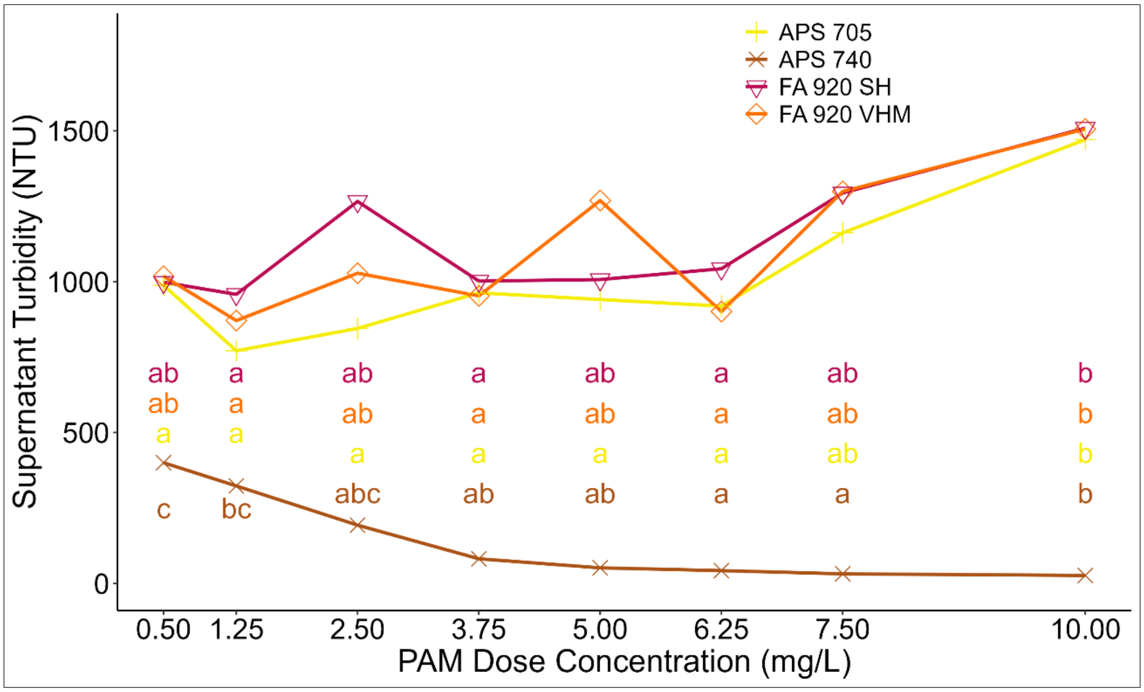

Figure 5. Flocculation Testing of I4400 DGS. Dose-response curve: supernatant turbidity (NTU) after PAM addition. Letters indicate significant differences ($p<0.05$) between the turbidity of the supernatant for different doses of PAM chemistry.

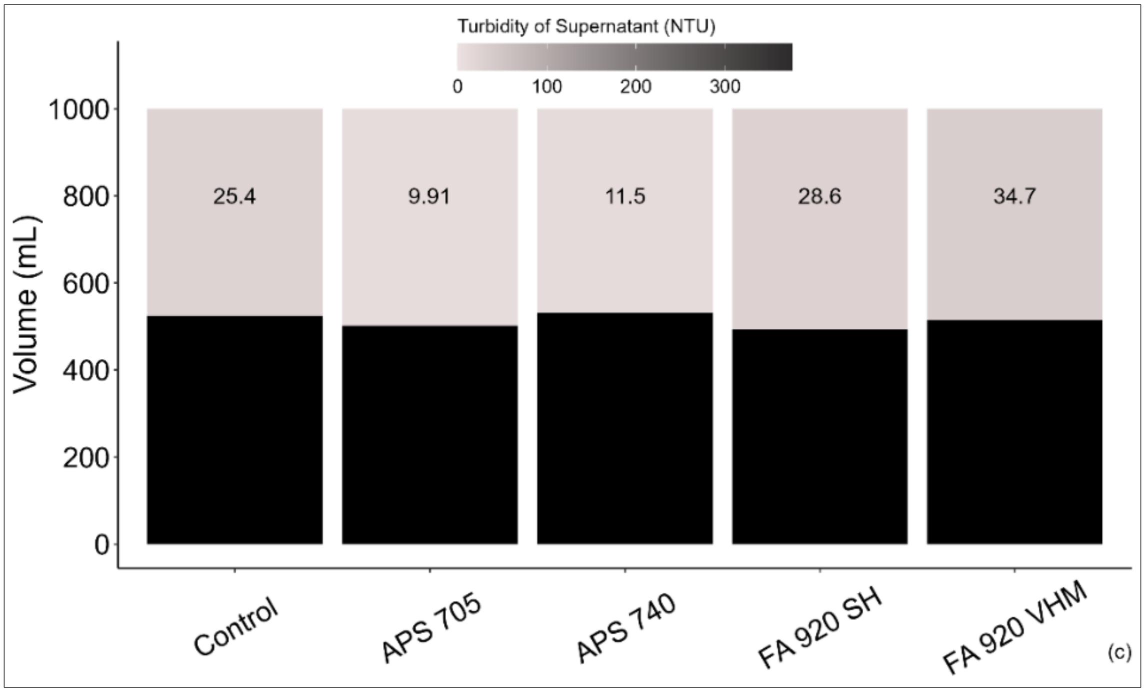

Figure 6. Flocculation Testing of I4400 DGS. Settleable solids testing: the volume of solids settled in one liter of slurry in mL is denoted by the black bars on the bottom of each treatment category, greyscale bars on the top indicate the volume of supernatant, and color intensity corresponds to the turbidity value, listed within the bar.

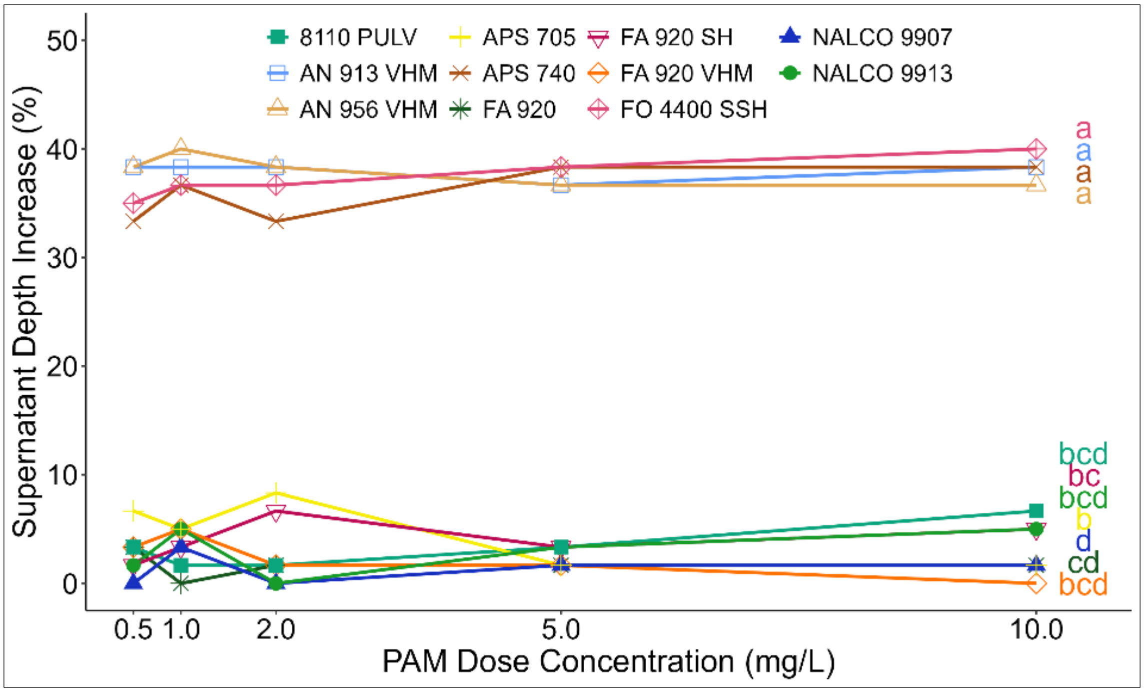

Figure 7. Flocculation Testing of I77/40 DGS. PAM screening: supernatant depth increase (%) after PAM addition displayed as a function of PAM dose concentration in solution (mg/L). Letters indicate significant differences (p<0.05) in average supernatant depth increase between PAM chemistries.

