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Concrete Grinding Residue: Its Effect on Roadside Vegetation and Soil Properties

Halil Ceylan, Principal Investigator
Institute for Transportation
Iowa State University

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16. Abstract (Limit: 250 words)

Concrete grinding residue (CGR) is a slurry waste consisting of water and concrete fines generated from diamond grinding operations that is used to smooth a concrete pavement surface. During this process, CGRs are mostly disposed along the roadside, which can influence soils and plant communities along the roadways. To understand the effects of CGR on soil physical and chemical properties and plant growth, a controlled field site at the Kelly Farm in Iowa was used with CGR application rates of 0, 10, 20, and 40 dry ton/acre to test properties of soils and plants before the application and one month, six months and one year after the CGR application. Two roadsides along Interstate 90 in Minnesota where CGR material was applied in the past were investigated as well. Laboratory and field experiments were conducted to measure plant biomass, bulk density, hydraulic conductivity, infiltration, pH, electrical conductivity (EC), alkalinity, metals, cation exchange capacity (CEC), exchangeable sodium percentage (ESP), and percentage base saturation (PBS) of soil samples collected from the test sites. Statistical analyses were conducted to correlate the CGR additions to the properties of soils and plants. The results of statistical analyses from the Kelly Farm indicated that CGR material did not significantly affect soil physical properties and plant biomass but impacted the chemical properties of soil. Changes in some soil properties such as pH and percent base saturation (PBS) due to CGR did not persist after one year. The results from two Minnesota roadsides indicated that the areas receiving CGR applications in the past did not negatively affect soil quality and plant growth.

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FINAL REPORT

Prepared by:

Halil Ceylan
Yang Zhang
Bora Cetin
Sunghwan Kim
Bo Yang
Chenyi Luo
Robert Horton
Kasthurirangan Gopalakrishnan
Institute for Transportation
Iowa State University

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

BACKGROUND

Diamond grinding of Portland Cement Concrete (PCC) pavement is a maintenance operation carried out to remove surface irregularities on concrete surface ultimately improves the ride quality and longevity of concrete pavement systems. During grinding operations, water is introduced to cool the diamond blades that combined with cutting residue generates a high pH and high alkaline slurry byproduct referred to as Concrete Grinding Residue (CGR). Currently, the spreading of CGR along roadsides is one of the most commonly used disposal methods, and there is potentially a large number of ongoing /forthcoming Minnesota Department of Transportation (MnDOT) construction projects to adopt this method to place CGR slurries along Minnesota roadsides. However, the spreading of CGR along roadsides not only can lead to reduced density of vegetation but can also alter the covering percentage of each plant species, all of which have the potential to increase maintenance costs. To gain a stronger understanding of CGR effects on soil properties, such as water infiltration and vegetation growth, an in-situ, statistically rigorous evaluation was conducted to assess soil and vegetation properties before and after the placement of CGR.

SUMMARY

Iowa State University (ISU) researchers established a one-year study to evaluate the effects of CGR on soil and vegetation properties. This study consisted of two field experiments: (1) the first one was conducted by using a controlled field experimental site at the Kelly Farm located in Boone, IA, and 0, 10, 20, and 40 dry ton/acre of CGR were applied. The influences of CGR on soil and plants before and one month, six months and one year after CGR application were evaluated in this site; (2) the second field study was conducted on two roadside fore slopes of I-90 highways in Austin, MN, (Site 1 and 2) in November 2016 in which CGR slurries were offloaded in 2009 and 2013, respectively. The properties of soils and plants that received CGR were measured and compared with adjacent soils and plants that did not receive CGR. For the study conducted at the Kelly Farm, CGR with pH of 11.7 collected from Apple Valley, MN, was applied on the soil on October 16, 2016. The results showed that the application of CGR did not significantly influence plant biomass and soil physical properties including bulk density, hydraulic conductivity, and infiltration, but plant growth for the warm-seasoned grasses and the legumes were promoted at 10 and 20 ton/acre levels of CGR. The results of chemical properties of soils indicated that soil pH, electrical conductivity (EC), alkalinity, content of metals (calcium, potassium, magnesium, sodium) and cation exchange capacity (CEC) were significantly elevated after additions of CGR, and the effects of CGR were increased with an increase in CGR rate and decreased with an increase in soil depth. However, the impacts of CGR on soil pH did not persist after one month. Although soil chemistry was altered due to the application of CGR, these changes did not negatively affect plant growth (Scott, 1985; Scott, 1986; DeSutter et al., 2011; Waskom et al., 2014). Therefore, the findings from the Kelly Farm site indicated that the application of slurry rate up to 40 ton/acre did not show negative impacts on soil properties and vegetation. The field study at the two Minnesota roadsides exhibited different results between each roadside. For example, soil bulk density and hydraulic conductivity in the CGR areas did

not significantly differ from the non-CGR areas at Site 1, but at Site 2 the differences were significant. For the other properties, such as EC, CEC, content of calcium, and percent base saturation (PBS), the CGR areas led to larger values than the non-CGR areas in general. The results from the Minnesota roadsides indicated that the application of CGR did not negatively affect roadside soil and vegetation growth long-term (over three years). Based on the findings from the Kelly Farm site and the Minnesota roadsides, spreading up to 40 ton/acre CGR along roadsides did not cause reductions in soil quality and vegetation growth. However, these results cannot be generalized because CGR compositions can vary considerably depending on the concrete source and water quality, resulting in different changes in soil properties and vegetation. In considering this issue, ISU researchers recommend MnDOT develop some quick field measurements regarding pH, EC and alkalinity of CGR to adjust CGR spreading rates during grinding operations.

CHAPTER 1: INTRODUCTION

Diamond grinding of Portland Cement Concrete (PCC) highway surfaces, a maintenance operation carried out to extend the pavement service life, generates a high-pH and high alkalinity slurry (water, concrete and aggregate residue), referred to as Concrete Grinding Residue (CGR). Based on the particle size distribution analysis, silt-sized particles were the major constituent of the CGR samples. The long-term impact of CGR slurry on soil properties (for example infiltration, etc.) and vegetation needs to be investigated. In terms of a number of ongoing/forthcoming MnDOT construction projects to place CGR slurries along MN roadsides, there are potential environmental and economic implications. For instance, disposal of slurry along the "sensitive" areas not only can lead to reduced density of vegetation resulting in erosion problems but can also alter the covering percentage of each plant species, especially for those that prefer open, well drained soils, all of which have the potential to increase maintenance costs.

A better understanding of the potential soil chemistry impacts resulting from the application of CGR slurry may indicate preemptive soil amendments. Some previous studies have focused on investigating the influence of CGR slurry on soil pH and soil water infiltration rates in laboratory settings. The objective of this proposed research is to gain a stronger understanding of the CGR effects on soil, water infiltration and vegetation through an in-situ, statistically rigorous study that analyzes in slope and/or back slope soil samples and assesses soil and vegetation properties before and after placement of the CGR.

Investigating the influences of CGR slurry applications on soils and vegetation through a comprehensive in-situ study covering a range of soil and associated plant types in Minnesota can lead to a stronger understanding of the potential soil chemistry and vegetation changes and a number of envisioned benefits including a reduction in maintenance costs. The ultimate question addressed by this research is whether this construction practice has a long-term effect on roadside vegetation, soil quality, and water infiltration.

Based on the study findings, the key benefit to state highway agencies (SHAs) and related industries is to guide pavement and geoenvironmental engineers with CGR slurry offloading or placement and disposition practices.

CHAPTER 2: LITERATURE REVIEW AND EXPERIMENTAL PLAN

2.1 LITERATURE REVIEW RESULTS AND FINDINGS

2.1.1 Properties of Concrete Grinding Residue

Holmes and Narver (1997) analyzed CGR slurry from a surface grinding operation. In order to isolate the impact of concrete residue, the chemical properties of the fresh water used in the concrete grinding operation were analyzed. Even though the leachates prepared from concrete (i.e., Portland cement concrete) were considered to be of moderate to high toxicity, the concrete residue showed no toxicity based on the 96-hour Acute Toxicity test. Volatile organic compounds in the solid phase and the liquid phase did not reach detection limits. However, semi-volatile compounds were detected in the liquid phase of the samples. The concentration of oil, grease and total petroleum hydrocarbon (TPH) in all the samples were beyond the detection levels. The cation and anion concentrations of Al, Fe, SO_4, NO_3/NO_2 exceeded the California Drinking Water Standard.

DeSutter et al. (2010) and DeSutter et al. (2011) obtained CGR slurry samples from multiple sites representing various geographical distributions in the United States, including I-10 near Los Angeles, CA; I-94 near Fergus Falls, MN; Highway 75 near Elkhorn-Bellevue, Nebraska (NE) ; I-82 in the state of Washington (WA) and I-69 in the state of Michigan (MI). Solution phases and solid phases of the CGR slurry samples were analyzed. The pH of the CGR slurry ranged from 11.6 to 12.5. Regarding the liquid phase, As, Ba, Cd, Cr, Pb, Se and Ag concentrations were below the toxic limits. The concentration values of the toxic elements in slurry solid phase were smaller than the values reported for surface soil at the sample locations, indicating the CGR slurry was not the dominant containment of the soil. None of the 16 polynuclear aromatic hydrocarbons (PAHs) were detected.

Mamo et al. (2015) reported that pH values of reconstituted slurry were 9 to 10. Effective Calcium Carbonate Equivalent (ECCE) and K, Ca, Mg, Na were measured. Heavy metals, such as Hg, As, Se, were below the detection levels, while all of the heavy metals were below the hazardous thresholds.

