dropped (not mechanically thrust down) for each drop/tamp. Each trial was performed on loess specimens prepared at 11.5% moisture content (MC), or -5.3% OMC. Interpolating from this the test trial data, a theoretical number of drops required to achieve 90% compaction was determined at 175 drops on the smaller 0.094 m^2 (1 ft^2) test form. However, due to equipment limitations, a reduced 125 drops per 0.094 m^2 (1 ft^2) was selected for this study, which produced a favorable 85%-90% compaction.

Figure 1: Uniform Tamping Apparatus (left) and Soil Racks and Forms (right)

With the number of drops per unit areas determined, several tamping (drop) patterns were considered for compaction of the larger 0.75 m^2 (8 ft^2) soil forms. The soil form was initially divided into a grid of 15 overlapping drop positions; however, this translated to 1,875 drops (or 125 drops x 15) in the larger 0.75m2 (8 ft2) soil forms. However, the feasibility of applying 1,875 drops to each soil form would risk breaking the UTA, so a reduced 8-position drop pattern was selected, which translated to 1,000 drops (or 125 drops x 8) in the larger 0.75m2 (8 ft2) soil forms. Retesting this drop configuration using the full soil form and sampling the compacted soil again produced the expected MDD of 85.1 lb/ft^3 at 86% compaction, which fell in the target range of 85%-90% compaction, although short of the desired 90% minimum compaction effort.

In choosing the CGR dosage for amending the Iowa loess, unconfined compressive strength (UCS) of CGR-amended soils was the primary dosage selection criterion. In a parallel 2019 Transportation Research Board (TRB) study, Yang et al. (2019) analyzed the feasibility of using 4 different CGR dosages (10%, 20%, 30%, and 40% CGR by weight) as a soil stabilizer for 2 common Iowa soils: a coarse sand (SC) and a silty clay (CL-ML). While Yang et al., found improved UCS with each of these dosages, a 20% CGR dosage resulted in the highest UCS values: Based on these findings, a 20% CGR dosage was selected for this study.

To ensure proper compaction, initial Standard Proctor tests (ASTM D698 2012) were performed on untreated loess as well as on CGR-1 and CGR-2 (CGR amended loess hereafter referred to as CGR-1L and CGR-2L). The primary loess control (Control-2) used for this study had an OMC of 16.8% at an MDD of 16.6 kN/m^3 (105.6 lb/ft^3). CGR-amended loess produced a differing Standard Proctor results. With CGR-1L the OMC decreased by 1% to 15.8% OMC with a virtually unchanged MDD. With CGR-2L the OMC increased by 0.5% to 17.3% OMC while slightly improving the MDD of the soil blend to 16.8 kN/m^3 (106.8 lb/ft^3). To simplify mixing, an 16.6% MC was selected for soils Control-2, CGR-1L, and CGR-2L tested in this study.

With respect to choosing storms to reproduce in the rainfall simulator, ASTM D6459 (2019) recommends 3 sequential 20-min storms with 5.1, 10.2, and 15.2 cm/hr (2, 4, and 6 in./hr) rainfall intensities. Rainfall data for Iowa was also compared to the ASTM D6459 specified rainfall rates. Data collected by the National Oceanic and Atmospheric Administration (NOAA) from 280 rain gauges from 9 different regions across Iowa is summarized in the Iowa Statewide Urban Design and Specification (Iowa SUDAS) manual. Comparing NOAA/Iowa SUDAS data to the storms specified in ASTM D6459 (2019) it was found that the average Iowa SUDAS rainfall intensities were slightly lower but similar in magnitude for Iowa 2-year, 5-year, and 10-year (20-minute) storms with 7.39, 9.25, and 10.87 cm/hr (2.91, 3.64, and 4.28 in./hr) (Iowa SUDAS 2013). Therefore, the selection of the ASTM D6459 recommended rainfall intensities 5.1, 10.2, and 15.2 cm/hr (2, 4, and 6 in./hr) were selected for simulation in this study.

An indoor, ceiling-mounted, 3-bay, 9-nozzle, Purdue-type, rainfall simulator (Figure 2) located in the Biorenewables Research Laboratory at Iowa State University (ISU) was used for this study. It employed a total of 9 VeeJet Model 80100 flat-spray nozzles (3 per bay), each with laminar flow fittings, to produce a fine rainfall spray with an 80-deg. fan spread.