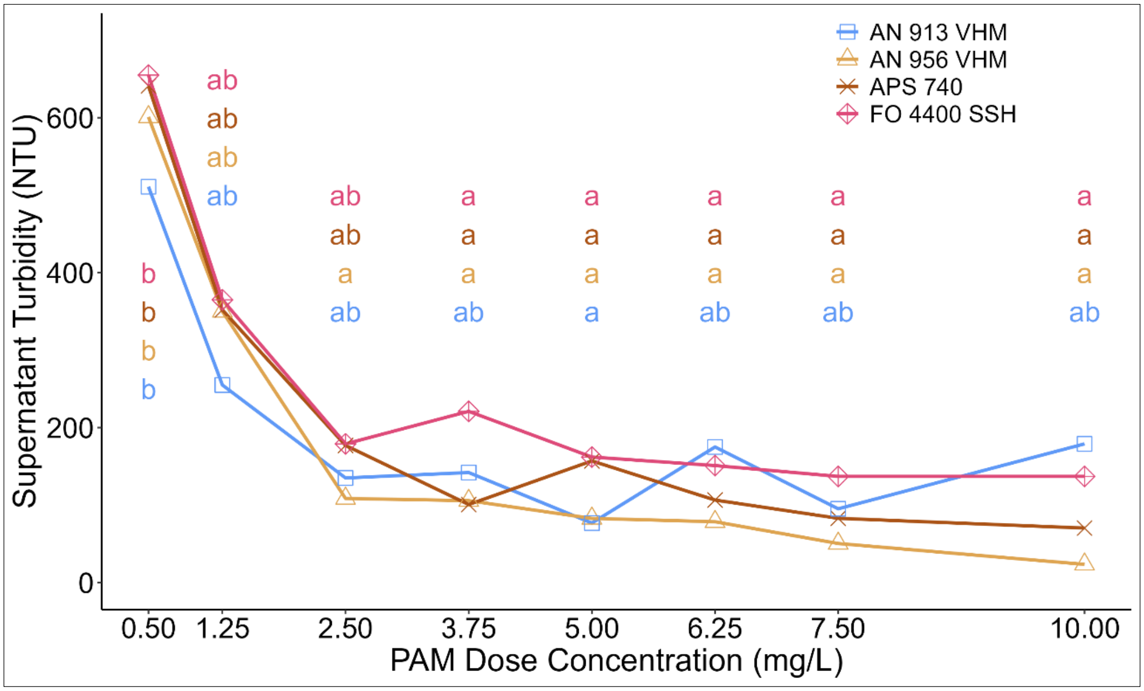

Figure 8. Flocculation Testing of I77/40 DGS. Dose-response curve: supernatant turbidity (NTU) after PAM addition. Letters indicate significant differences (p<0.05) between the turbidity of the supernatant for different doses of PAM chemistry.

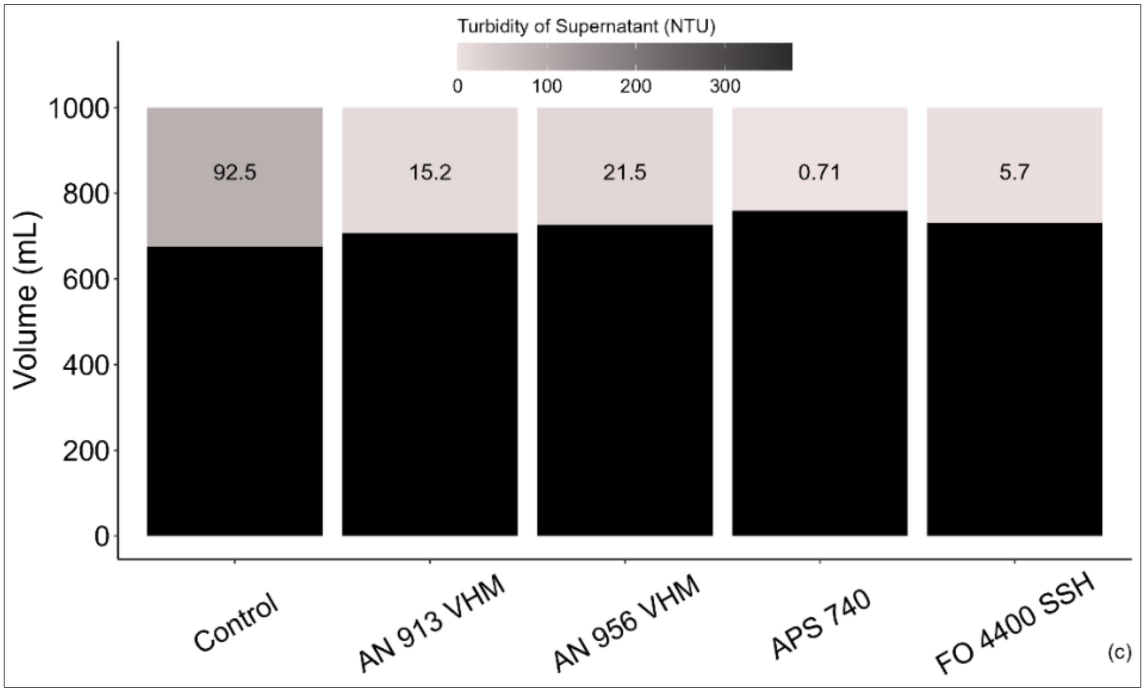

Figure 9. Flocculation Testing of I77/40 DGS. Settleable solids testing: the volume of solids settled in one liter of slurry in mL is denoted by the black bars on the bottom of each treatment category, greyscale bars on the top indicate the volume of supernatant, and color intensity corresponds to the turbidity value, listed within the bar.

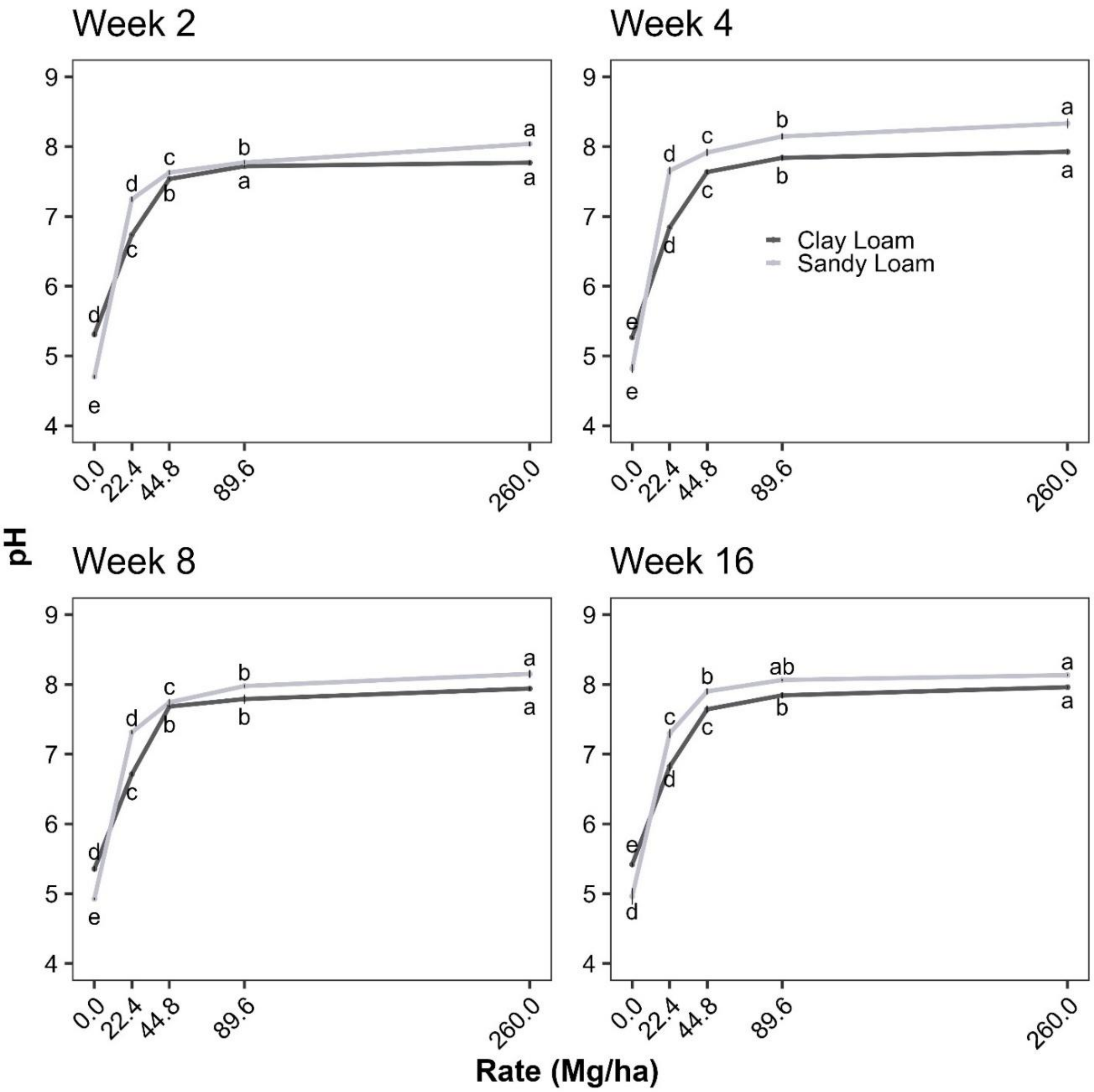

Figure 10. Soil incubation pH results for clay loam and sandy loam soils at two, four, eight, and sixteen weeks, amended with increasing rates of DGS. Letters indicate a significant difference ($p<0.05$) between treatment rates for a given soil and sampling time interval. Error bars represent one standard error.