Other researchers also reported similar results regarding the properties of concrete residues. For example, in concrete residue recycling, Goodwin and Roshek (1992) reported the pH of concrete residues from multiple sources were within the range of 12.0 to 12.6. Yonge and Shanmugam (2005) reported that pH values of slurry in the state of Washington ranged from 11.9 to 12.1 in a slurry neutralization experiment. Hanson et al. (2010) reported that pH values of CGR samples from the state of Washington were 10.2 and 10.9. Druschel et al. (2012) reported several concrete residue properties, including the CGR slurry in MN in their research of concrete wastewater and best management practices project. The pH of a reconstituted slurry sample was 9.4, and the particle size characterization was silt-sized or finer. Chini and Mbwambo (1996) reported the pH values in concrete wastewater samples as 11 to 12. Sulfates, hydroxides, chlorides, as well as small quantities of both hydrocarbons and admixture compounds were also found in the concrete wastewater.

2.1.2 Soil and Plant Responses to CGR Application

In the study by Yonge and Shanmugam (2005), a long term (6 to 10 years) slurry effect on soil pH was characterized. The pH values of soil without CGR slurry were 6.3 to 7.2; while the pH of soil with CGR slurry increased by 1 to 2 units. The concentrations of Pb, Cu, Zn and Cd were measured at a range of soil depths, and there were no significant differences between the soil background values and the values of soil in slurry disposal areas. However, the concentrations of Mg and Ca were increased due to the slurry application.

Wingeyer et al. (2013) reported that after a four-week period after the application of slurry (9 kg/m^2), soil pH increased by 0.11 unit compared to the control site and soil EC also increased. Compared to the control site, there was a significant decrease in Mg and K in the 0-20 cm soil layer. Exchangeable Na levels in the 0-20 cm layer increased due to CGR application. Exchangeable Ca increased in 0-10 cm layer compared to the control site. The botanical composition of treated plots was not affected by the slurry. Ground cover of slurry-treated plots was similar to the control.

DeSutter et al. (2010) studied the influence of slurry on infiltration. The infiltration time of soil with slurry was shorter than the soil without slurry, contradicting the results reported by Favaretto et al. (2006). However, the differences of infiltration time were not significant for all of the soil types. DeSutter et al. (2011) reported the short term (99 days) soil and plant responses to CGR slurry. The shoot growth was promoted for low slurry rates, while it was inhibited for high slurry rates. The metal concentrations in plant shoots, such as Ca, Mg, K, Na, Cr, Pb, Sr, were influenced by the soil, CGR, CGR rate and its two way interactions. Soil pH after CGR application was greater than soil without CGR, while electrical conductivity (EC) was increased significantly only for relatively high CGR rates. The concentration of non-trace metals and trace metals were also significantly influenced by CGR applications; however, the influences were due to the main effect of soil type, CGR and CGR rate or the two-way interactions based on the type of metals.

Mamo et al. (2015) studied both short term (1 month) and long term (1 year) effects of slurry on soil chemical properties and the biomass of the plant cover. Two research sites were included, i.e., NE State HWY 31 MM36 and NE State HWY 31 MM 34. Slurry, depth and slope were the three factors considered in the study. Slurry, slope, depth and slurry-depth interaction were the most important factors affecting the soil pH, EC, K, Ca, Mg and Na for the first month after slurry application. After a one-year period, slurry effects were not significant. The runoff total volume, runoff fraction, pH, EC, total suspended solids (TSS) were not affected by the slurry. The aboveground biomasses of the two sites were measured at one month and one year among different treatments. For NE State HWY 31 MM36, the differences of biomass between seeded and non-seeded species was enlarged one year after the slurry application. The slurry-slope interaction had a significant effect on the biomass of seeded species after one month and one year. In Nebraska State HWY 31 MM 34, the one-month biomass response to the slurry application was not significant.

2.1.3 Best Management Practice of CGR Application

CGR slurry from diamond grinding may be highly alkaline, and carry silica, cadmium and other pollutants to soil and nearby water bodies. Thus, developing the best management practice was required.

CGR slurry application rates are currently regulated by states. In Nebraska, the disposal of slurry should meet the National Pollutant Discharge Elimination System (NPDES) permit (NDEQ, 2010; Mamo et al., 2015), which estimates the application rate based on the agronomic rate. Another kind of restriction is used in the States to dispose CGR at a specific location, such as a containment pond, in California (California DOT, 2010).

Besides the limitation of application rate, there are sophisticated ways to control the influence of CGR on roadside soil, water and plants. For example, Yonge and Shanmugam (2005) recommended to use Washington State University Compost or EKO to neutralize the pH of slurry. Slurry collection and plant processing is another way to control any storm water runoff with slurry using some pre-designed plant belt (Druschel et al., 2012).

In MN, the disposal of CGR slurry along the roadside is regulated by the Minnesota Pollution Control Agency (MPCA, 2012). In rural areas, the slurry can be deposited in the in-slope side of vegetated areas, at least 1 foot from the shoulder. The slurry should be vacuumed from the roadway and spread evenly on the roadside. The hydrological connection between the deposited slurry and the outer area should be minimized, i.e., the in-slope should be 3:1 or flatter and the deposited slurry should be discharged at an acceptable rate which will not allow it to reach the wetting perimeter of the highway ditch. Wetlands or other sensitive areas should be avoided during the slurry depositing. Slurry depositing should be well prepared and monitored during the diamond grinding process.

2.2 EXPERIMENTAL PLAN DEVELOPMENT

2.2.1 Controlled Field Experiment

The Kelly Farm located at 1119-1149 XL Ave, Boone, IA (Northwest of Ames, IA) was chosen as the site for a CGR controlled field experiment where a field study was conducted to quantify the influence of CGR slurry on soil and plant properties. The research site has about a 6% slope in the southeast direction.

The total area of the Kelly Farm site is 196 m^2 divided into 16 (4 by 4) plots, as shown in Figure 1. Each plot is a 2 m (6.56 ft.) by 2 m area and the distance between any two adjacent plots is 2 m. CGR slurry was applied onto the 16 sites at 4 different rates (dry slurry weight/area), i.e., A = control (0 ton/acre), B = 2.24 kg/m^2 (10 ton/acre), C = 4.48 kg/m^2 (20 ton/acre), D = 8.96 kg/m^2 (40 ton/acre). Since 32 individual buckets of concrete slurry were obtained from the first MN field trip, and because there was a possibility of different slurry content in each bucket, Iowa State University (ISU) researchers mixed all slurry together in a single tank to obtain a homogenous mixture, then put the mixed slurry of identical weights and solid content amounts back in the buckets. The source from which the slurry was obtained did not provide detailed information such as concrete constituents about this concrete. To document this information, ISU researchers conducted the X-ray fluorescence (XRF) study to determine the constituents of the slurry applied at the Kelly Farm. The detailed results and discussions on XRF study are presented on Table 4 in chapter 4.

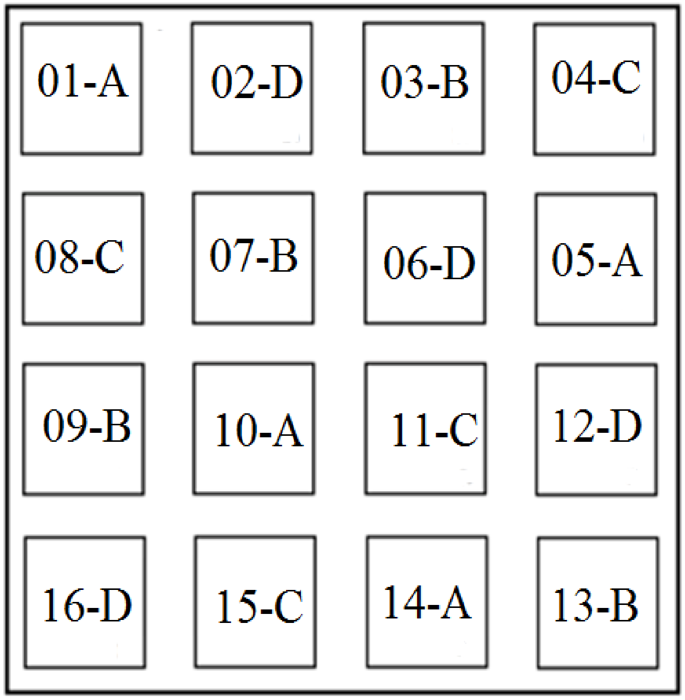


Figure 1. The layout of treatments at the Kelly Farm. The research site has about a 6% slope in the southeast direction.

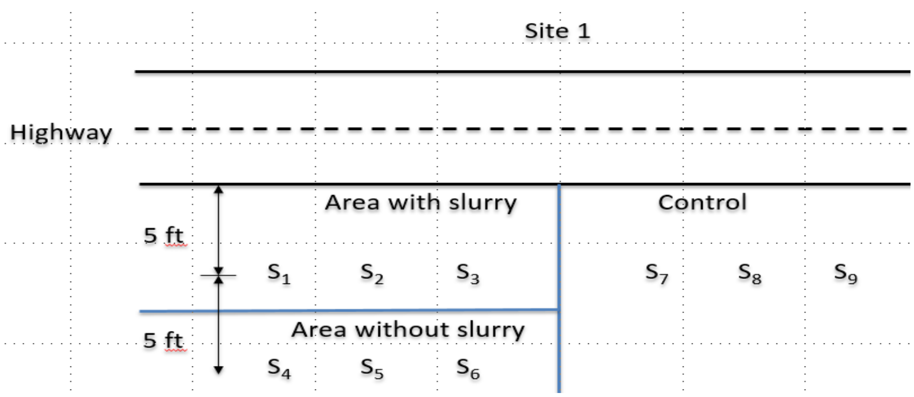
A plant species investigation was performed at the site prior to establishing the controlled field experiment. Vegetation at the research site included cool-seasoned grasses (e.g., Canada wild rye, Virginia wild rye), warm-seasoned grasses (e.g., Indian grass, Switchgrass,), forbs (e.g., Showy golden rod, Heath aster, Common Milkweed, Wild Bergamot, Smooth blue aster, Queen Anne's lace, Cup plant, Maximilian sunflower), and legumes (e.g., Wild white indigo, Crown vetch).