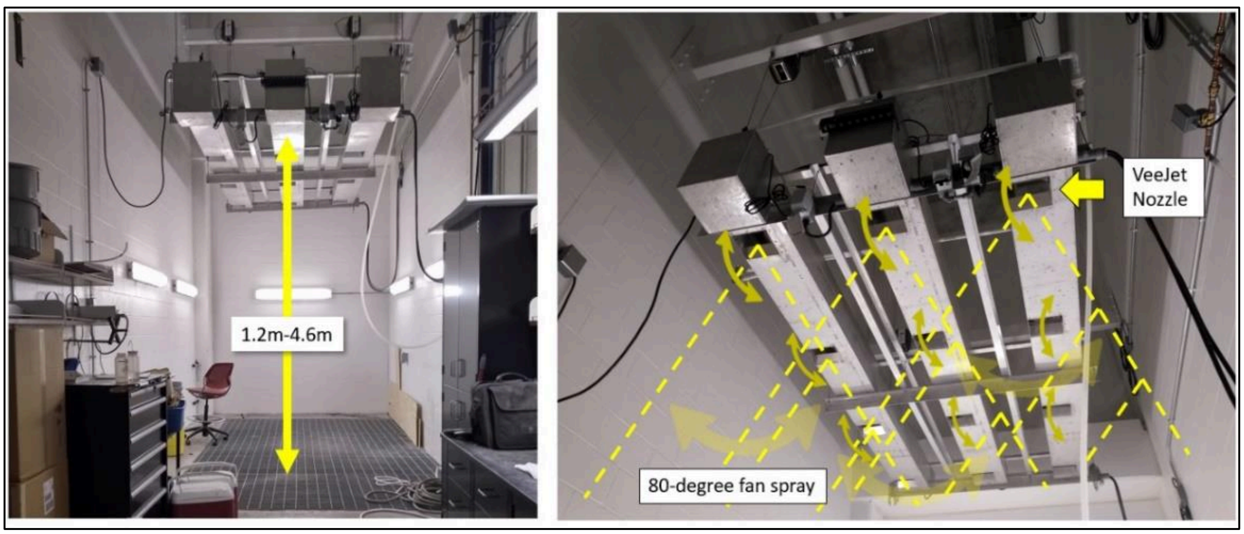

Figure 2: Iowa State University Indoor Rainfall Simulator

Four independently controlled winches were connected to the simulator corners to control its height, that ranged from approximately 1.2 m (4 ft) to 4.6 m (15 ft), measured from the ground to the bottom of the metal simulator troughs. An optimal height of between 2.3 m (7.5 ft) to 3 m (9.8 ft) was determined by the late distinguished USDA Agricultural Engineer, Dr. L. Donald Meyer for use in rainfall simulators using the same VeeJet 80100 nozzles with 41 kPa (5.9 psi) spray pressure (Meyer 1958). Since the 80100 nozzles and similar water pressures were used in the ISU simulator, a working height of 2.4 m (8 ft) – selected within the Meyer range – was chosen for this study. Potable water from the Ames, Iowa was controlled in the simulator with ballcocks (floats) attached to lever arms that opened and closed supply valves to regulate the amount of water supplied to reservoir tanks in each metal bay/trough.

Rainfall intensities were set through a combination of adjustments to 3, 15 psi pressure gauges (1-per bay) and a central GraLab Model 451 electronic timer. By changing water pressure and timing calibration settings, rainfall intensities from 2.54 cm/hr (1 in./hr) to 20 cm (7.87 in./hr) could be generated. The 3 rainfall intensities (storms) reproduced in this study were 5.1, 10.2, and 15.3 cm/hr (2, 4, and 6 in./hr). The rainfall footprint generated by the simulator was approximately 3.4 m (11 ft) wide (left-to-right) by 4.6 m (15 ft) deep (front to back), with a reduced "workable" (uniform rainfall) area of approximately 2.8 m (9 ft) wide by 3 m (10 ft) deep. Overlap of nozzle spray between the bays initially caused rainfall under the center bay to be higher, but lowering the water pressure in the center bay, effectively reduced (minimized) the overlap-spray produced within the workable rainfall area.