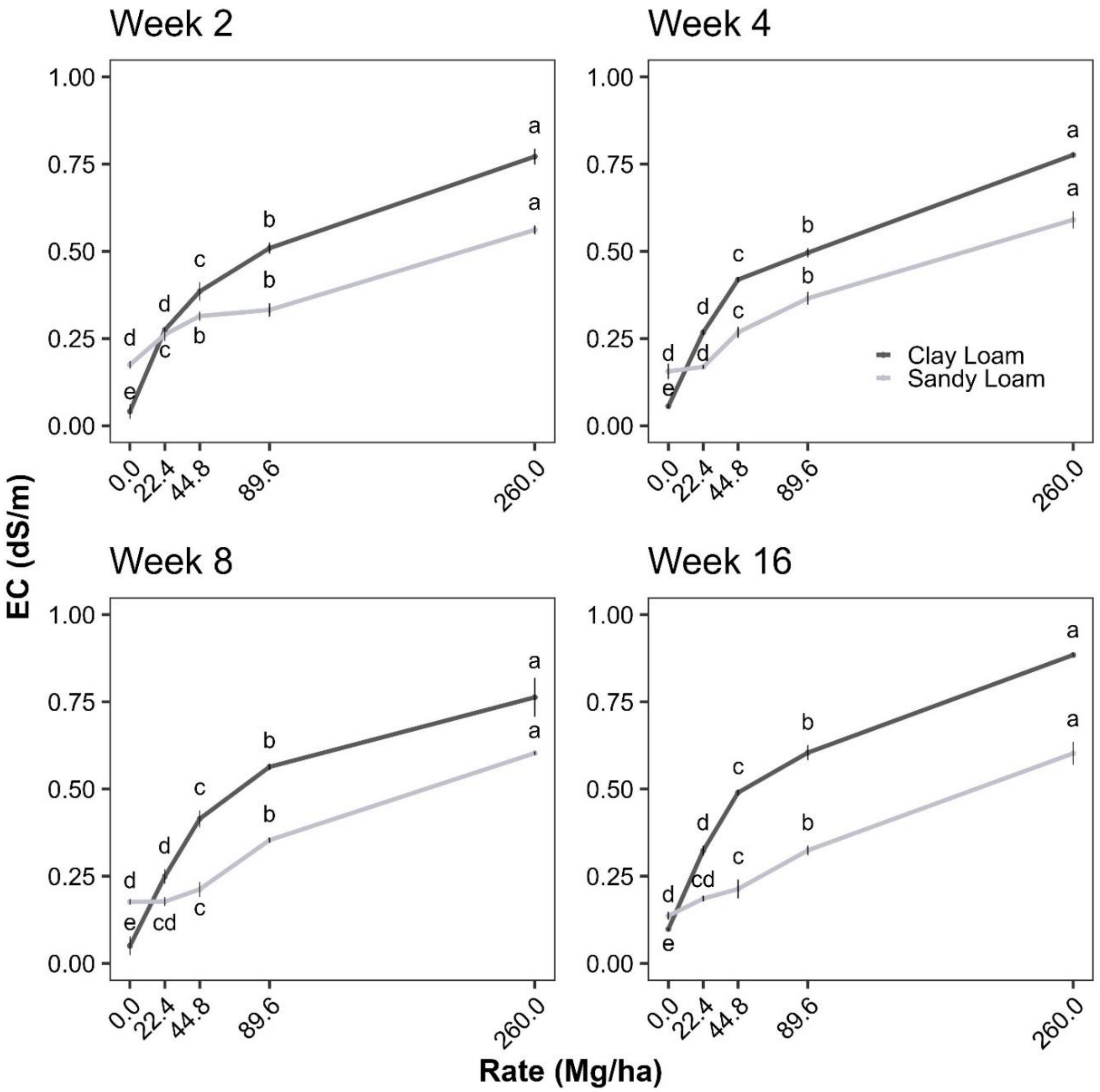

Figure 11. Soil incubation EC results for clay loam and sandy loam soils at two, four, eight, and sixteen weeks, amended with increasing rates of DGS. Letters indicate a significant difference ($p<0.05$) between treatment rates for a given soil and sampling time interval. Error bars represent one standard error.

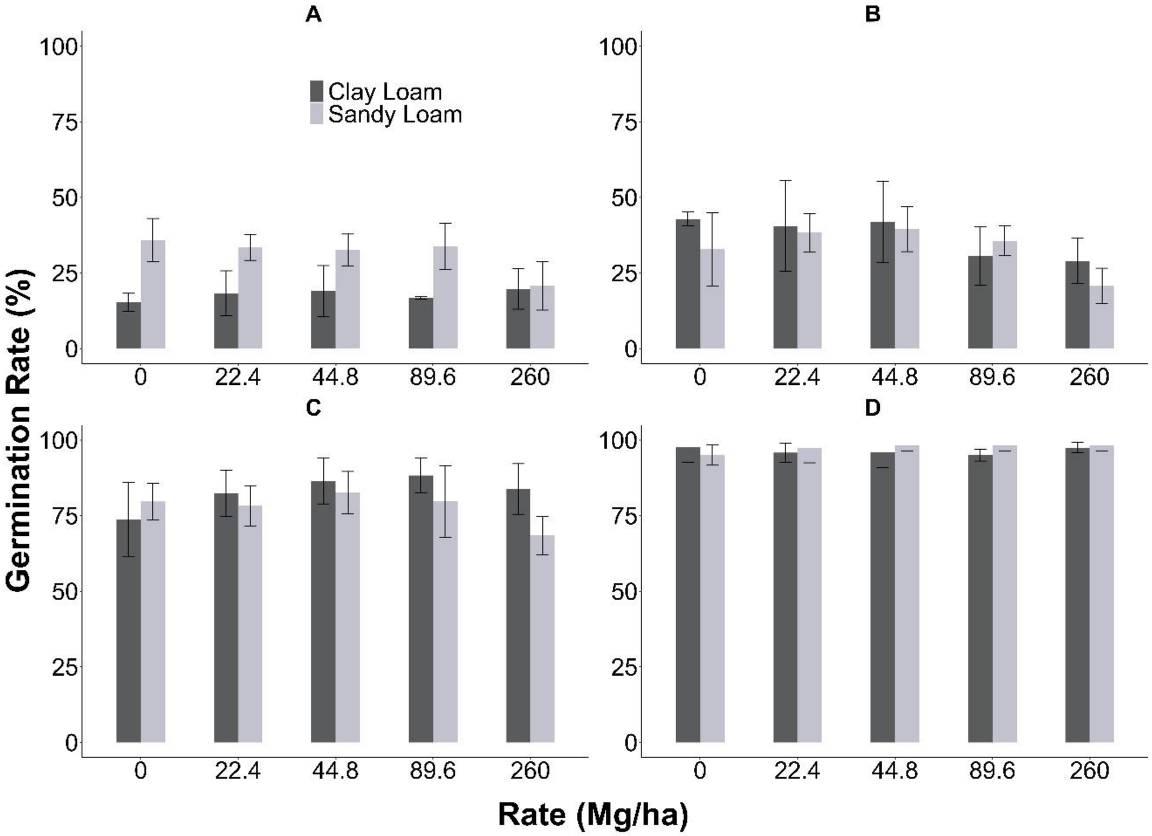

Figure 12. Trial 1 seed germination percentages for Bermuda grass (A), centipede grass (B), Kentucky bluegrass (C), and rye grain (D) with increasing rates of DGS. Error bars represent one standard deviation. Differences between treatment rates for each soil were not found to be statistically different with α = 0.05.

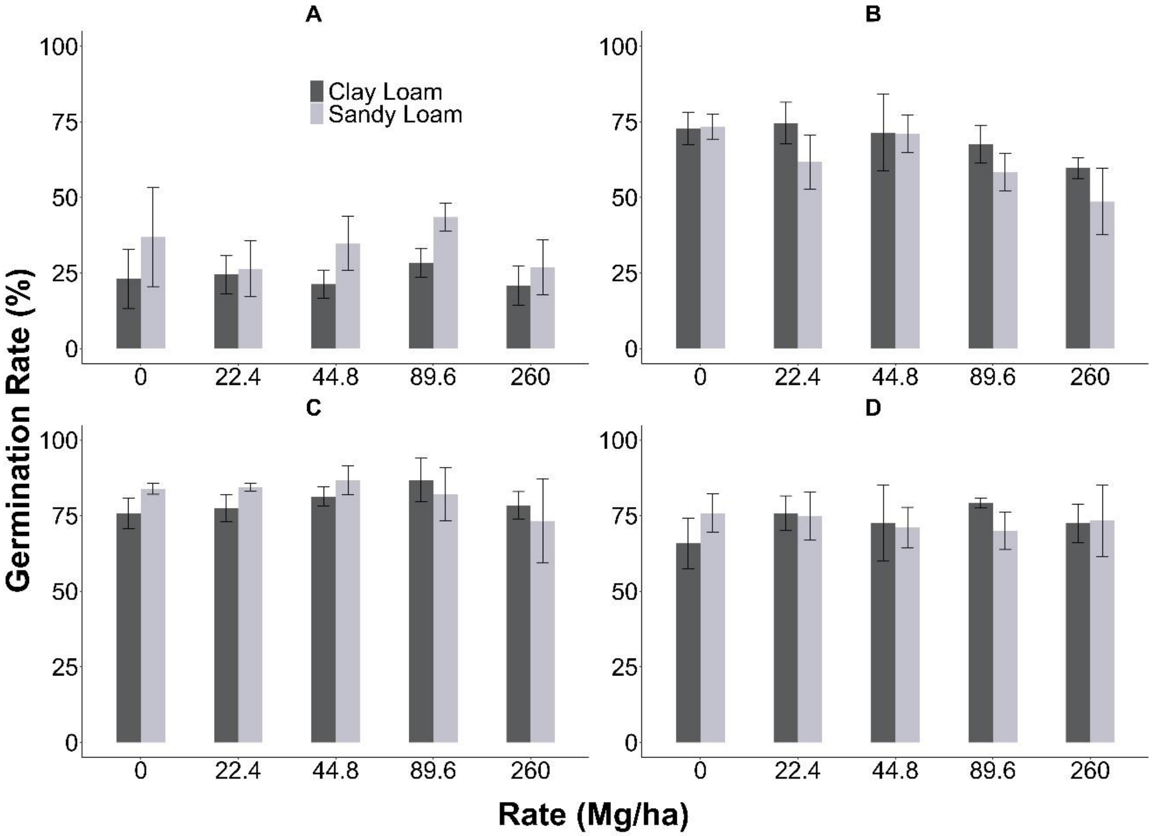

Figure 13. Trial 2 seed germination percentages for Bermuda grass (A), centipede grass (B), Kentucky bluegrass (C), and rye grain (D) with increasing rates of DGS. Error bars represent one standard deviation. Differences between treatment rates for each soil were not found to be statistically different with α = 0.05.