Field measurements were performed on vegetation biomass, soil bulk density, soil saturated hydraulic conductivity, soil water infiltration and soil chemical properties (soil pH, soil EC, soil alkalinity, cation exchange capacity (CEC), exchangeable sodium percentage (ESP) and percent base saturation (PBS)). Each plot was divided into four quarters, one for plant investigation and sampling, one for infiltration, and one for soil sampling; a final quarter of the plot was reserved for any additional tests. For each plot, three 7.62 cm (3 in.) by 7.62 cm soil cores (the upper and lower surfaces were marked and the vegetation on both surfaces were clipped) were taken near the soil surface using aluminum rings and a soil sampler. The samples were covered with aluminum film, sealed with electrical tape, and stored in plastic bags. Single 7.62 cm soil samples at soil surfaces were taken using a soil probe, then stored in aluminum soil cans for soil water content measurement. Three 0-10.16 cm (0-4 in.), 10.16-20.32 cm (4-8 in.), and 20.32-30.48 cm (8-12 in.) soil probe samples were taken from each plot for the chemical measurements. Single plant biomass samples were also taken at the same time. A Cornell Sprinkle infiltrometer was used for the infiltration measurements in each plot. Compared to the traditional ponded infiltration method, the Cornell Sprinkle Infiltrometer is better at simulating natural rainfall runoff-infiltration conditions. In addition, the Cornell Sprinkle Infiltrometer does not create a persistent ponded water condition on the soil surface. The Cornell Sprinkle Infiltrometer is an advanced method that can represent water infiltration under artificial rainfall conditions.

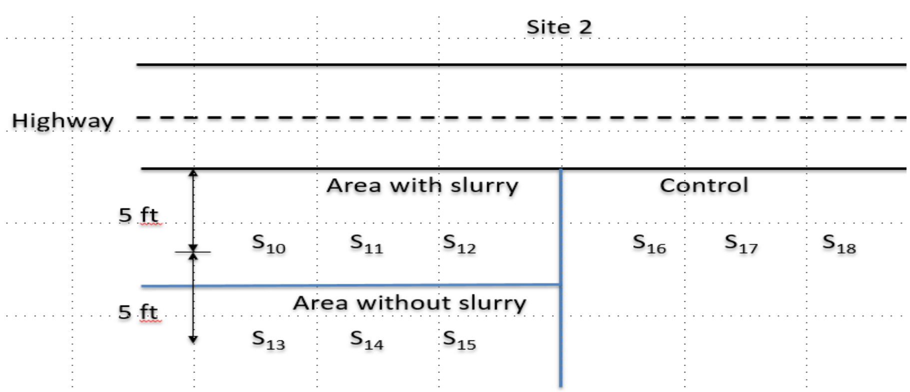
Measurements of initial soil and vegetation properties were conducted from 8 to 14, October 2016 before the slurry application, for one month (11 to 16 November 2016), six months (13 to 16 May 2017), and one year (in October 2017) after the application of slurry to monitor changes in soil and vegetation properties.

2.2.2 Roadside Experiment

Roadside experiments were performed at two sites (where CGR was previously offloaded) along I-90 near Austin, MN. The locations were at 43°40'N, 93°53'W (Site 1) and 43°43'N, 92°40'W (Site 2). The sampling points at each site are shown in Figure 2.



(a)



(b)

Figure 2. The sampling points at the Minnesota roadsides (a) Site 1 and (b) Site 2.

ISU researchers conducted several field trips in MN to collect soil samples from Site 1 and Site 2. For Site 1, S1, S2 and S3 were the sampling points in the slurry offloaded area; S4, S5, S6, S7, S8 and S9 were the sampling points in the area without slurry (control group). For Site 2, S10, S11 and S12 were the sampling points in the slurry offloaded area; S13, S14, S15, S16, S17 and S18 were the sampling points in the area without slurry (control group). In total, 18 sampling points were taken for the roadside experiments. The biomass measurements, soil bulk density samples, soil hydraulic conductivity samples, soil chemical samples (same measurements as at the Kelly Farm) and infiltration measurements were taken at each of the 18 sampling points.

CHAPTER 3: FIELD VISITS, SOIL SAMPLING, AND LABORATORY TESTS

3.1 MINNESOTA FIELD VISTIS

3.1.1 The First Minnesota Field Trip

ISU researchers made their first MN field trip to 6078-6216 McAndrews Road, Apple Valley, MN, on August 24, 2016 (Figure 3). The purpose of this trip was to collect CGR material from an ongoing concrete pavement diamond grinding project (Figure 4). During this field trip, 32 of 5-gallon buckets were used to obtain the CGR slurry samples. The CGR from the diamond grinding machine was first transported to a hauling truck next to the grinding machine; each bucket was filled with CGR from the hauling truck. All of the samples were moved to ISU for the application at the Kelly Farm experimental site.

Figure 3. The diamond grinding project in Minnesota.

Figure 4. The collected CGR material from the first Minnesota field trip.

3.1.2 The Second Minnesota Field Trip

Table 1. List of properties measured on samples from the second Minnesota field trip.

Measurements	Number of Samples
Bulk density	9
Saturated hydraulic conductivity	9
Chemical analysis	27
Infiltration & runoff (Field measurement)	9
Biomass	9
Sum	63

ISU researchers made the second field trip to Austin, MN on November 1, 2016. Slurry from roadside sites near Austin along highway I-90 (State Project 5080-159 (I-90)) was offloaded during the period of September-November 2014 (Site 1). The objective of this field trip was to measure physical and chemical properties of above-ground biomass in multiple existing concrete residue slurry roadside areas and to perform comparative sampling measurements in areas not experiencing slurry offloading. The tests were similar to those at the Kelly Farm experimental site in IA. During this field trip, ISU researchers conducted infiltration tests at the six locations (S1 to S6) marked in Figure 2 (a), and collected biomass samples and soil samples from all nine locations for physical and chemical property measurements. To ensure that the soil at S1, S2 and S3 had received CGR slurry, and S4, S5 and S6 had not, surface soil samples were taken and visual inspections were made. The CGR slurry was visible as a material with light color (grayish white), so the CGR material was easily distinguished from dark soil particles. Light-colored materials were visible in the soil from the CGR-affected area; while the soil from the non-CGR area had a dark, homogeneous color. Samples for chemical measurements at each sampling location were collected at different depths, 0-10.16 cm (4 in.), 10.16-20.32 cm (4-8 in.), and 20.32-30.48 cm (8-12.). All testing data are listed in Table 1.

3.1.3 The Third Minnesota Field Trip

Table 2. List of properties measured on samples from the third Minnesota field trip.

Measurements	Number of Samples
Bulk density	21
Saturated hydraulic conductivity	21
Chemical analysis	27
Infiltration & runoff (Field measurement)	9
Biomass	9
Sum	87

The third field trip was to the east of Austin, MN, on November 17, 2016. During this field trip, ISU researchers investigated additional roadside sites along I-90, starting at Exit 193. This site also had slurry offloading, but its application was during 2013. The project number for this site east of MN 16 was State Project 5080-162 (I-90). The purpose and experimental plan of this field trip were like those for the second visit and are shown in Figure 2 (b). ISU researchers conducted field tests, biomass collection, and soil sampling at this site as before. However, the number of samples was increased as shown in Table 2, i.e., repeats were performed on each sampling location to reduce the effects due to random error. Such sampling design was based on the data analysis of the second Minnesota field trip.

3.2 EXPERIMENTAL MEHODOLOGY

To investigate the effects of CGR on soil properties and plant growth, the experimental plan was separated into plant species investigation, soil physical properties measurements and chemical properties measurements. Plant species investigation was conducted only at the Kelly Farm. Soil samples and biomass samples collected from the Kelly Farm and the MN sites were investigated through the same physical and chemical measurements.

3.2.1 Plant Measurements and Soil Physical Tests

3.2.1.1 Plant Species Investigations and Biomass Measurements

The plant identification at the Kelly Farm research site were made in a 50 cm by 100 cm quadrat near the northeast corner of each plot. The percentages of spatial cover of each plant species were observed and estimated using the scale 1%, 1-5%, 5-25%, 25-50%, 50-75%, and 75-95%. The plant cover percentage values represent the ratio of the plant canopy area to the quadrat area. Since the plant canopy had multiple layers, the sum of the cover percentages within each quadrat was larger than 100%. Results were recorded for each species and each plant type. A set of sample data is shown in Figure 5.

Plant Classification	Plant Name	1	2	3	4	5	6	7	8
legume	*Astragalus canadensis*								
legume	*Chamaecrista fasciculata*		25-50%		1-5%		5-25%		
legume	*Lespedeza capitata*	1-5%							
legume	*Securigera varia*	25-50%	25-50%						
non-legume forb	*Arctium minus*			1-5%					
non-legume forb	*Achillea millefolium*			0-1%				0-1%	
non-legume forb	*Aster ericoides*	5-25%					25-50%	25-50%	5-25%
non-legume forb	*Aster laevis*		1-5%						
non-legume forb	*Aster pilosus*			1-5%		0-1%		0-1%	
non-legume forb	*Cirsium altissimum*			5-25%					
non-legume forb	*Cirsium arvense*								

Figure 5. Sample data sheet for plant species investigations.