After a series of 28 trials using bucket rain gauges, 3 pressure and timing calibration sets were chosen to closely model the desired 60-minute, 3-storm (3 x 20-minutes) rainfall simulation. The margins of error for each calibration set were calculated as 1.08%, 0.95%, and 8.36% for the 5.1, 10.2, and 15.3 cm/hr storms (2, 4, and 6 in./hr), respectively. Volumetric rainfall tests for each calibration set also produced similar low margins of error ranging from 1.36% to 4.46% error for each of the 3-rainfall intensities. Each volumetric rainfall test was based on 20-min rainfall simulations performed separately for each of the 3 rainfall intensities. Christiansen Uniformity Coefficients (Cu) were calculated at 88.1%, 82.44%, and 57.41% for the 5.1, 10.2, and 15.3 cm/hr (2, 4, and 6 in./hr) rainfalls, respectively. The Cu's for the 5.1 (2 in./hr) and 10.2 cm/hr (4 in./hr) storms produced high (>80%) rainfall uniformity while the Cu for the 15.3 cm/hr (6 in./hr) storm produced moderate-to-low uniformity. The disparity in the last 15.3 cm/hr (6 in./hr) storm was attributed to limitations of the simulator in uniformly producing this heavy rainfall event. However, since the volumetric margin of error was less than 5% for this 15.3 cm/hr (6 in./hr) storm, this final 20-minute storm simulation was considered satisfactory for this study.

Water Quality (ss. turbidity) testing was performed in accordance with the Standard Test Method for Determination of Turbidity in Static Mode (ASTM D7315 2017). Turbidity tests were performed on sediment-laden runoff water collected during 4 indoor rainfall simulations, with turbidity (grab) samples collected at 3-minute intervals (from 3 separate soil forms) over the duration of each 60-minute rainfall simulation. A HACH 2100Q portable turbidimeter was used to test turbidity readings for each grab sample with results reported in nephelometric turbidity units (NTUs). The 2100Q unit was calibrated using 10 ml sealed cells (comprised of 0, 10, 100, and 800 NTU specimens). Since the maximum range for the turbidimeter was 1,000 NTUs, significant dilution (as much as 40 times) using high-purity deionized water was required with each grab sample.

A total of 60 grab samples per simulation (20 per soil form) were collected into 50 ml (1.69 oz) clear plastic centrifuge tubes with screw-top caps, and the remaining sediment laden runoff water (flowing off the surface of each soil form) was funneled into 19 L (5 gal) buckets. Three 20-minute rainfall events were continuously run with no breaks between rainfall intensities. Each simulation progressed in rainfall intensity, beginning with a 5.1 cm/hr (2 in./hr) storm and advancing to a 10.2 cm/hr (4 in./hr) storm, before finishing with a 15.3 cm/hr (6 in./hr) storm. Buckets were swapped at each rainfall storm transition to separate runoff corresponding to each rainfall intensity. Extra buckets were used when required to ensure that no buckets overflowed during the simulations. Snap-on lids were used to seal each bucket, to prevent cross-contamination and protect against evaporation after testing. Packing tape was used to seal any buckets stored for any extended time.

RESULTS

After compaction, each soil form was covered with plastic for 24 hours prior to testing. Four rainfall simulations were performed in total, including loess at 11.5% MC (Control-1), loess at 16.5% MC (Control-2), and CGR-1 and CGR-2 amended soils (CGR-1L and CGR-2L) also at 16.5% MC. Recall 16.5% is near OMC for the 3 primary trials, excluding Control-1. Testing of Control-1 did not exhibit consistent soil erosion behavior between the 3 soil forms tested. This was attributed to the dryer-than-optimum Control-1 soil, which absorbed virtually all of the rainwater runoff during the initial 10 minutes of the simulation, and produced loose saturated soil that eroded erratically across the 3 soil forms. Control-2 (at OMC) was performed as a second control to address this concern and was ultimately selected as the primary control because it produced more consistent results across the 3 soil forms as evidenced in Figure 3 below.