TRACK-OUT PREVENTION

This research assessed how effective different track-out prevention methods are and how soil properties influence their effectiveness. Soils with different textures and clay mineralogy were used at different moisture contents to determine the effectiveness of a stone exit pad, FODS Track-out Control Mat, and RubberForm Trackout Control Mat.

Materials and Methods

Soil Selection, Collection, and Preliminary Testing

Soil Collection. Eighteen soils were collected from the Coastal Plain and Piedmont regions of NC at a minimum depth of 15 cm below the soil surface (Table 4). Together, these regions comprise 84% of the area of the state, and approximately 90% of the state's population lives within them (Certified County Population Estimates, 2022; Daniels et al., 1999). Particle size analysis via the hydrometer method (Gee & Or, 2002) was conducted to determine their USDA textural classification (Table 4).

Atterberg Limits. The consistency of the fine-grained fraction of soil samples was determined using ASTM procedure D4318-17, Atterberg Limits (ASTM, 2017). This test establishes the plasticity range for each soil's fine-grained fractions, and there is an established correlation between the activity of the soil and the clay mineralogy present (Holtz & Kovacs, 1981). Soil specimens were prepared for testing using the wet preparation method.

Soil Mixing Test. A soil mixing test was adapted from Zumsteg and Puzrin (2012) to quantify the stickiness of each soil over a range of water contents. For each soil, ten tests were conducted using increasing water contents of 10 to 100 g. One hundred grams of dried soil was placed into the glass bowl of a stand mixer (KitchenAid Artisan Design Series 5 Quart Tilt-Head) fitted with a paddle attachment. The soil was mixed dry for one minute at the lowest speed ("stir" approximately 60 rpm) to distribute it evenly throughout the bowl. After one minute, deionized water was poured into the bowl and the mixture was allowed to mix for three minutes. The paddle was then removed and weighed to determine the amount of wet soil that adhered to it during the test (G_{MT}). Stickiness was quantified for each water content using the empirical stickiness ratio (λ): the ratio of the mass of soil-water mixture which adhered to the mixing paddle during the test, G_{MT}, to the total mass of soil and water used in the test, G_{TOT} by:

$$\lambda = \frac{G_{MT}}{G_{TOT}}$$

Field Testing

Soil and Tire Preparation. Of the soils collected and categorized, three were chosen for field testing. A sandy loam (SL) from the Felsic Crystalline System, a silty clay (SiC) from the Carolina Slate Belt System, and a sandy clay loam (SCL) from the Triassic Basin System (Table 4). The soil mixing test determined the stickiness of soil over a range of water contents. From this, the stickiest water contents were chosen for each soil, the sandy loam soil was used in field testing at 0.2 and 0.3 g g^{-1}, the silty loam at 0.4 and 0.5 g g^{-1}, and the sandy clay loam at 0.2 and 0.3 g g^{-1}.

New tires (275/55R20) were cut into approximately 40 cm long sections for testing. Two sets of holes were drilled into the top and bottom of each piece. Zip ties were used to secure the sections to the right rear tire of a Ford F-150 truck with four-wheel drive (Figure 14 & 15).

Site Design and Preparation. Testing was conducted at the Sediment and Erosion Control Research and Education Facility in Raleigh, NC. The length for devices used in testing was set to 4.2 m, the length of two FODS and one RubberForm mat. All three prevention methods were built or installed to NCDOT or manufacturer specifications. Before any tests occurred on a given day, the prevention methods were brushed with firm-bristle cleaning brushes to clear any mud or debris adhered to the contact surface. Additionally, after each testing day, the devices were rinsed with water to wash away any mud that may have adhered to them during the testing.

Testing Procedure. The experimental design used three soils and two water contents. Pre-portioned mud was applied to pre-weighed tire sections using a putty knife. The muddy tire sections were weighed and attached to the vehicle (Figure 14 & 15). By driving the truck forward and back in four-wheel drive, the sections made four contacts with the respective track-out device being tested, two contacts forward and two contacts back for a total distance of 8.4 meters. After the contacts, the sections were removed and weighed to determine the mass of mud removed. A subset of the soil conditions was chosen for eight-contact testing. The eight contacts occurred over 16.8 m. The eight-contact testing was conducted by driving back and forth on the devices four times.

Data Analysis

All statistical analysis was performed in R version 4.3.1 (R, 2023). An ANOVA was performed on all the data sets. A Fisher's Least Significant Differences (LSD) test (α = 0.05) was conducted to determine which means differed significantly. To determine the difference in mud removal with four versus eight contacts with a track-out device, a Welch two-sample t-test (α = 0.05) was conducted on that subset of data.

Results and Discussion

Atterberg Limits

Preliminary testing using Atterberg limits showed tested soils had a range of plasticity (Figure 16). The soil with the highest plasticity index, 34%, was a clay-textured soil from the Triassic Basin, and the soil with the lowest plasticity index, 4%, was a sandy loam-textured soil from the Felsic Crystalline System. The soil with the highest activity number, 0.93, was a sandy clay loam textured soil from the Triassic Basin. The lowest activity number was 0.37 in a sandy loam textured soil. When plotted on a Casagrande Plasticity Chart (Figure 16), the fine-grained (<425 µm) fraction of ten of the soils can be categorized as lean clays, two as silty clay, one as silt, and five as fat clay (ASTM, 2018). Fifteen soils are considered inactive, while the remaining three are considered normally active (Skempton, 1953). The values of the Atterberg limits of the soils used in field testing are shown in Table 5. These soils were selected based on their varied geographic regions and Atterberg limits.

Soil Mixing Test

The curves created by the soil mixing test results are displayed in Figure 17. The soils with the lowest peak empirical stickiness ratios (λ) of 0.069, 0.038, 0.112, and 0.118 were SC-1, SCL- 3, SL-1, and SL-2, respectively (Figure 17). Conversely, the highest peak λ values of 0.485, 0.564, 0.563, and 0.633 belonged to C-1, CL-1, CL-2, and SCL-4, respectively (Figure 17). All four of the stickiest soils were collected from the Triassic Basin and exhibited properties of soils with mixed clay mineralogy that includes some proportion of 2:1 shrink-swell clays. This is reinforced by the Triassic Basin being an area known to have 2:1 shrink-swell clays, and these soils often being categorized as having mixed mineralogy with 10% or greater 2:1 shrink-swell clays (Bain & Brown, 1981; Daniels et al., 1999). Additionally, while these soils had the highest peak λ values and activity numbers, they did not have the highest clay contents relative to the tested soils, indicating the contribution of sticky clays to these high values.

Similar to their Atterberg limit results, the three soils used in field testing had a range of peak λ values of 0.118 (sandy loam), 0.355 (silty clay), and 0.633 (sandy clay loam). This pattern mirrors the plasticity index results for the three soils, in which the sandy loam was slightly plastic, the silty clay was medium plastic, and the sandy clay loam soil was highly plastic, indicating a possible relationship between peak λ value and plasticity.

The liquid and plastic limits of the sandy loam soil were 20 and 16, respectively, and the peak λ of this soil was at a water-to-soil ratio of 0.2 g g^{-1}, which corresponds with the liquid limit. The liquid and plastic limits for the silty clay soil were 41 and 24, respectively, and the peak λ value was at 0.4 g g^{-1} water to soil, which is slightly below the liquid limit. The sandy clay loam had liquid and plastic limits of 18 and 44, respectively, and a peak λ value at 0.2 g g^{-1}, slightly higher than the plastic limit. While the peak λ values for sandy loam and silty clay are near their liquid limit water contents, the peak λ value for sandy clay loam was closer to its plastic limit, reinforcing the inference that sandy clay loam has different clay mineralogy.

Using the Atterberg limits and soil mixing test as indicators for a soil's stickiness provides a better picture of how soil properties may influence the removal of these soils from vehicle tires when they exit construction sites. With these indicators, the sandy clay loam is the stickiest, followed by the silty clay and sandy loam. The ease with which these soils could be removed from a vehicle tire should be inversely related to the stickiness.

Field Testing

Initial field testing using six soil conditions and four contacts between track-out prevention devices and tires yielded variable results (Table 6). When comparing the mud removal efficiency of the devices to one another, the RubberForm Trackout Control Mat performed the best in four of the six soil conditions: SL at 0.2 g g^{-1}, silty SiC at both water contents, and SCL at 0.3 g g^{-1}. The FODS Trackout Control Mat performed the poorest for the SL at 0.3 g g^{-1} and SiC at 0.5 g g^{-1}; however, its performance was not statistically different from that of the stone exit under all other conditions. The only condition under which the stone exit performed the best was the SL soil at 0.3 g g^{-1}.

The RubberForm mat had the fewest significant differences in mud removal across soil conditions. Increasing the water content of the SL from approximately its liquid limit of 0.2 to 0.3 g g^{-1} did not yield a significant difference in mud removal for the RubberForm or the FODS; however, the mud removed by the stone exit at the higher water content was significantly more than that of the lower water content in SL. In contrast, when the SiC was tested at its liquid limit of 0.4 g g^{-1} and then 10% higher, mud removal by the RubberForm mat and the stone exit was significantly increased with the increased water content. FODS, however, did not have a significant difference between the two conditions.

While the RubberForm mat tended to remove 25% or more of the applied mud on average, it could not remove quite as much of the SCL soil. While the differences between the mud removals by the three devices were not significantly different for the SCL at 0.2 g g^{-1}, the mean mud removal for the RubberForm itself was the poorest for that soil condition, with only 13.4%. The narrowest range of average mud removal belonged to the FODS Trackout Control Mat, with 17.9%, followed by RubberForm, with 35.7%, and finally, the stone exit, with a range of 61.8%.