After the first plant identification, the plants at the research site, inside each plot, were mowed on October 5, 2016 to a height of 30.48 cm (12 in.) in order to simulate the plant height on the roadside when CGR was applied. The following figure (Figure 6) shows an example sampling area for biomass measurements. A 20 cm by 50 cm quadrat was used for sampling biomass near the plant identification area. Photos were taken for each sample, the aboveground part of the green vegetation was clipped and stored in paper bags, and the samples were oven-dried at 65 ^{o}C for four days as following the methods described in the previous study (García, et al., 1993). The weights of oven-dried biomass samples were measured.

Figure 6. Example sampling area of biomass measurements.

3.2.1.2 Saturated Hydraulic Conductivity

The lower surface of each soil core was sealed using cheesecloth and electrical tape, and the soil was saturated from the bottom with 0.05 mol/L of $CaCl_2$ solution using a vacuum pressure chamber. After soil saturation, approximately 5 cm of ponded water was maintained on the soil surface using a Marriott bottle. Outflow flow rates were measured with a graduated cylinder and a stopwatch. The inner diameter of the cylindrical column (D), the soil length (L), and the ponded depth (P) were measured. The vacuum chamber is shown in Figure 7 (left), and the experimental setup for saturated hydraulic conductivity is shown in Figure 7 (right).

Figure 7. Vacuum chamber (left) and hydraulic conductivity measurement (right).

The saturated hydraulic conductivity (K_s, m/s) was calculated using the following equation.

$$K_s = \left(\frac{Q}{At}\right)\frac{L}{H}$$

Where $A = \frac{\pi}{4} D^2$ is the soil cross-sectional area (m^2); Q is the volume of outflow (m^3) with time interval (t); H=L+P is the total hydraulic head (m) (Klute, 1965).

3.2.1.3 Soil Bulk Density and Water Content Measurements

The soil cores used for saturated hydraulic conductivity measurements were also used to determine bulk density (ρ_b, Kg/m^3). Solid was transferred in 7.62 cm (3 in.) by 7.62 cm (3 in.) soil cores from the aluminum ring to aluminum cans that were weighed (M_{can}, kg) before use. The samples were oven-dried at 105 °C for multiple days and the weight of soil plus that of the aluminum cans were measured every 24 hours until the weight became constant (M_{final}, kg), i.e., the difference between two consecutive measurements fell within 0.1 g. The bulk density was calculated with the following equation (Blake, 1965).

$$\rho_b = \frac{M_{final} - M_{can}}{V}$$

Where $V = \frac{\pi}{4} D^2 L$ represents the volume of the soil core.

7.62 cm (3 in.) soil probe samples were used for soil water content measurements. The mass of aluminum can (M_{can}, kg) was weighed immediately before sampling, and the samples were placed into cans and weighed immediately ($M_{initial}$, kg) to determine the mass of wet soil plus can. The samples were then oven-dried at 105 ℃ for multiple days. The weights of soil plus aluminum cans were measured every 24 hours until they became constant (M_{final}, kg), and the water content values were calculated with the following equations (Gardner, 1965).

$$\theta_g = \frac{M_{final} - M_{initial}}{M_{final} - M_{can}}$$

$$\theta_v = \theta_g \frac{\rho_b}{\rho_l}$$

Where θ_g (kg/kg) represents the gravimetric water content; while θ_v (m^3/m^3) (the unit should be "(m^3/m^3)") is the volumetric water content. ρ_l (kg/m^3) is the liquid water density.

3.2.1.4 Soil Water Infiltration Measurement

The Cornell Sprinkle infiltrometer system consists of a rainfall simulator placed on a single 24.1 cm (9.5 in.) inner diameter infiltration ring. The rainfall rate can be controlled using the simulator, and the surface runoff can be collected from the infiltration ring (Van Es and Schindelbeck, 1997; Ogden, et al., 1997).

To perform the experiment, an infiltration ring was first inserted into the soil until the lower point of the runoff hole matched the soil surface, with the upper edge of the infiltration ring kept in a horizontal orientation. The rainfall simulator was positioned on a stable flat surface and filled with water, and then the large rubber stoppers were removed, allowing water to pour into the rainfall simulator. The stoppers and air-entry tube into the rainfall simulator were then reinserted. The rainfall simulator was placed on the infiltration ring and a Tygon tube was inserted into the runoff hole and connected to a beaker to collect surface runoff. The experimental setup is shown in Figure 8.

The height of the water surface in the rainfall simulator was recorded (H_0, cm) before infiltration measurements started, then the air-entry tube was opened and a stopwatch started. The outflow tube was monitored until runoff occurred, at which point the time (T_{ro}, min) was recorded. For each 3-minute interval, the runoff quantity was measured using a graduated cylinder ($\mathrm{V}_{t(i)}$, ml), and the water surface height ($\mathrm{H}_{(i)}$, cm) and time ($\mathrm{T}_{(i)}$, s) were recorded, while i represented the index of each runoff measurement, $i = 1,2,3, \ldots$. After the runoff became stable, i.e., the $\mathrm{V}_{t(i)}$ was identical for at least 5 consecutive measurements, the infiltration measurements were terminated. To stop the infiltration, the air entry tube was closed and the final water surface height ($\mathrm{H}_{(n)}$, cm) in the rainfall simulator and the time ($\mathrm{T}_{(n)}$, s) were recorded. Runoff was collected until the last drop (V_f, ml) occurred and the corresponding time (T_f, s) elapsed.

The infiltration values were calculated. The simulated rainfall rate ($\mathrm{r}, \mathrm{cm/min}$) was determined by

$$r = \frac{\mathrm{H}_{(1)} - \mathrm{H}_{(n)}}{\mathrm{T}_{(n)} - \mathrm{T}_{(1)}}$$

The runoff rates ($\mathrm{r}_{\mathrm{out}}, \mathrm{cm/min}$) were determined by

$$r_{out(i)} = \frac{V_{t(i)}}{457.3 \times \left(T_{(i)} - T_{(i-1)}\right)}$$

Where 457.3 is the area of the ring, and $T_{(i)} - T_{(i-1)}$ is the time interval for runoff water collection. Infiltration rates ($I_{(i)}$) are the differences between the rainfall rate and the runoff rate.

$$I_{(i)} = r - r_{out(i)}$$

For the last 3-5 repetitions, the surface runoff values were stable, and their mean value was taken as the experimental runoff, the same was done for the infiltration rate. T_{ro} was related to initial soil water conditions and the rainfall rate, r. Sorptivity (S), a more universal soil hydraulic property that describes early infiltration independent of rainfall rate, was estimated using the following equation (Kutilek, 1980):

$$S = \sqrt{2T_{ro}}r$$

Field-saturated infiltration (I_{fs}) reflects the steady-state infiltration rate of the soil after it wets-up. It reflects the vertical infiltration rate; while the measured infiltration $I_{(i)}$ includes both the vertical infiltration and the potential side infiltration under the bottom edge of the infiltration ring. I_{fs} in our experiments can be adjusted from $I_{(i)}$ using the following equation (Reynolds and Elrick, 1990):

$$I_{fs} = 0.8 \times I_{(i)}$$

Figure 8. Setup for the Cornell Sprinkle infiltrometer.

3.2.2 Soil Chemical Tests

Soil chemical analyses include the measurements of soil pH, soil EC, soil alkalinity, CEC, ESP, PBS. All these laboratory chemical tests were performed at ISU for the soil samples collected from the two roadside sites, in Minnesota and at the Kelly Farm experimental site.

3.2.2.1 Soil Sample Preparation

Before laboratory chemical testing, the soils should be prepared to meet the appropriate testing requirements. The purpose of soil preparation is to remove moisture and coarse particles in the soil. It is worth noting that cans, bags, and other tools or supplies should be cleaned before their use in sample preparation procedures to avoid contamination, since chemical tests are very sensitive and sample contamination could alter the results. The steps of soil preparation are as follows.

1. Prepare a clean metal can and put the raw soil inside.
2. Put the can containing soil in the storage room for air drying (20-25°C).
3. After drying, collect the soil passing a No. 10 sieve (opening diameter of 2.00 mm).
4. Store the sieved soil in a new clean zip-lock bag, and label the soil sample.

3.2.2.2 Soil pH

Soil pH is a measure of acidity and alkalinity in soils. It is an important indicator related to environmental conditions, and ASTM D 4972-01, "Standard Test Method for pH of Soils" (Method A) was followed for the pH measurement using the Oakton PC 2700 Meters (Figure 9). The pH meter was calibrated with a buffer solution of pH 4.00 before use. The measurement procedure used was to place 10 g of dry soil passing a No.10 sieve into a glass container, add 10 mL of distilled water, mix thoroughly and let stand for 1 hour, then use the pH meter to record the reading when the mixture became stable.

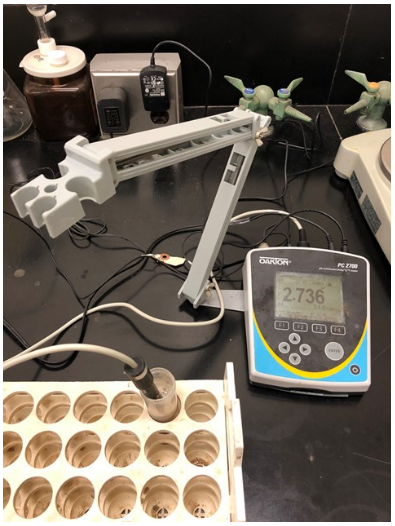


Figure 9. Oakton PC 2700 Benchtop pH/Conductivity Meters.