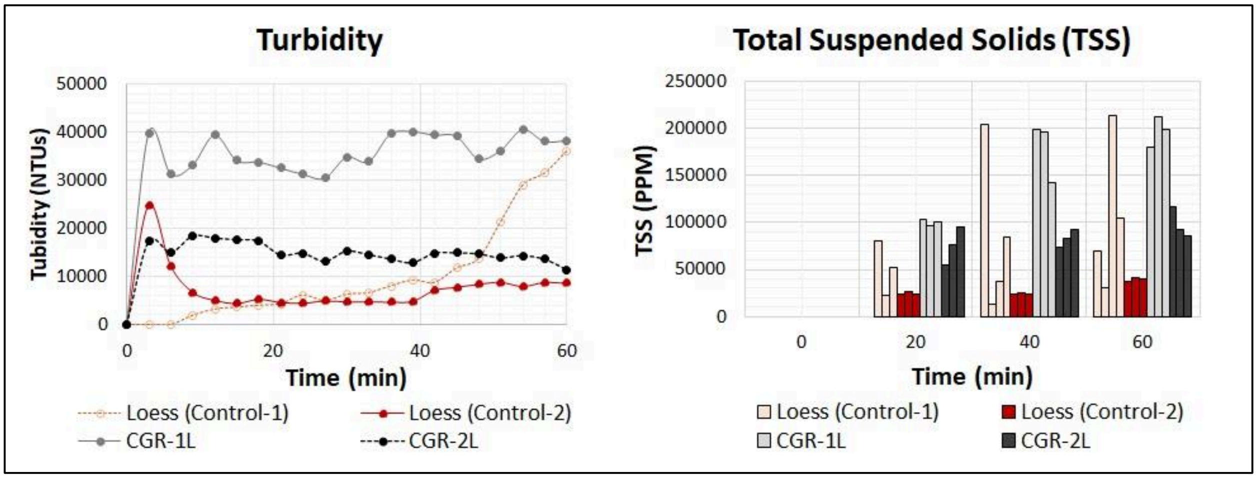

Figure 3: Rainfall Simulation Turbidity and TSS Results

With respect to Control-2, turbidity values leveled-off starting at the 12-minute mark of the simulation, resulting in relatively uniform erosion rates throughout the balance of the simulation. In comparison, Control-1 exhibited virtually no runoff until the soil forms were saturated, and then showed significant erosivity approaching values close to those of CGR-1L at the end of the simulation. The turbidity for CGR-1L fluctuated between 30,000 and 40,000 NTUs, with the highest average turbidity values exceeding 39,000 NTUs several times during the simulation. CGR-2L produced turbidity levels between those of Control-2 and CGR-1L, peaking at 18,400 NTUs at the 9-minute mark, before gradually decreasing for the remainder of the simulation. CGR-2L also plateaued at 14,400 NTUs between 30 and 48 minutes before decreasing to its lowest value of 11,400 NTUs at the end of the trial.

Total Suspended solids (TSS) testing was performed in accordance with ASTM D3977-97 (2019), the Standard Test Methods for Determining Sediment Concentration in Water Samples. Rainwater runoff buckets were collected by row and by rainfall intensity for each of the 3 soil forms tested during each rainfall simulation. For each bucket collected, sediment was allowed to settle for a minimum of 24 hours prior to decanting. After decanting, the remaining solids were vacated from each bucket using deionized water (as required) to effectively rinse and capture fine particles from the sides of the buckets. Solids were then baked and weighed to determine the amount of soil particles in the sediment-laden (runoff) water. Overall, the TSS results shared the same trends shown in the turbidity testing in this study. Control-2, for example, exhibited the lowest turbidity values as well as the lowest TSS (soil loss) during the simulation compared to both of the CGR-amended soil mixtures CGR-1L and CGR-2L.

Control-2 showed a consistent average soil loss of 24,600 ppm for the first 40-minutes of the simulation, before increasing by 60% to an average final peak of 39,500 ppm. CGR-2L soil loss behavior was similar to Control-2, except that soil loss averages were as much as 300% higher for CGR-2L at 79,300 ppm through the 40-minute mark of the simulation, before increasing another 24% to an average final peak value of 98,500 ppm at the end of the simulation. TSS values for all of the simulations paled in comparison to CGR-1L which demonstrated the most significant soil loss. CGR-1L averaged 99,600 ppm at end of the first 20-minute storm before increasing by 80% to 179,400 ppm during the second storm and increasing another 10% to a final average peak value of 197,500 ppm (or 5 times the soil loss of Control-2) by the end of the simulation. Table 2 shows the average soil losses for each of the 4 rainfall simulations. Control-1 reflected the most favorable early results, with only 0.12 MT/ha (0.05 tons/acre) soil loss, but increased dramatically after saturation, producing an average soil loss of over 20 MT/ha by the end of the simulation, (more than 200% of the final soil loss for Control-2).