The results for successive testing utilizing three of the original soil conditions and eight contacts between track-out prevention devices and tires are displayed in Table 7. The soil condition for which the FODS Trackout Control Mat performed poorest was 20.7% mud removal over eight contacts for SiC at 0.4 g g^{-1}. The other two soil conditions did not have statistically different percentages of average mud removal for FODS, 36.0 (SL at 0.3 g g^{-1}) and 32.0% (SiC at 0.5 g g^{-1}). The soil condition where the RubberForm Trackout Control Mat removed the most mud after eight contacts was for the SL soil at 0.3 g g^{-1} with an average of 70.4%, followed by SiC at 0.5 g g^{-1} (54.9%) and SiC 0.4 g g^{-1} (47.6%). The average values for mud removal by the stone exit for SL at 0.3 g g^{-1} and SiC at 0.5 g g^{-1} were not statistically different, 53.3% and 50.6%, respectively. These averages contrast the mud removed by the stone exit with SiC at 0.4 g g^{-1}, which was only 8.1%.

With the eight-contact testing, SiC was again tested at its liquid limit of 40% and 10% higher. In this case, the increase in water content above the liquid limit increased the average mud removal value for all three devices. However, this increase was only significant for the FODS and stone exit.

For FODS Trackout Control Mat (Figure 18) and RubberForm Trackout Control Mat (Figure 19), doubling the number of contacts from four to eight did not result in a proportional increase in mud removal. Doubling the number of contacts under some soil conditions for these devices did result in a significant increase in mud removal but not double. There is only one instance where doubling the number of contacts doubled the average mud removal percentage. The stone exit removed 3.6% of the SiC soil at 0.4 g g^{-1} after four contacts and 8.1% (more than double) after eight contacts (Figure 20). The doubling of contacts not yielding a proportional doubling in mud removal in most instances indicates some diminishing return on mud removal for all three tested devices under the three soil conditions.

Based on the preliminary lab testing, the soil that should have had the highest mud removal percentages was SL, followed by SiC and SCL. However, in general, this pattern did not emerge with field testing. At four contacts, when the soils are grouped by their respective higher and lower water contents for comparison, there were three instances, one per device, in which the anticipated pattern does emerge. First, when considering only the higher water contents, 0.3 g g^{-1} for SL and SCL and 0.5 g g^{-1} for SiC, the mud removal by FODS decreased as the activity number of the soils increased, 28.7% (SL), 16.6% (SiC), and 14.2% (SCL). However, the difference in mud removal between SiC and SCL was not significant (Table 6). Similarly, when considering only the higher water contents, the mud removal by the stone exit decreased significantly as the activity number of the soils increased, 58.4% (SL), 41.3% (SiC), and 8.8% (SCL) (Table 6). Finally, when the lower water contents, 0.2 g g^{-1} for SL and SCL and 0.4 g g^{-1} for SiC, were grouped, the mud removal by the RubberForm significantly decreased as the activity number of the soil increased, 49.1% (SL), 31.4% (SiC), and 13.4% (SCL).

There are several possible reasons why the relationship between soil activity and stickiness established in lab testing did not translate uniformly to the field testing. One possibility is the nature of the laboratory tests versus the field tests. The mixing test is conducted in a bowl, and the mud is sheared against the bowl as the test takes place. In the field, each device has a slightly different contact method and pattern, but the devices rely on shaking rather than shearing for mud removal. Another possible explanation is the water contents at which the soils were tested. While the water contents were determined based on the mixing test results, the sandy loam and silty clay soils were tested at and above their liquid limits during field testing. On the other hand, the sandy clay loam was tested at water contents that fell within its range of plasticity. Differences in the soil behavior between the two soils that would act as a liquid and the soil acting plastically may have played a role in the mud removal efficiencies. Finally, there may be a mismatch between the lab tests measuring mud stickiness and the field tests measuring mud removal, which limits their direct comparison.

Even though no device consistently had high mud removal across all conditions, inferences can still be made as to what soils each device may be suited towards and how soil properties influence the effectiveness of these devices. The FODS Trackout Control Mat performed its best with sandy loam and had a similar performance with the drier sandy clay loam soil. This device would likely make a good candidate for track-out prevention in coarser textured soils and potentially soils with lots of gravel. Additionally, the efficacy of FODS at sites with finer textured soils like silty clay may be slightly improved by increasing the lengths used. The RubberForm Trackout Control Mat performed best with sandy loam and silty clay soils, and there was some indication that greater lengths of these prevention methods may be advantageous for mud removal. This device was also the most consistent in the mud removal across the six soil conditions used, possibly because it "bounced" the tires more than the other systems (based on driver experience). Therefore, it may be suitable for preventing track-out under more soil conditions throughout the Carolina Slate Belt and Felsic Crystalline geologic regions. The efficacy of the stone exit with changing soil properties is more variable. For the sandy loam and silty clay soils, at water contents 10% higher than the liquid limit, the mud removal more than doubled on average. The differences in mud removal from texture to texture and within the textures for the stone exit indicate that soil properties greatly influence the device's efficacy. It is also important to note that the results of the stone exit come from a freshly installed exit, which is not always the case on an active construction site. Intensive use can lead to the settling and compaction of the stone and inundation with sediment.

Tables and Figures

Table 4. Soil collected for testing.

USDA Class	ID Code	Soil System
Clay	C-1	Triassic Basin
	C-2	Carolina Slate Belt
	C-3	Carolina Slate Belt
Clay loam	CL-1	Triassic Basin
	CL-2	Triassic Basin
	CL-3	Felsic Crystalline
Sandy clay	SC-1	Upper Coastal Plain and Piedmont
	SC-2	Felsic Crystalline
	SC-3	Felsic Crystalline
	SC-4	Upper Coastal Plain and Piedmont
Silty clay	SiC-1	Carolina Slate Belt System
	SiC-2*	Carolina Slate Belt System
Sandy clay loam	SCL-1	Upper Coastal Plain and Piedmont
	SCL-2	Upper Coastal Plain and Piedmont
	SCL-3	Upper Coastal Plain and Piedmont
	SCL-4*	Triassic Basin System
Sandy loam	SL-1	Felsic Crystalline
	SL-2*	Felsic Crystalline

Note: Soil systems correspond to the North Carolina Soil Map Unit System where each sample was collected. Asterisks denote soils used in field testing.

Table 5. Results of Atterberg limits for soils used in field testing of track-out prevention devices. ASTM Procedure D4318-17 (ASTM, 2017).

ID Code	Liquid Limit	Plastic Limit	Plasticity Index	Activity
SCL-4	44	18	26	0.93
SiC-2	41	24	17	0.43
SL-2	20	16	4	0.37

Table 6. Average mud removed by each track-out prevention method after four contacts.

	Average Mud Removed (%)					
	Sandy Loam		Silty Clay		Sandy Clay Loam	
	$0.2\ g\ g^{-1}$	$0.3\ g\ g^{-1}$	$0.4\ g\ g^{-1}$	$0.5\ g\ g^{-1}$	$0.2\ g\ g^{-1}$	$0.3\ g\ g^{-1}$
FODS	22.6 ab B	28.7 a C	10.8 d B	16.6 bcd C	22.0 abc A	14.2 cd B
RubberForm	49.1 a A	44.3 a B	31.4 b A	48.7 a A	13.4 c A	26.7 b A
Stone Exit	19.4 c B	58.2 a A	3.6 d B	41.3 b B	22.9 c A	8.8 d B

Note: Letters indicate a significant difference in average mud removed. Differences denoted with lower-case letters are significant across rows and indicate significant differences in the amount of mud a given device removes as a function of soil condition. Differences denoted with upper-case letters are significant down columns and indicate differences in mud removal as a function of device under a given soil condition. Determined using a Fisher-LSD test with $\alpha = 0.05$.

Table 7. Average mud removed by each track-out prevention method after eight contacts for a select subset of soils.

	Average Mud Removed (%)		
	Sandy Loam 0.3 gg^{-1}	Silty Clay 0.4 gg^{-1}	Silty Clay 0.5 gg^{-1}
FODS	36.0 a C	20.7 b B	32.0 a B
RubberForm	70.4 a A	47.6 b A	54.9 b A
Stone Exit	53.3 a B	8.1 b C	50.6 a A

Note: Letters indicate a significant difference in average mud removed. Differences denoted with lower-case letters are significant across rows and indicate significant differences in the amount of mud a given device removes as a function of soil condition. Differences denoted with upper-case letters are significant down columns and indicate differences in mud removal as a function of device under a given soil condition. Determined using a Fisher-LSD test with α = 0.05.