3.2.2.3 Soil Electrical Conductivity

Soil EC is a measurement that correlates with soil properties affecting crop productivity, including soil texture, cation exchange capacity, drainage conditions, organic matter level, salinity, and subsoil characteristics. The procedures described in standard C1A/3 (2013), "Soil Survey Standard Test Method Electrical Conductivity" developed by the Department of Sustainable Natural Resources were followed for EC measurements. EC was measured using Oakton PC 2700 Meters (Figure 9.) as well. Before use, the EC meter was calibrated with a KCl reference solution. The measurement steps were to prepare 10 g of dry soil passing a No. 10 sieve into the shaking bottle, add 50 mL of deionized water into the bottle, mechanically shake it for 1 hour, and then use the EC meter to record a reading when it became stable.

3.2.2.4 Soil Alkalinity

Alkalinity is the quantitative capacity of an aqueous solution for neutralizing acidic pollution from rainfall or wastewater, and the soil alkalinity was measured using a HACH alkalinity test kit (Figure 10) that use a titration method to count how many drops of acid was added into a solution to change its color. The result was expressed as the number of mg/L of $CaCO_3$. This test kit supports both low-range (5 to 100 mg/L) and high-range (20 to 400 mg/L) measurements using the following procedure:

1. Prepare 3 g of dry soil passing through a No. 10 sieve. Place the soil into a shaking tube and add 30 mL deionized water, then shake the tube for about 1 hour.

2. Prepare a filter consisting of a 25-mm syringe filter holder, filter paper, and a rubber ring.

3. Connect the filter with the syringe and pour the soil solution into the syringe, then press a piston to make the solution pass through the filter. Collect the solution after filtering.

4. Starting first with the low range method, fill the mixing bottle to the 23 mL mark with the sample solution.

5. Add the contents of one Phenolphthalein Indicator Powder Pillow and one Bromcresol Green-Methyl Red Indicator Powder Pillow to the mixing bottle and swirl to mix.

6. Add Sulfuric Acid Standard Solution one drop at a time while counting each drop. Swirl the mixing bottle after each drop is added. Add drops until the sample turns pink.

7. If the number of acid drops required to change the color is less than 20, record the number of drops. If not, use the high range method described in steps 8 to 10.

8. Starting with the high range method, fill the plastic test tube provided in the test kit with the sample solution and pour the contents into the mixing bottle.
9. Add the contents of one Phenolphthalein Indicator Powder Pillow and one Bromcresol Green-Methyl Red Indicator Powder Pillow to the mixing bottle. Swirl to mix.

10. Add Sulfuric Acid Standard Solution one drop at a time while counting the number of drops. Swirl the mixing bottle after each drop is added and add drops until the sample turns pink.

11. Calculate the alkalinity. For the low-range method, multiply by 5 the total number of drops of titrant used in step 6. For the high-range method, multiply by 20 the total number of drops of titrant used in steps 10. These numbers represent the total mg/L of methyl orange alkalinity as calcium carbonate ($CaCO_3$).

Figure 10. HACH alkalinity test kit.

3.2.2.5 Cation Exchange Capacity

CEC is a measure of the soil's ability to hold positively charged ions (nutrients). It is an important soil property influencing soil structure stability, nutrient availability, soil pH, and the soil's reaction to fertilizers and other ameliorants. In this study, five main cations (H^+, Na^+, K^+, Ca^{2+}, and Mg^{2+}) associated with CEC in soils can be measured using a batch water leach test in accordance with ASTM D 3987-04, "Standard Test Method for Shake Extraction of Solid Waste with Water". The steps are as follows:

1. Place 4 g of the air-dried soil sample passing No. 10 into a 50 mL plastic centrifuge tube followed by 40 mL of leachant. The tubes should be rotated end-over-end at 28 rpm at approximately 22 °C for 18±2 hours to reach equilibrium conditions.
2. After equilibrium is reached, allow samples to settle for 5 min before measuring pH values.
3. Next filter the samples through a 0.2-μm pore size membrane disk filter using a 25-mm syringe filter holder and a 60 mL plastic syringe into an acid-cleaned 50-mL centrifuge tube.
4. Acidify the samples with 10 % of trace metal grade nitric acid (HNO_3) to a pH value less than 2, then store the samples in a refrigerator at a temperature between 0 and 4°C.
5. Prepare suitable calibration standard solutions of Ca, K, Mg and Na for inductively coupled plasma atomic emission (ICP-AES) spectroscopy measurements (Figure 11). Set up the perfect standard curves for ICP measurements.
6. Concentrations of all metals can then be determined by simultaneous ICP-AES spectroscopy.
7. If the measured concentration of metal is outside the standard range, dilute the sample and measure again until the concentration value is within the standard range, then modify the results based on the dilution rate.
8. Calculate CEC based on the equivalent weight and measured concentration of cations.

The concentration of metals (Ca, K, Mg and Na) can be used for CEC calculations. The Periodic Table lists the individual atomic weights for each element that in this study is 40 for Ca, 23 for Na, 24 for Mg, 39 for K, and 1 for H. Among these elements, Ca and Mg have two valences while the others have only one. Since the equivalent weight can be determined by dividing the atomic weight by the number of valences, the equivalent weight for Ca is 20, for Na is 23, for Mg is 12, for K is 39, and for H is 1. The equivalent weight can be used to divide the measured concertation of each element, and summing the results of all five cations can produce the CEC. Since the CEC should be reported in meq/100 g, the units should be converted based on a 100-g sample size.

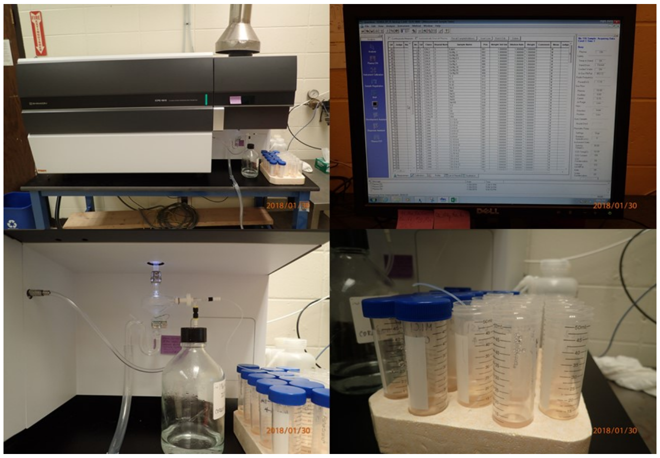


Figure 11. Inductively coupled plasma atomic emission spectroscopy.

3.2.2.6 Exchangeable Sodium Percentage

Exchangeable sodium percentage is an index that characterizes soil sodicity, the sodium adsorbed on soil particles as a percentage of cation exchange capacity. It is calculated as:

$$ESP = \frac{[\mathrm{Na}^{+}]}{\mathrm{CEC}} \times 100$$

3.2.2.7 Percent Base Saturation

Percent base saturation refers to a measurement or an estimate of the percentage of the soil CEC that is occupied by the sum of a group of nutrients. Percentage base saturation is the combined percentage saturation of the three major cations that have a basic or alkaline reaction (K^{+}, Ca^{2+}, and Mg^{2+}). It is calculated using the following equation:

$$PBS = \frac{[\mathrm{Ca}^{2+} + \mathrm{K}^{+} + \mathrm{Mg}^{2+}]}{\mathrm{CEC}} \times 100$$

3.2.3 Statistical Modeling

3.2.3.1 Statistical Modeling for Soil Physical Tests

In this report describing soil physical and plant measurements, analysis of variance (ANOVA) models with $\alpha = 0.05$ level are used to analyze the bulk density, soil hydraulic properties, and biomass data from the Kelly Farm, while the paired t-test are used to analyze roadside data. The goal is to test for significant differences in soil and plant properties (plant biomass, soil bulk density, saturated hydraulic conductivity, and soil infiltrability) at the Kelly Farm. The CGR treatments, i.e., four rates and block effects are considered in the ANOVA models.

For the roadside measurements, the samples from the CGR affected areas and non-CGR areas are paired, followed by a t-test adopted for appropriate data analysis. The goal is to test for significant differences in soil and plant properties (plant biomass, soil bulk density, saturated hydraulic conductivity, and soil infiltrability). After the paired t-test analysis, the ANOVA model is used to do further analysis, including consideration of CGR treatments, i.e., with or without CGR, and block effects in the ANOVA models. Overall, ANOVA and paired t-test models are used in this report for data analysis.

3.2.3.2 Statistical Modeling for Soil Chemical Tests

In this study, the results and statistical analysis related to soil chemical properties at the Kelly Farm and at MN roadsides are presented. To consider whether depth is an important factor in the chemical analysis, a two-way ANOVA model with $\alpha = 0.05$ level is developed for both sites. At the Kelly Farm control site, four blocks are considered as four replications to reduce the number of factors. Treatments of CGR and soil depth are variables in this model for analyzing the pH, EC, alkalinity, concentrations of metals (Ca, K, Mg and Na), CEC, ESP, and PBS. The calculated probability values (p value) can serve as evidence as to whether or not a particular factor causes a significant difference, in other words, an effect of factor is considered significant when its p value is less than 0.05.

At the two MN roadsides, in addition to the treatment of CGR and soil depth, the slope (position) is also considered as a variable in the ANOVA model, because it is thought that the slurry might slide into the ditch area. However, three factors cannot all be analyzed at the same time since there is no CGR treated area close to the ditch, so three separate groups are created for analyzing the statistical results. Group 1 contained the CGR area close to the highway and the control area with no CGR but close to the highway), Group 2 consists of the control area and non-CGR area close to the ditch, and Group 3 contains both the CGR area and the non-CGR area. This choice of analysis method is used to test how these three factors influence the chemical properties of the soil.