Table 2: Total Soil Loss, MT/ha (tons/acre)

Rainfall Intensity	Loess (Control-1)	Loess (Control-2)	CGR-1L	CGR-2L
5.1 cm/hr (2 in./hr)	0.12 (0.05)	1.60 (0.71)	12.14 (5.41)	5.69 (2.54)
10.2 cm/hr (4 in./hr)	8.85 (3.95)	3.54 (1.58)	28.51 (12.72)	15.90 (7.09)
15.3 cm/hr (6 in./hr)	22.35 (9.97)	10.35 (4.62)	49.56 (22.11)	27.99 (12.48)

Overall, CGR-1L and CGR-2L both produced much heavier soil losses compared than Control-2. CGR-2L produced soil losses ranging from 270% to 450% of the soil losses of Control-2, while CGR-1L showed soil losses close to 800% of Control-2 for the first 2 storms and ended with close to a 500% higher soil loss over that of Control-2.

CONCLUSIONS

From the results above, a 20% CGR-amended, 24 hour cured loess significantly increased rain-induced erosion compared to untreated loess compacted at OMC. The turbidity of the grab samples degraded much more over time for CGR-amended soils, consistently ranging from 1.8 to 4.7 times greater (worse) than Control-2 samples throughout these simulations. Average turbidity values for CGR-2L (11,400 NTUs) and CGR-1L (38,400 NTUs) outpaced average values measured for Control-2 (8,200 NTUs) even with the final average turbidity reading (8,600 NTUs) for Control-2 at the end of simulation. Overall compared to Control-2, TSS soil loss during each simulation ranged from 2.2 times worse with Control-1 to 2.7 and 4.8 times worse with CGR-2L and CGR-1L, respectively. At the end of the simulation, CGR-1L lost a staggering 49.56 MT/ha (22.11 tons/acre) compared to the untreated loess in Control-2 at 10.35 MT/ha (4.62 tons/acre).

LIMITATIONS AND FUTURE RECOMMENDATIONS

Limitations of this study included the testing of one soil type (Western Iowa loess) at a single dosage (20% CGR), with only 2 of the 5 CGRs collected. Future testing of additional Iowan soils (e.g., glacial till and alluvium) with 20% CGR dosages (as well as other CGR dosages) would more conclusively determine whether these erodibility trends would continue for CGR-amended soils. Additionally, the 24-hour curing time limited the potential reaction of the CGR to the loess. A 7-day cure time after compaction is recommended for future trials. Loess was selected for this study because of its fine particle size, low plasticity, and (generally) poor drainage and strength characteristics associated with silts and loams, which makes it a problematic soil for use in roadside embankments. The cementitious properties of silt-sized particles in the CGRs used in this study and described by Yang et al. (2019) were hypothesized to positively affect the cohesion and strength of the loess soil particles, but conversely behaved opposite to suppositions. Again, this could be due to the limited 24-hour cure time. Additional tests with loess and CGR cured 7-days would more conclusively determine the impact of amending loess with CGR. Additional research may be useful to explore and characterize the mechanisms behind the erosion of CGR-amended loess.

With respect to future rainfall simulations, it is recommended that simulations be extended beyond 60 minutes to determine whether leveling-off trends continue or change with longer trials. Finally, rainfall simulations using other sustainable soil amendments such as corncob ash, rice-husk ash, and bamboo ash (and/or CGR amended soils with these materials) could be performed to determine if the pozzolanic characteristics in these materials might serve as a catalyst toward improving the cohesive properties of loess and other Iowan soils.

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REFERENCES

ASTM International. D3977-97(2019) *Standard Test Methods for Determining Sediment Concentration in Water Samples*. West Conshohocken, PA; ASTM International, 2019.

ASTM International. D6459-19 *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion*. West Conshohocken, PA; ASTM International, 2019.

ASTM International. D698-12 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))*. West Conshohocken, PA; ASTM International, 2012.

ASTM International. D7315-17 *Standard Test Method for Determination of Turbidity Above 1 Turbidity Unit (TU) in Static Mode*. West Conshohocken, PA; ASTM International, 2017.