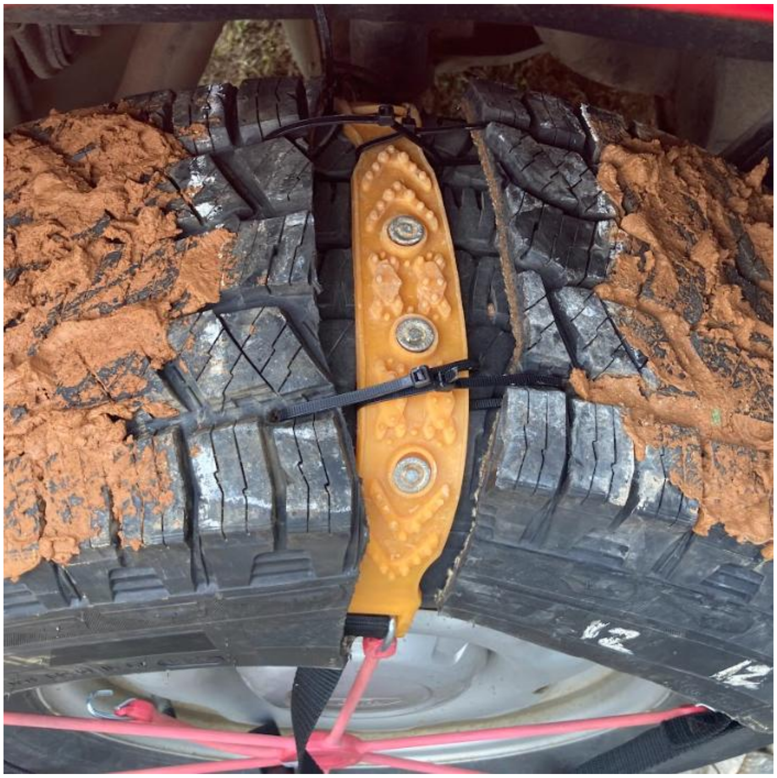

Figure 14. Tire sections fastened to plastic tire chains via zip ties.

Figure 15. Track-out testing tire set-up.

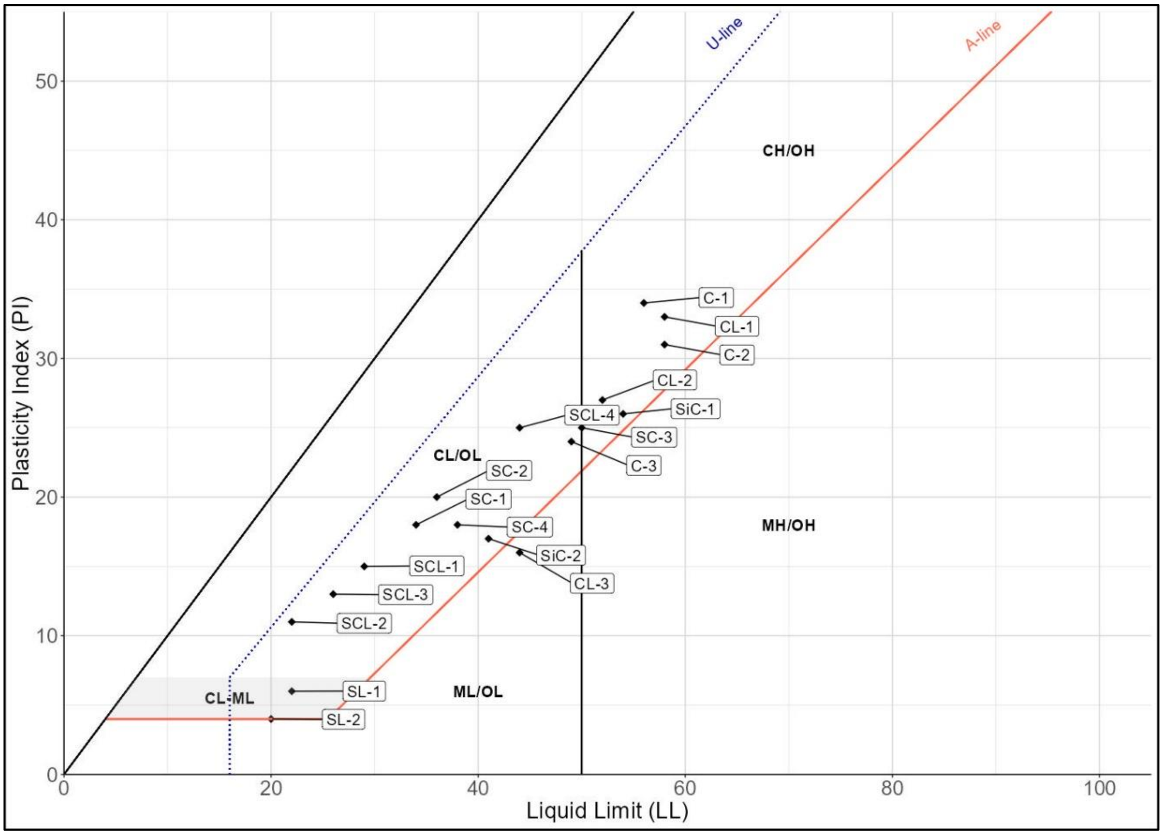

Figure 16. Casagrande plasticity chart for classification of fine-grained fraction of select coarse NC soils (Casagrande, 1948). Soils classified based upon where they fall within the chart, with letters indicating soil class. CH – fat clay, inorganic clay of high plasticity, OH – organic silts and clays of high plasticity, CL – lean clay, inorganic clay of low to medium plasticity, OL – organic silts and clays of low to medium plasticity, ML – silt, inorganic silts and clayey silts of low to medium plasticity, MH – elastic silt, inorganic silts, micaceous or diatomaceous silty soils (ASTM D2487). A-line is horizontal at PI = 4 from LL = 4 to LL = 25.5, then PI = 0.73 (LL-20). U-line is vertical at LL = 16 from PI = 0 to PI = 7, then PI = 0.9 (LL-8).

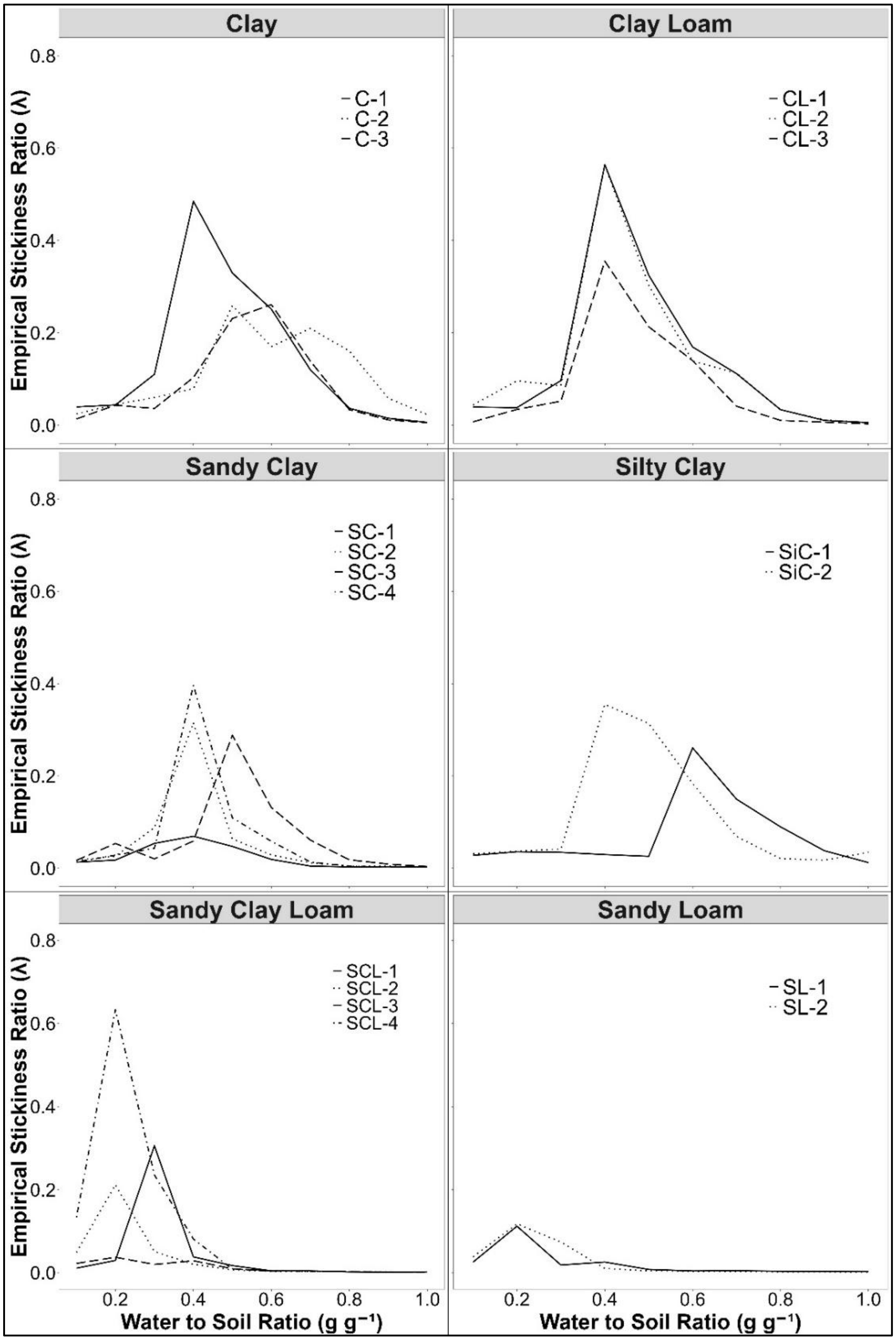

Figure 17. Soil mixing test results. Empirical stickiness ratio is the ratio of the mass of soil and water mixture that sticks to the mixing paddle during testing to the total soil and water mass used in the test.