CHAPTER 4: EXPERIMENTAL RESULTS AND STATISTICAL ANALYSES

4.1 RESULTS OF MATERIALS PROPERTIES

4.1.1 Properties of CGR Collected from Minnesota

Fresh CGR materials were obtained from a diamond grinding operation on McAndrews Road in Apple Valley, MN. The slurry was offloaded into 5-gallons of buckets and transported to the laboratory. Due to the different solid contents in each bucket, all collected slurry were mixed together in a single tank to obtain a homogenous mixture for application. The physical properties of the CGR are given in Table 3. The specific gravity (Gs) of the CGR, determined using a water pycnometer (ASTM D 854-14, 2014), was 2.4. The mixed slurry had a solid content of 44%, and its sand, silt and clay fractions were 43%, 42.8% and 14.2%, respectively. The pH, EC, and alkalinity of the CGR were 11.7, 13.7 dS/m and 300 mg/L of calcium carbonate ($CaCO_3$), respectively. These measurements showed that CGR was a fine material with high pH (>11) and alkalinity. XRF analyses were carried out to identify elemental constituents of the CGR sample.

Table 4 shows the chemical compositions, including specific oxides of the CGR. The two most prevalent compounds in the CGR were Silica (SiO_2) (53.12%) and lime (CaO) (16.82%) of which were also the major compounds in concrete materials (

Table 4).

Table 3. Characterization of CGR and soil at the Kelly Farm site.

Characterizations	Soil	CGR
AASHTO Soil Classification	A-2-6 (silty or clayey gravel and sand)	-
Unified Soil Classification	SC (clayey sand)	-
Specific Gravity	2.8	2.4
Sand (%): 0.074 mm - 4.76 mm	69.4	43.0
Silt (%): 0.074 mm - 0.002 mm	23.1	42.8
Clay (%): < 0.002 mm	7.5	14.2
Plasticity index (%)	16.5	
$pH_{1:1}$	5.6	11.7
$EC_{1:1}$ (ds/m)	0.6	13.7
$Alkalinity_{1:10}$ (mg/L of $CaCO_3$)	25.3	300

Table 4. XRF analysis of elemental abundances of the CGR sample.

Sum (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)	TiO_2 (%)	BaO (%)	SrO (%)	Mn_2O_3 (%)	LOI[a] (%)
100	53.12	7.87	3.81	0.68	16.82	2.84	1.51	1.82	0.10	0.44	0.04	0.04	0.07	10.85

a. LOI: Loss on ignition.

4.1.2 Properties of Soil at the Kelly Farm

The properties of the Kelly Farm soil before application (initial stage) of CGR are provided in Table 3. Soil was classified as clayey sand according to Unified Soil Classification System (USCS). It had an average pH of 5.6, EC of 0.6 ds/m, and an alkalinity of 25.3 mg/L as $CaCO_3$. There results showed that the soil was slightly an acidic soil.

4.2 RESULTS AND STATISTICAL ANALYSES FROM SOIL PHYSICAL TESTS

4.2.1 Soil Physical and Plant Measurements at the Kelly Farm

4.2.1.1 Plant Species Investigation and Biomass Measurements

For a controlled field study at the Kelly Farm, coverage percentages for each plant species were measured in October 2016 and August 2017. To mimic typical roadside management as well as help facilitate uniform CGR applications on soil surface, the plants were mowed on October 7, 2016, i.e., after the first plant identification, but before all other field experiments. The above-ground biomass was measured in October 2016 (before CGR application and after mowing the plots), in November 2016 (one month after CGR application), May 2017 (seven months after CGR application), and in October 2017 (twelve months after CGR application). The ANOVA results and the measured biomass values are listed in Table 5.

Table 5. The ANOVA results of CGR on Kelly Farm plant biomass.

		Biomass (g)				
Treatment	(ton/acre)	0	10	20	40	p-value
Background	Oct-2016	61	68	70	60	0.33★
One Month	Nov-2016	35	47	45	39	0.55
Seven Months	May-2017	47	54	38	42	0.48
One Year	Oct-2017	73	100	85	65	0.36

The p-values with ★ markers are related the block factor. Without ★ marker, p-values indicate the CGR effects

The *p*-values in Table 5 show the effects of block and treatment (4 CGR rates) on plant biomass. For the background measurement (the first row of the data), the *p*-value is larger than 0.05, reflecting no significant differences among the background values in the four blocks. After the CGR application (the other three rows of the data), the *p*-values indicate the effect of CGR application, which are larger than 0.05. Thus, there is no significant influence of CGR application on plant biomass.

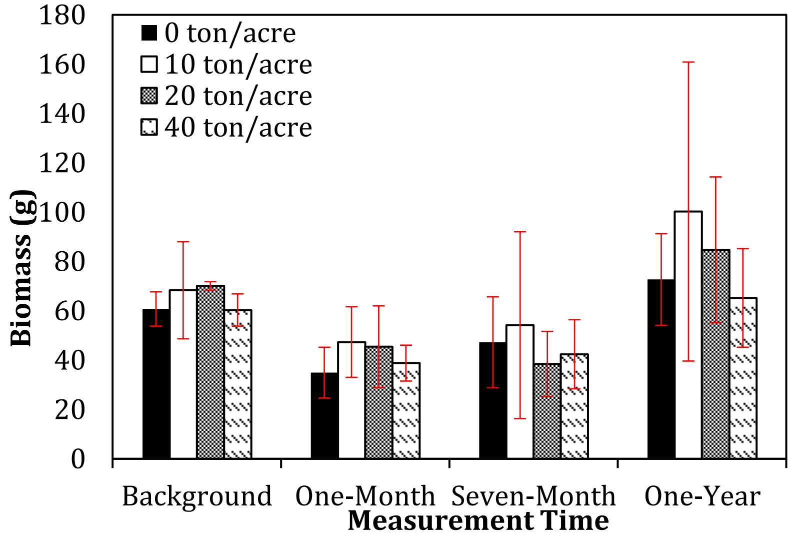


Figure 12. The plant biomass at the Kelly Farm.

To help in interpreting the measured results, we plotted the plant biomass in Figure 12 and the number of plant species with increased or decreased coverage percentages in Figure 13. Since in Figure 13, we classified the plant species into four categories, i.e., cool-seasoned grasses, legume, non-legume forbs, and warm-seasoned grasses, the numbers of plant species are counted and plotted based on those four categories. Because of field mowing and growing seasonality, the biomass values decreased from October 2016 to November 2016. Since the last two field measurements, in May 2017 and October 2017, represented the plant growth pattern in a new growing season after CGR application, we focused on data from those two experiments. Although the differences in biomass for the different CGR rates were not statistically significant, the patterns among those treatments were consistent. Although plant biomass at the 10 ton/acre rate exhibited values 15% and 38% larger than that of the control treatment, when compared to other treatments, the biomass at larger CGR rates tended to have smaller biomass values.

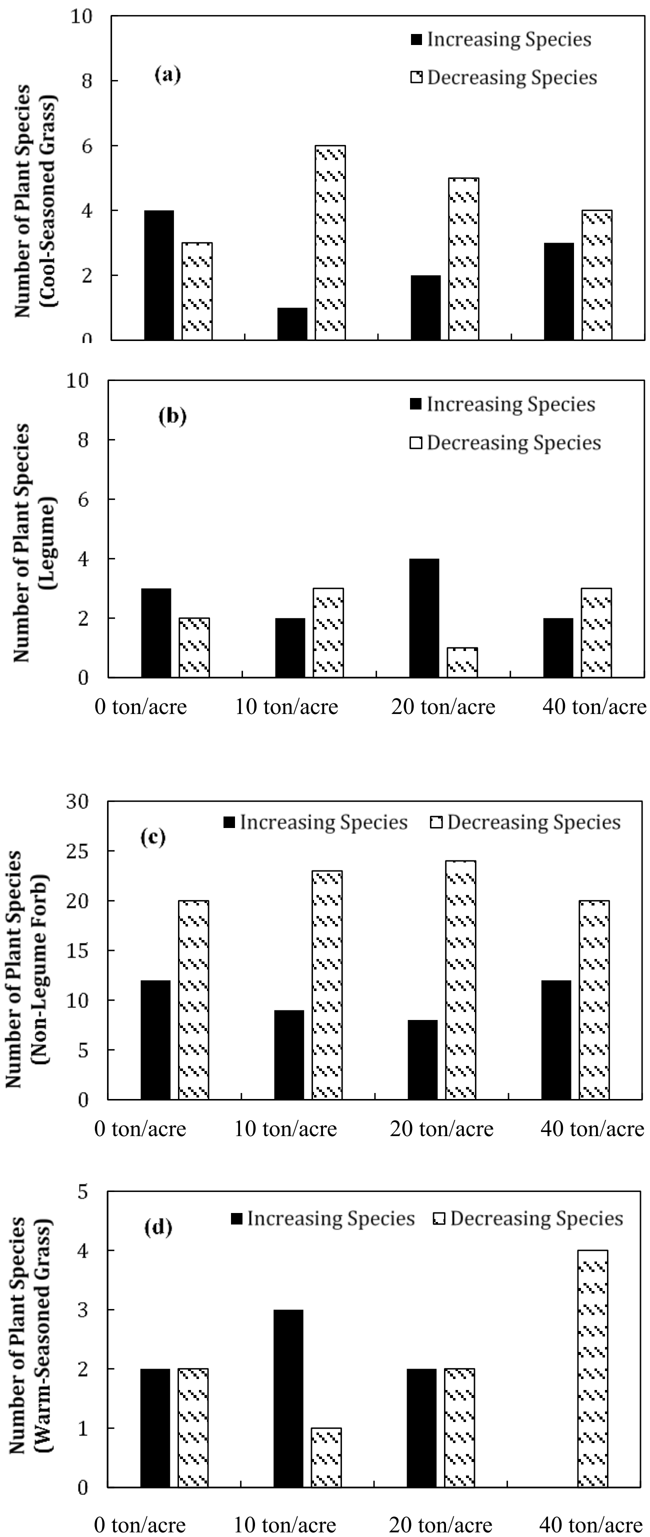


Figure 13. The number of plant species. The solid bars represent the number of plant species with increasing coverage between the two plant identification times, while the dashed bars represent the number of plant species with decreasing coverage between the two plant identification times.