Christopher, B. R., Schwartz, C. W., and Boudreau, R. L. 2006. FHWA NHI-05-037 Geotechnical aspects of pavements, Washington, DC: FHWA.
Coban, H. S. 2017. *The use of lime sludge for soil stabilization.* M.S. thesis, Ames, IA: Iowa State Univ.
Correa, A. L., and Wong, B. 2001. FHWA-SRC 1/10-01(5M) Concrete Pavement Rehabilitation – Guide for Diamond Grinding, Washington, DC: FHWA.
FHWA (Federal Highway Administration). 2013. FHWA-HRT-13-046 Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support. Washington, DC: FHWA.
FHWA (Federal Highway Administration). 2008. FHWA-RD-97-148 User guidelines for by product and secondary use materials in pavement construction. Washington, DC: FHWA.
Iowa DOT (Iowa Department of Transportation). 2015. *General Supplemental Specifications for Highway and Bridge Construction*. Series 2015. Ames, IA: Iowa DOT.
Iowa DOT (Iowa Department of Transportation). 2013. *Statewide Urban Design and Specifications (SUDAS)*. Ames, IA: Iowa DOT.
Kluge, M., Gupta, N., Watts, B., Chadik, P. A., Ferraro, C., and Townsend, T. G. 2018. "Characterisation and management of concrete grinding residuals." *Waste Mgmt. and Res.* 36(2), 149–158.
Mahedi, M., Cetin, B., and Dayioglu, A. Y. 2019. "Leaching behavior of aluminum, copper, iron and zinc from cement activated fly ash and slag stabilized soils." *Waste Mgmt.* 95, 334-355.
Meyer, L. D. 1958. "An investigation of methods for simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles." USDA-ARS Special Report*,* 81, 1-86.
Ricks, M. D., Horne, M. A., Faulkner, B., Zech, W. C., Fang, X., Donald, W. N., and Perez, M. A. 2019. "Design of a pressurized rainfall simulator for evaluating performance of erosion control practices." *Water (Switzerland)*, 11, 2386.
Schaefer, V. R., White, D. J., Ceylan, H., and Stevens, L. J. 2008. "Design Guide for Improved Quality of Roadway Subgrades and Subbases." Iowa Hwy. Res. Board*,* Rep. No. IHRB Project TR-525.
Shoemaker, A. L. 2009. *Evaluation of Anionic Polyacrylamide as an Erosion Control Measure Using Intermediate-Scale Experimental Procedures*. M.S. thesis, Auburn, AL: Auburn Univ.
Wilson, W. T. 2010. *Evaluation of Hydromulches as an Erosion Control Measure Using Intermediate-Scale Experiments.* M.S. thesis, Auburn, AL: Auburn Univ.
Yang, B., Zhang, Y., Cetin, B., and Ceylan, H. 2019. "Concrete Grinding Residue: Management Practices and Reuse for Soil Stabilization." *Transport. Res. Record*: *J of the Transport. Res. Board*, 2673(11) 748–763.

Modification of Sands Using *N*-Sodium Silicate Grout: Impact of Permeation versus Gelation Times

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ABSTRACT

Grouting is a method used regularly to alter in situ engineering soil properties, mainly strength, stiffness, and permeability. Chemical grouting constitutes injection of one or more fluids in grouting holes, with the aim of permeating the desired volume before the grout gels. Engineers require vital parameters during pre-gelation and post-gelation to quantify the economics and the efficiency of the treatment. The field of chemical grouting is highly contingent on laboratory and field pilot experiments, due to the convolution of its mechanisms and processes. This study aims at understanding the performance of Ottawa sand grouted using a commercial *N*-sodium silicate grout neutralized by dibasic ester. Particularly, this research seeks to investigate the impact of the gelation time, relative to grout permeation time, on the strength of the grouted sand. After studying, the rheology and syneresis of various mixes, candidate mixes were selected and permeated through 6-in. sand columns. Unconfined compressive strength tests were then performed on the specimens after their extraction to characterize the effect of sedimentation and filtration mechanisms during and post grouting (but prior to gelling). Two grouts with different gelation times were used in this study (20 and 30 min), and the specimens were permeated with different number of pore volumes (1–9). The permeation process was initiated either right after mixing or after a delay such that the permeation is concluded at the onset of gelation. The compressive strength increased with increasing number of pore volumes permeated; additionally, specimens with delayed permeation yielded higher strengths and stiffnesses than those permeated without a delay at a similar grout intake.