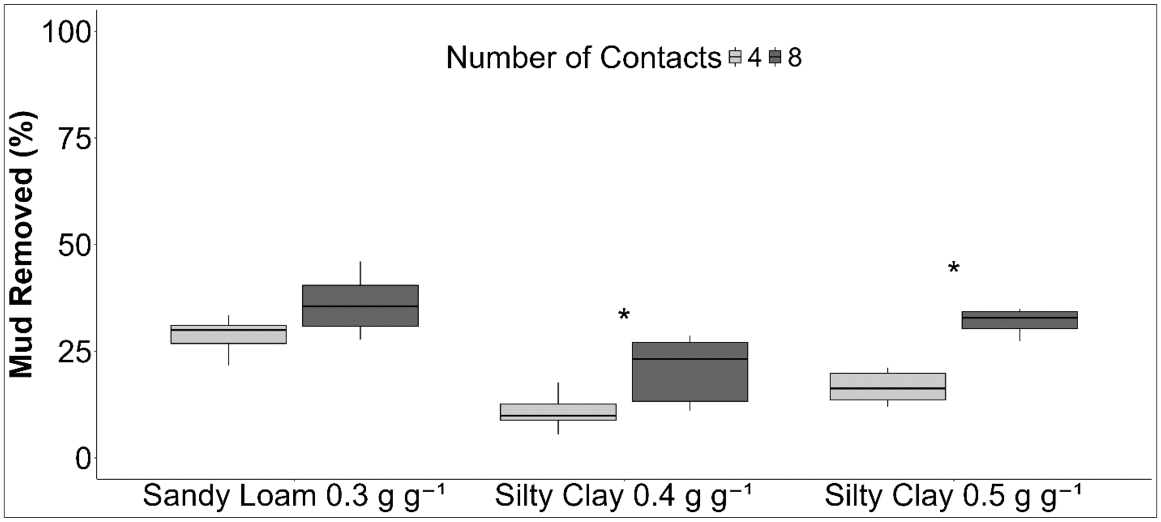

Figure 18. Comparison of mud removal by FODS Trackout Control Mat after four and eight contacts under select soil conditions. The asterisk indicates a significant difference between four and eight contacts using a given soil condition at α = 0.05 using a Welch two-sample t-test.

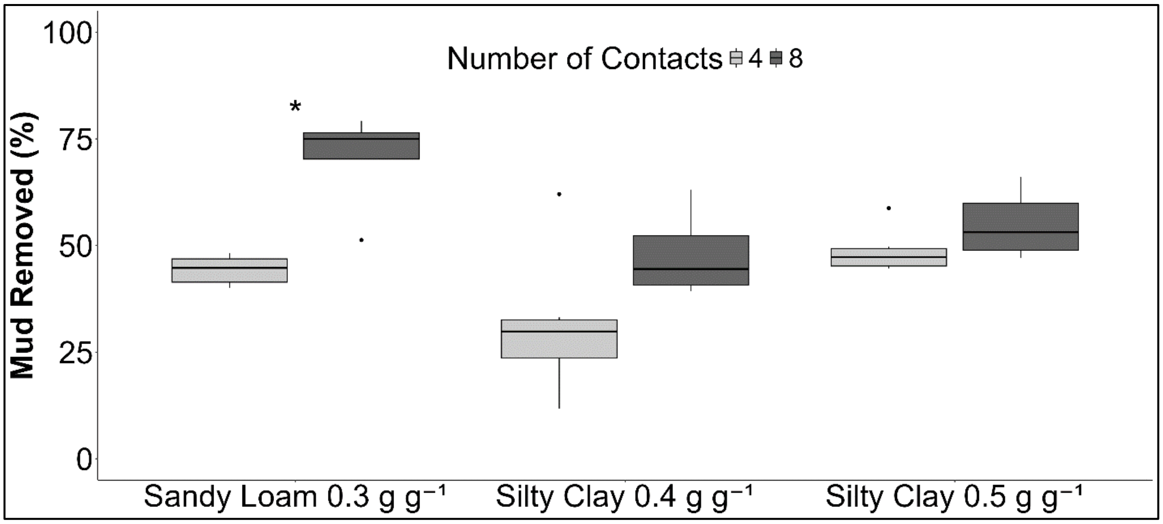

Figure 19. Comparison of mud removal by RubberForm Trackout Control Mat after four and eight contacts under select soil conditions. The asterisk indicates a significant difference between four and eight contacts using a given soil condition at α = 0.05 using a Welch two-sample t-test.

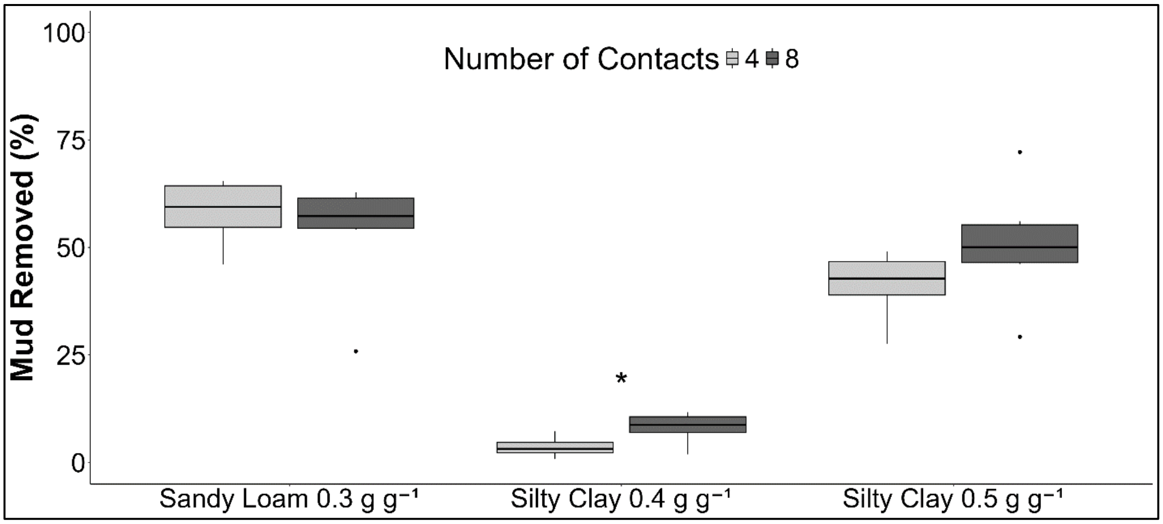

Figure 20. Comparison of mud removal by standard stone exit after four and eight contacts under select soil conditions. The asterisk indicates a significant difference between four and eight contacts using a given soil condition at α = 0.05 using a Welch two-sample t-test.

FINDINGS AND CONCLUSIONS

DGS Conclusions

The current management and disposal options for DGS in North Carolina are limited to land application and press plate separation and disposal, with the latter being the most common. The use of a sediment basin for DGS separation and PAM to enhance separation were identified as possible options to improve the efficiency and sustainability of the management or disposal of concrete grinding waste.

Using the sediment basin design to separate DGS draws on an established sediment and erosion control practice, modifying it to accommodate the more solids-concentrated waste material. At the time of publishing, two DGS basins were successfully used in North Carolina. The second basin was the subject of the data collected in Appendix 1. DGS from three road grinding projects was tested with various PAMs to determine if DGS basin settling could be enhanced with PAM. All three slurries were successfully matched with one or more PAMs, reducing the supernatant turbidity, the volume of settled solids, or both. This research establishes that the chemical properties of DGS that allow it to be flocculated by a given PAM vary from grinding project to grinding project. Several factors may influence this, including the geographic area of the road, which would impact the type of aggregate being used in the concrete mix, and the age of the road, which would affect the admixtures in the concrete and the amount of exhaust deposition.

Through soil incubations and seed germinations, this research has established that there is potential for DGS to be used as lime during revegetation on construction projects. The acidic subsoil common in North Carolina is recommended to be limed before seeding to bring the pH up to optimal levels for grass growth. Using DGS instead of or in addition to commercial lime can enhance the environment and economic sustainability of road grinding projects. While DGS additions increase soil EC values due to the increase in soluble salts, particularly the calcium present in concrete, the pH increase due to DGS addition is the limiting factor for its use as a soil amendment. Additions of DGS up to 260 Mg ha^{-1} did not increase soil EC in either the clay loam or sandy loam soils above 1 dS m^{-1}, and neither soil would be classified as saline. The same high DGS additions increased the soil pH to about 8, which is too high for many grasses planted along North Carolina roadways. Hence, pH could be the limiting factor for using DGS as a liming material during vegetation establishment, particularly if the vegetation used has low or narrow soil pH tolerance. Germination tests with the common grasses used on NCDOT roadsides did not indicate intolerance to the highest DGS application rate, however. Soil and DGS testing should be conducted when using DGS as a liming material. The calcium carbonate equivalency of the DGS determined from testing, paired with the lime requirement from soil testing, would enable contractors to determine the appropriate rate of DGS to use as lime during vegetation establishment.

Overall, the management and disposal of diamond grinding slurry from concrete highway grinding in North Carolina has the potential to have increased economic and environmental sustainability. Using sediment basins to separate DGS could reduce costs relative to current practices by reducing transport costs and providing a passive separation option akin to land application without the required land area on road shoulders. Reducing DGS transportation lessens the environmental impacts of road grinding by reducing the dependence on fossil fuels. Environmental sustainability can be further increased by using the solid waste byproduct of DGS collected in these basins as lime during on-site vegetation establishment. This is also economically desirable, as it reduces additional costs incurred on projects to purchase lime. Implementing the practices outlined would benefit contractors, helping them lower costs, improve efficiency, and become more sustainable overall.

Additionally, if PAM is used to enhance the settling of DGS in sediment basins, the settleable solids test will be an important metric to consider. Basins designed to settle DGS alone may not be able to accommodate an increased volume due to flocculation. As such, the basin design should account for a possible solids volume increase from PAM flocculation, or PAM should be selected based on its ability to reduce the volume of settleable solids.