The numbers of plant species with increasing and decreasing coverage percentages are shown in Figure 13. For the 40 ton/acre CGR application rate, more than 60% (cool-seasoned grass, legume and non-legume forb) and 100% (warm-seasoned grass) of the plant species exhibited a decreasing coverage percentage. For the 20 ton/acre CGR rate, the coverage percentage decreased for more than 50% of the plant species, except for legumes. For the 10 ton/acre CGR application rates, 60% to 80% of plant species, including warm-seasoned grasses, suffered from a decreasing coverage percentage.

For cool-seasoned grasses, with 0 ton/acre CGR application rates, 60% of the plant species exhibited increasing coverage percentages. However, with CGR applications, the coverage percentages of more than 60% of the plant species decreased. For non-legume forbs, with control and CGR treatments more than 60% of the plant species exhibited a decreasing coverage percentage. For legumes, 0 ton/acre and 20 ton/acre CGR application rates resulted in more than 50% of the plant species exhibiting an increase in coverage percentage; while 10 ton/acre and 40 ton/acre resulted in 60% of the plant species exhibiting decreased coverage percentage. For warm-seasoned grasses, 10 ton/acre CGR application rates resulted in 75% of the plant species exhibiting increased coverage percentage; 40 ton/acre CGR application rates led to a decreased coverage percentage for all the plant species; with 0 ton/acre and 20 ton/acre treatments, 50% of the plant species exhibited increased coverage percentages, and 50% of the plant species exhibited decreased coverage percentage.

4.2.1.2 Soil Bulk Density

Soil bulk density (ρ_b) values were determined after the K_s measurements, from the same soil cores. For the controlled field study at the Kelly Farm, a one-way ANOVA model was used to process the ρ_b data, with the results listed in Table 6.

Table 6. The ANOVA results of CGR on Kelly Farm ρ_b.

		ρ_b (g/cm^3)				
Treatment	(ton/acre)	0	10	20	40	*p-value*
Background	Oct-2016	1.24	1.21	1.25	1.26	0.83★
One Month	Nov-2016	1.25	1.33	1.25	1.19	0.11
Seven Months	May-2017	1.33	1.32	1.31	1.27	0.41
One Year	Oct-2017	1.26	1.27	1.26	1.18	0.16

The *p*-values with ★ markers are related to the block factor. Without ★ marker, *p*-values indicate the CGR effects.

Based on the ANOVA results, there are no significant background differences among the four blocks. After CGR application, all *p*-values for the treatment are larger than 0.05, demonstrating no significant influence of CGR on ρ_b. The mean oscillations of the ρ_b values presented in Table 6 are as little as 0.1 g/cm^3 in general, ρ_b is a relatively stable property under the influence of CGR. The largest data fluctuations occurred for the 40 ton/acre CGR rate, where the mean values range between 1.18 and 1.27 g/cm^3.

4.2.1.3 Saturated Hydraulic Conductivity

In the controlled field study at the Kelly Farm, soil was sampled for saturated hydraulic conductivity (K_s) measurements in October 2016 (before CGR application), November 2016 (one month after CGR application), May 2017 (seven months after CGR application) and October 2017 (twelve months after CGR application), and a one-way ANOVA model used to analyze the K_s data. A logarithm transformation was applied to the data to ensure data normality before using the ANOVA models (Jabro, 1992; Kosugi, 1996; Smith and Hebbert, 1979). The ANOVA results and the measured K_s values are listed in Table 7.

Table 7. The ANOVA results of CGR on Kelly Farm K_S.

		K_s (cm/s)				
Treatment	(ton/acre)	0	10	20	40	*p-value*
Background	Oct-2016	0.0509	0.0220	0.0384	0.0317	0.50★
One Month	Nov-2016	0.0608	0.0577	0.0378	0.0368	0.09
Seven Months	May-2017	0.0376	0.0279	0.0365	0.0348	0.35
One Year	Oct-2017	0.0342	0.0314	0.0223	0.0211	0.12

The *p*-values with ★ markers include the block factor. If there is no ★ marker, the *p*-values reflect CGR effects.

For background measurements, the *p*-value is larger than 0.05, reflecting no significant difference among the four blocks. After CGR application, all of the *p*-values for the treatment are larger than 0.05, and show no significant influence of CGR on K_s. In addition to the *p*-values, the one-year data show a decreasing pattern with respect to the CGR rates, For example, K_s for the 40 ton/acre CGR application rate is 30% smaller than the K_s for the control treatment for the one-year measurement. This pattern can also be observed in the log-scale plot of the Kelly Farm K_s values with standard deviation (Std), as shown in Figure 14.

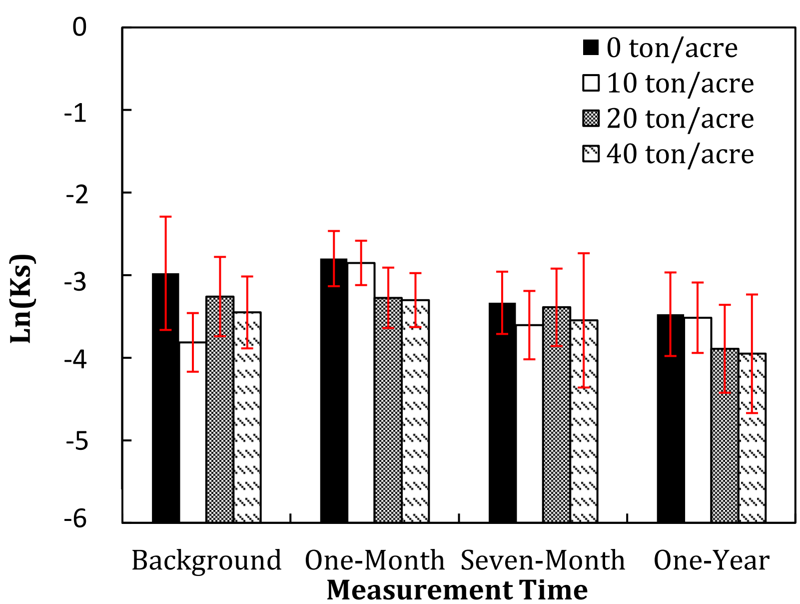


Figure 14. The Ln(K_S) at the Kelly Farm

4.2.1.4 Soil Water Infiltration Measurements

In the controlled field study at the Kelly Farm, soil water infiltration I_t measurements were made in October 2016 (before CGR application), November 2016 (one month after CGR application), May 2017 (seven months after CGR application), and October 2017 (twelve months after CGR application). A one-way ANOVA model was used to process the I_t data from the Kelly Farm and a logarithmic transformation was applied to the data to ensure its normality (Jabro, 1992; Kosugi, 1996; Smith and Hebbert, 1979). The data and the ANOVA results are given in Table 8.

Table 8. The ANOVA results of CGR on Kelly Farm I_t.

		I_t (cm s^{-1})				
Treatment	(ton/acre)	0	10	20	40	*p-value*
Background	Oct-2016	0.0081	0.0069	0.0070	0.0074	0.40★
One Month	Nov-2016	0.0056	0.0070	0.0069	0.0072	0.33
Seven Months	May-2017	0.0105	0.0087	0.0088	0.0075	0.11
One Year	Oct-2017	0.0098	0.0093	0.0093	0.0096	0.95

The *p*-values with ★ markers are related to the block factor. Without ★ marker, *p*-values indicate the CGR effects.

There is no significant background difference among the four blocks from the ANOVA results. After CGR applications, all *p*-values among treatments are larger than 0.05, showing no significant influence of CGR on I_t. The I_t results after the logarithmic transformation are also shown in Figure 15. Similar to the K_s results, the I_t values tend to decrease as the applied CGR increase. For example, in the seven-month measurement, where the I_t-values with CGR is 20%-30% smaller than the I_t in the control plots.

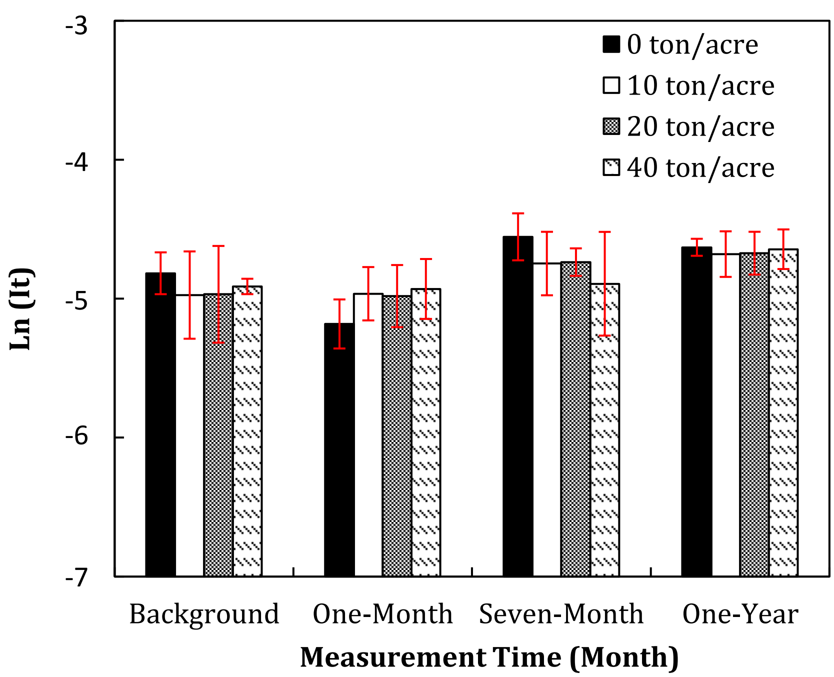


Figure 15. The Ln(I_t) at the Kelly Farm.