INTRODUCTION

Grouting is not a new "transforming" technology although recent advances in materials used and field equipment has transformed its applications and effectiveness. Early applications of grouting bedrock underlying dams dates to as early as the 1800s (Warner, 2004). The solutions were constituted of aqueous suspensions, with consideration to maximum particle size versus discontinuity/fissure width. However, it was quickly understood that particulate grouts are of limited success upon permeating soils (Warner, 2004). Particulate grouts are limited by filtration; a phenomenon that occurs due to the clogging of the pores in the soil as more and more of the suspension solution is permeated (Yoon and El Mohtar, 2015). Filtration will limit the radius of the treatment, particularly for soils with smaller particle sizes (and therefore, void size), which can limit the cost-effectiveness of grouting. For such soils, the grouting community often opt for chemical grouts: aqueous solutions that penetrate the soil and gel at a later stage. While chemical grouts do not provide the same level of high strength as cementitious grouts, they can be very effective in reducing permeability and reducing groundwater flow problems (Powers, 2007; Guyer, 2015).

As demand for lower viscosity grout that gels or hardens upon placement arouse, Jeziorski, in 1897, developed a solution via sodium-silicate combined with an organic setting agent in a one-shot rapid injection process (Warner, 2004). problems arose because of the almost instantaneous gelling of the grout, limiting penetration distance as well as clogging the grouting equipment. It was quickly understood that some delay to start of gelation is required, and this time must be both, adjustable and practical. Hugo Joosten proposed his two-shot Joosten process in 1925. The first stage included the injection of “water-glass” better known as sodium silicate into the ground, followed by a second stage of strong brine injection to result in an almost instantaneous gelation (LittleJohn, 1985). Calcium chloride was the common inorganic setting reagent that neutralized the sodium and precipitated the silica. The Joosten process was used until the late 1960s and idealized as one of the first successful processes in the world of grouting, initiating its modern era (Karol, 2003).

Chemical grouting is often used to increase the strength of the soil, along with its initial stiffness. This increase in strength is attributed to the individual soil particles being glued together by the chemical adherence property; an internal force restraint phenomenon (Schiffman & Wilson, 1956). Many researchers (Schiffman & Wilson, 1956; Diefenthal et al., 1979; LittleJohn, 1985; Dano et al., 2004; Ortiz, 2015) have concluded that the gel matrix adds cohesion to the strength of the soil, but the internal friction angle of the material remains unchanged. This warrants characterizing grouted sands by the less costly unconfined compression test (Christopher et al., 1989). The most basic products often used in chemical grouting are alkali silicates, sodium silicate being the predominant form in all ground chemical grouting work (Tallard & Caron, 1977; PQ Corporation, 2003; PQ Corporation, 2004). Sodium silicate is a chemical product consisting of silica, sodium oxide, and water (Xue, 2018). The compound is of tetrahedral structure, with the presence silicic chains on a tridimensional network having a solid macroscopic structure with silica as a basic atom (Tallard & Caron, 1977). The process by which a sodium silicate grout gels in the soil matrix is attributed to polymerization or precipitation, where organic and inorganic reactants are used to neutralize the silica respectively (Krumine & Boyce, 1985).

In this paper, the performance a commercial N-sodium silicate (N is the grade based on SiO_2:Na_2O ratio) grout neutralized by dibasic ester is evaluated. Particularly, this paper focus on the impact of the number of pore volumes permeated and grout permeation time (relative to gelation time) on the strength of the grouted sand. Two grouts with different gelation times were used in this study and the specimens were permeated with different number of pore volumes (1-9). The permeation process was initiated either right after mixing or after a delay such that the permeation is concluded at the onset of gelation. Unconfined compressive strength tests were then performed on the specimens after their extraction to characterize the effect of sedimentation and filtration mechanisms during and post grouting (but prior to gelling).

Materials and Experimental Setup

Sodium silicate, tap water, dibasic ester, white vinegar, and Tergitol NP-9 were used in generating the different grout mixes used in this study. A commercially available sodium silicate was used in this study with an alkali silica ratio of 2.6-3.2 and pH of 11-12. Tap water was used to prepare the grouts along with Hill Country Fare distilled white vinegar with 5% acidity. Brenntag Dibasic Ester solution and Brenntag Surfactant NP-9 were used as well to modify the mixes properties. The grouts were prepared by mixing the sodium silicate with water first, then adding to it the premixed Tergitol NP-9, dibasic Ester and white vinegar. Two mixes (AA and T1) were used in this study. Table 1 shows the percentages of the different components of each mix.