Track-out Conclusions

Track-out is a complex problem, but all too often, a single solution, the stone exit, is employed, and if that fails, wheel washing may be used. However, with increasing demand for more sustainable practices, there are more options for reusable track-out prevention products and more implementation of these methods on construction sites. The complexity of track-out prevention is primarily due to soil properties. While a soil's texture indicates how much clay is present in a soil, texture alone does not capture the consistency or plasticity of a soil when clay mineralogy and water content also play significant roles. Water content is dynamic and can change rapidly. While texture and mineralogy are static properties of soils, they can differ greatly from site to site, particularly as the physiographic region changes. This research has shown how these soil properties impact the stickiness of soil and, therefore, the effectiveness of track-out prevention methods. Incorporating Atterberg limits makes this information translatable to construction projects where site assessments determine the subsoil properties. The mixing test allows for a quantifiable measure of soil stickiness across a range of water contents. In general, the higher the soil activity, the higher the peak empirical stickiness ratio the soil has in the mixing test, reinforcing that texture alone does not predict soil stickiness.

In field testing, differences emerged in the efficiency of mud removal by devices based on soil texture and water content. No single prevention method performed unequivocally best under the six soil conditions used in four-contact testing. The best performances of each prevention method still had mud removal averages of 40% or more remaining on the tires.

Upon doubling the number of contacts from four to eight, there was only one instance where the mud removal by a track-out device doubled with increased contacts. This diminishing return on mud removal indicates that while increasing the length of a track-out device may, in some cases, increase mud removal, increased lengths will not usually solve the issue of track-out.

Establishing variation in soil stickiness with differing soil properties and the impacts of this on track-out prevention device efficacy reinforces the need for more site-specific and soil-specific guidance for contractors to prevent track-out. Developing the connection between soil properties and track-out is a start for improving track-out prevention. Testing a more extensive breadth of soil conditions would help to inform the potential for track-out under more than the six conditions tested here. Additionally, there may be value in determining at which contact number there is a diminishing return to mud removal on each track-out prevention device. Although there was not a single best practice determined from this research, the nature of soil and the stickiness of different soils under varying conditions likely bar a single solution to track-out from ever being the case. The lack of a single solution reinforces the need to take soil properties into consideration during sediment and erosion control planning to better prevent track-out.

RECOMMENDATIONS

- DGS can be used as a liming alternative or in conjunction with traditional lime to increase the pH of soil. The limiting factor of DGS application rate will depend on the pH increase needed for the grass species planted. To find the rate of DGS, the calcium carbonate equivalency of DGS should be determined and then scaled based on the lime requirement of the soil. It is important to note that at a DGS application rate of 260 Mg ha^{-1}, none of the grass species tested had diminished germination, and neither of the soils were classified as saline.

- PAM can be used to increase the settable solids in DGS. The specific PAM and rate will depend on the concrete mix. Each DGS project will need to determine the PAM and application rate using jar testing or the settable solids methods outlined in this report.

- A sediment basin is an effective way to enhance the separation of DGS on construction sites and reduce the cost associated with DGS transport and disposal. If PAM is going to be used to enhance the separation of DGS, then the sediment basin needs to be sized to handle the increased volume of solids from the flocculation. The solids have a higher water content than soil, and the water may need to be skimmed off the top or dried.

- Track-out devices work best for different soil textures, stickiness, and moisture contents. The soil texture and Atterberg limits can be used to classify the stickiness of soil on construction sites. This will allow for more site-specific recommendations for track-out device selection.

- Doubling the number of tire contacts to the track-out device did little to proportionally increase the device's effectiveness. This demonstrates that increasing the length of the track-out device will not always proportionally increase the mud removed from vehicle tires.

- Regardless of the track-out device, 40% or more mud remained on vehicle tires after testing. This demonstrates that innovation in the track-out space is needed to further improve sediment and erosion control on construction sites. In critical areas where track-out must be prevented, wheel washing is likely the only option.

IMPLEMENTATION

Our research results and recommendations can optimize DGS separation and increase the environmental impact of DGS operations in North Carolina to ensure a low-cost effective solution to the current system for diamond grinding. Sediment basins can continue to be used to separate DGS to reduce the cost associated with trucking and disposing of the materials. The water can be reused in the DGS operation. The solids can be sent off to the North Carolina Department of Agriculture for testing to get the calcium carbonate equivalence. This data, along with the amount of lime needed for the soil and grass species intended to be planted, the contractor can calculate the amount of DGS needed to use as a liming material. Alternatively, the solids can be left in the basin and capped off when the grinding operation is complete. For new construction projects, PAM is already in the planning and budgeting of construction projects. PAM testing for DGS samples can be added with the soil samples to ensure the right PAM and rate is obtained for each project. In older grinding operations, if PAM is going to be used to enhance settling, then PAM testing will have to be incorporated in the planning and budgeting of the construction project.

Our track-out device results can optimize track-out control on construction sites. We anticipate the NCDOT will be able to immediately incorporate our recommendation for soil considerations affecting device performance. Atterberg limits, soil texture data, and geological data are collected during the initial site evaluation by engineers. Doing this during the planning stage will allow the engineers to pick the track-out device based on the stickiness of the soil.

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APPENDIX 1: DIAMOND GRINDING SLURRY BASIN WATER SAMPLING DATA

This appendix includes a water sampling schematic and data from the sediment basin where DGS was separated without PAM.

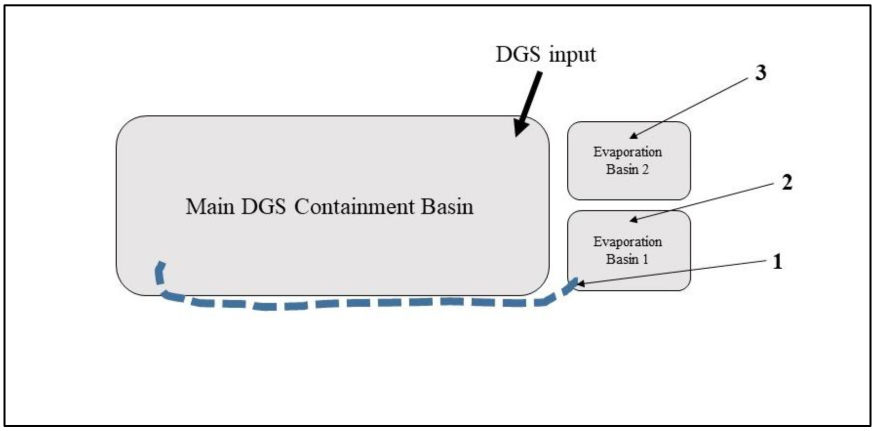

Figure A.1. Sampling point map I77/40 DGS basin. Samples taken from sampling point 1 were collected directly from the hose pumping water skimmed from the main basin into the first evaporation basin. Sampling point 2 was the first evaporation basin, and sampling point 3 was the second evaporation basin. Sampling from point 1 was only conducted when sufficient water was being pumped to the evaporation basins. The final date of road grinding was October 16, 2023, and there was no additional DGS added to the basin beyond this date; however, samples continued to be collected as the DGS in the basin was dewatered.

Table A.1. Water sampling data for sampling point 1.

Date	pH	EC (dS/m)	Turbidity (NTU)	Date of Grinding	Field pH of Slurry
9/11	10.96	1.94	3.27	9/8/2023	10.68
9/25	12.27	8.27	7.51	9/22/2023	12.26
10/4	11.98	4.11	9.27	10/3/2023	12.31
10/5	12.09	4.69	24.20	10/4/2023	12.32
10/18	11.37	1.59	350	10/16/2023	12.08

Note: Sampling at this point was only conducted on days when there was flow from the main containment basin up to the evaporation basins. Grinding took place overnight throughout the duration of sampling; date of grinding lists the calendar day on which the most recent grinding began. Field pH of the slurry is an average of the recorded slurry pH values taken in the field prior to slurry transport.

Table A.2. Water sampling data for sampling point 2.

Date	pH	EC (dS/m)	Turbidity (NTU)	Date of Most Recent Night Grinding	Field pH of Slurry
9/11	11.03	1.89	4.34	9/8	10.68
9/14	11.91	4.44	12891.67	9/13	11.59
9/23	12.25	8.49	72.40	9/22	12.26
9/25	11.92	4.37	8.35	9/22	12.26
9/29	12.13	6.30	89.67	9/28	12.38
10/4	12.07	4.70	10.22	10/3	12.31
10/5	11.99	3.95	2.11	10/4	12.32
10/19	11.51	1.81	15.40	10/16	12.08
10/24	10.51	1.35	0.00	10/16	12.08
10/29	10.26	1.35	1.51	10/16	12.08

Note: Grinding took place overnight throughout the duration of sampling, date of grinding lists the calendar day on which the most recent grinding began. Field pH of the slurry is an average of the recorded slurry pH values taken in the field prior to slurry transport.

Table A.3. Water sampling data for sampling point 3.

Date	pH	EC (dS/m)	Turbidity (NTU)	Date of Most Recent Night Grinding	Field pH of Slurry
9/11	11.06	1.85	3.39	9/8	10.68
9/14	11.62	2.62	34.43	9/13	11.59
9/23	12.03	5.08	32.30	9/22	12.26
9/29	12.10	6.24	6.60	9/28	12.38
10/4	11.91	3.42	72.7	10/3	12.31
10/5	11.96	4.22	1.42	10/4	12.32
10/18	10.41	1.86	6.90	10/16	12.08
10/19	10.37	1.88	3.76	10/16	12.08
10/24	9.82	1.88	3.22	10/16	12.08
10/29	9.61	1.87	2.47	10/16	12.08

Note: Grinding took place overnight throughout the duration of sampling, date of grinding lists the calendar day on which the most recent grinding began. Field pH of the slurry is an average of the recorded slurry pH values taken in the field prior to slurry transport.