Table 1: Mixes Used in the Testing Series

Table 1: Mix Proportions by Volume					
Mix	N-Sodium Silicate (%)	Tap Water (%)	Dibasic Ester (%)	Tergitol NP-9 (%)	Vinegar (%)
AA	50.00	31.23	6.14	0.14	12.50
T1	50.00	35.73	6.14	0.14	8.00

Ottawa ASTM C778 graded sand was used in this study. The sand is poorly graded with a D10, D30 and D60 of 0.2, 0.32 and 0.4 mm, respectively. The sand was used to prepare 6in long and 2.8in diameter specimens in the permeation setup shown in Figure 1. The setup consisted of a 6in split mold with 1.5in sections below and above it. A coarse and fine aggregate was used for the filter material at the top and bottom of the sand specimen to ensure uniform flow of grout across the whole area of the specimen. The column was first flushed with water (three pore volumes) and then the grout was permeated using a constant flow pump while the pressure buildup at the base of the column was monitored.

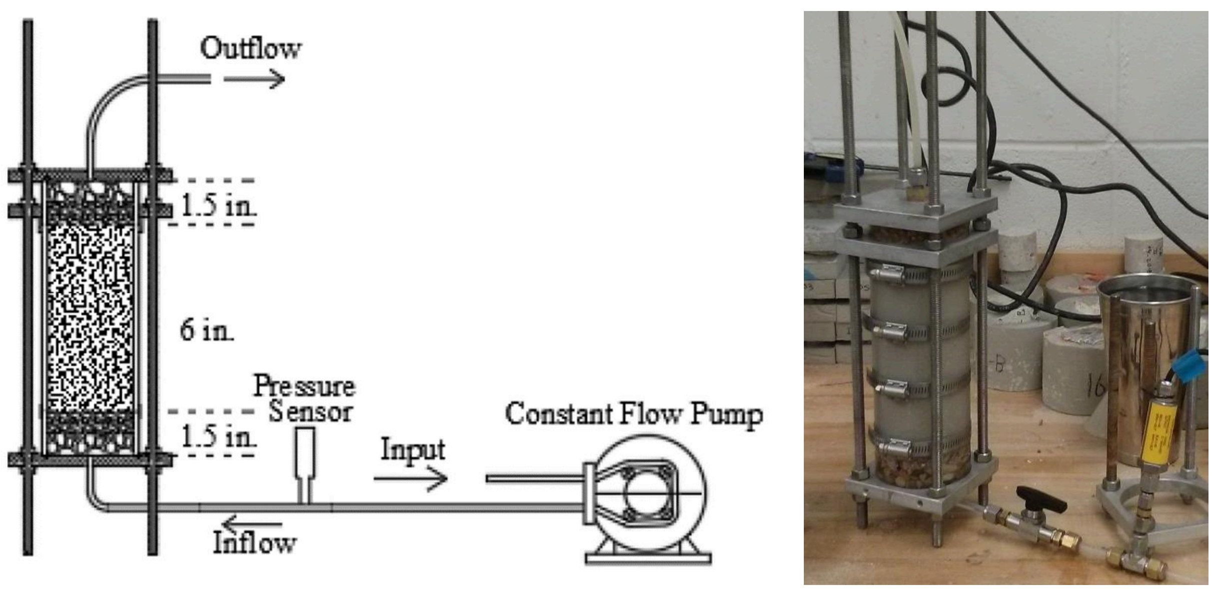

Figure 1: Permeation setup for preparing 6-inch Specimens

The grouted sand is kept in the permeation mold for 24 hours after which it is extracted, end trimmed square to the longitudinal axis of the specimen and the trimmed specimen is weighed and its height and dimeter measured before being sheared under unconfined compression at a rate of 1% per minute.

An advanced rheometer Physica MCR 301 by Anton Paar was used with cone and plate configuration and with the hood on to preserve the mixture moisture. A small amount of grout was injected using a syringe from the mother batch onto the plate, and the top conical plate was lowered to 0.093 mm squeezing the excess grout. This excess was carefully removed and