4.2.2 Soil Physical and Plant Measurements at the Minnesota Roadsides

4.2.2.1 Biomass Measurements

For the roadside experiment, the above-ground biomass at the two sites was sampled in November 2016, and the paired t-test results and the measured biomass values are listed in Table 9.

Table 9. The paired t-test results of CGR on Minnesota roadside plant biomass.

Location	Sampling Points	Slope (deg.)	Biomass (g)		*p*-value
			CGR	Non-CGR	
Site 1	A	16	42.0	53.8	0.91
	B	18	56.7	34.1	
	C	16	59.5	74.1	
Site 2	A'	10	23.3	34.4	0.18
	B'	12	23.5	35.4	
	C'	10	23.5	23.7	

The *p*-values for both sites are larger than 0.05, indicating that the CGR effects on roadside plant biomass are not significant. However, we note that the *p*-value for Site 2 is close to 0.05, and examination of measured data reveals that plant biomass without CGR is approximately 50% larger than the biomass values with CGR at two out of three of the sampling points.

4.2.2.2 Soil Bulk Density

For the roadside experiments, the soil samples for ρ_b measurements are from the same samples used for the K_s measurements. Paired t-test results are shown in Table 10.

Table 10. The paired t-test results of CGR on Minnesota roadside ρ_b.

Location	Sampling Points	Slope (deg.)	ρ_b ($\mathrm{g\ cm^{-3}}$)		*p*-value
			CGR	Non-CGR	
Site 1	A	16	1.40	1.36	0.93
	B	18	1.27	1.32	
	C	16	1.17	1.14	
Site 2	A'	10	1.29	1.24	0.0056**
	B'	12	1.33	1.23	
	C'	10	1.33	1.23	

The *p*-values with ** markers indicate the very significant effect of CGR.

The *p*-value of the paired t-test for Site 1, indicates that the ρ_b values with or without CGR are almost equal, while for Site 2, CGR shows very significant effects on roadside ρ_b, with a *p*-value equal to 0.0056. From Site 2, the ρ_b values with CGR are significantly larger than ρ_b values in the non-CGR area. To further examine the significant difference at Site 2, we use an ANOVA model, with CGR treatment, roadside slope, and their interaction as input factors. The results are shown in Table 11. By separating treatment from slope and their interaction, the effect of CGR is found to be significant (*p*-value < 0.019).

Table 11. The paired t-test results of CGR on Minnesota roadside ρ_b for Site 2

Item	*p*-value		
	Treatment	Slope	Treatment × Slope
ρ_b (g cm^{-3})	0.019*	0.93	0.69

The *p*-values with * markers indicate the significant effect of CGR.

4.2.2.3 Saturated Hydraulic Conductivity

For the roadside experiments, the soil samples for K_s measurements were taken from two sites in November 2016, and a paired t-test was used for data analysis. A logarithmic transformation was applied to the data before the t-test. The paired t-test results, as well as the measured K_s values, are listed in Table 12.

Table 12. The paired t-test results of CGR on Minnesota roadside K_S.

Location	Sampling Points	Slope (deg.)	K_s (cm s^{-1}) CGR	Non-CGR	*p*-value
Site 1	A	16	0.0010	0.0057	0.55
	B	18	0.0371	0.0367	
	C	16	0.0154	0.0110	
Site 2	A'	10	0.0265	0.0384	0.024*
	B'	12	0.0152	0.0459	
	C'	10	0.0259	0.0363	

The *p*-values with * markers indicate the significant effect of CGR.

The *p*-value for Site 1 is larger than 0.05, indicating that CGR effects on roadside K_s are not significant, while for Site 2, CGR shows significant effects on roadside K_s, with a *p*-value of 0.024. From Site 2, the K_s values in the non-CGR area are significantly larger than the K_s values with CGR applied at Site 2 four years before the measurements. Similar to the analysis of ρ_b, we use an ANOVA model for Site 2, with CGR treatment, roadside slope, and their interaction as input factors. The ANOVA results are listed in Table 13. The ANOVA confirms a significant difference due to CGR. By separating treatment from slope and their interaction, the effect of CGR is shown to be very significant (*p*-value<0.01).

Table 13. The ANOVA results of CGR on Minnesota roadside K_S for Site 2

Item	*p*-value		
	Treatment	Slope	Treatment×Slope
K_s (cm s^{-1})	0.006**	0.45	0.059

The *p*-values with ** markers indicate the very significant effect of CGR.

4.2.2.4 Soil Water Infiltration Measurements

For the roadside experiments, the infiltration measurements were made in the CGR affected area and the non-CGR area in pair-wise fashion, and a paired t-test was used for data interpretation. The results are given in Table 14.

Table 14. The ANOVA results of CGR on Minnesota roadside I_t.

Location	Sampling Points	Slope (deg.)	I_t (cm s^{-1}) CGR	I_t (cm s^{-1}) Non-CGR	*p*-value
Site 1	A	16	0.00399	0.00281	0.98
	B	18	0.00500	0.00432	
	C	16	0.00272	0.00457	
Site 2	A'	10	0.00062	0.00174	0.75
	B'	12	0.00250	0.00139	
	C'	10	0.00091	0.00014	

The *p*-values for both sites are larger than 0.05, indicating no significant influence of CGR on soil water infiltration.

4.3 RESULTS AND STATISTICAL ANALYSES FROM SOIL CHEMICAL TESTS

4.3.1 Soil Chemical Measurements at the Kelly Farm

4.3.1.1 pH

pH is the logarithmic scale of concentration of hydrogen ions. The pH results with Std up to one year after the application of slurry at the Kelly Farm control site are shown in Figure 16. They indicate that offloading of slurry at the Kelly Farm slightly increased the soil pH, and this increase in pH, is observed to be related to the slurry application rate. The increased pH is caused by the high content of CaO and MgO in the slurry that can create hydroxides to contribute to high pH and alkalinity (DeSutter, et al., 2011; Mamo, et al., 2015; Kluge, et al., 2018). The highest pH is observed after six months, and it then decreases with time. There are two reasons that can cause the reduction of pH after one year. One explanation is the influence of rainfall and snow that not only could cause the sliding of CGR into a clear zone, but can also help CGR penetrate into deeper soil layers; these activities can lead to the reduction of CGR density on topsoil. The other reason is the presence of CO_2 that through carbonation can reduce pH (Townsend, et al., 2016). For the CGR treated plots, pH decreases with increasing soil depth because a great deal of slurry is retained in the top layer. The initial pH of Kelly Farm soil is also moderately acidic, and the application of slurry could change it to slightly acidic or neutral (less than 7), an acceptable range from the perspective of vegetative growth.

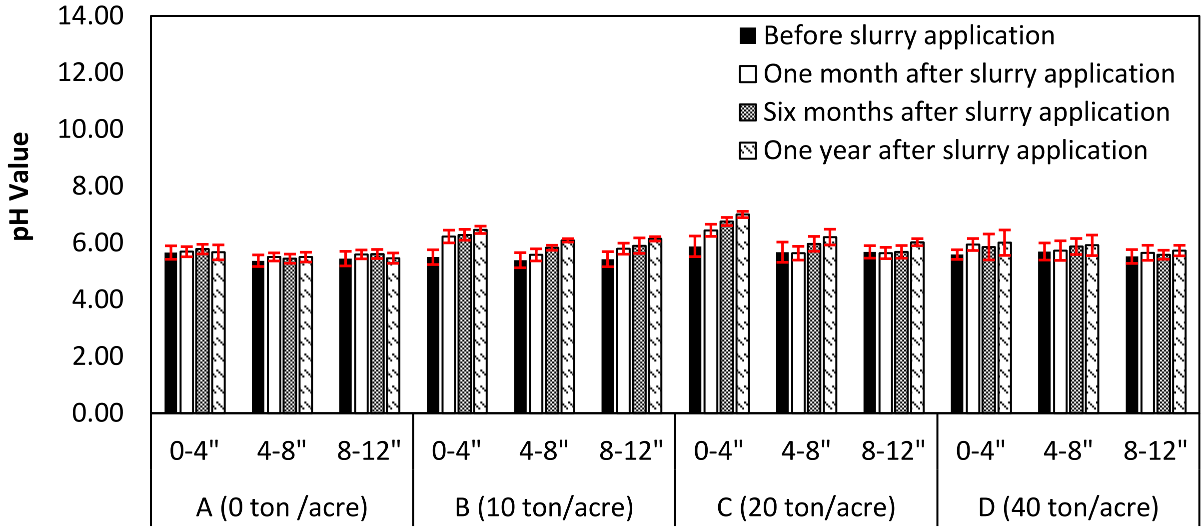


Figure 16. The results of pH at the Kelly Farm.

The pH results from the Kelly Farm ANOVA model are shown in Table 15. In such a statistical model, a factor with significant effect is defined as one having a *p*-value lower than 0.05. From Table 15, at the initial stage without CGR treatment the depth causes no the significant difference, but after one month of CGR application, CGR treatment causes a significant effect on soil pH. After six-month and one-year stages, CGR treatment do not significantly affect soil pH, indicating that the effect of CGR on soil pH is of short duration.

Table 15. The ANOVA results of pH at the Kelly Farm.

Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		0.0005	0.0853	0.4177
Depth	0.0284	0.1935	0.0144	0.2759
Treatment × Depth		0.9841	0.8680	0.9922

4.3.1.2 Electrical Conductivity

Soil EC is a measure of salinity of soil. It is important to soil health and can affect crop productivity. The measured EC with Std values at the Kelly Farm are shown in Figure 17, showing that slurry can increase soil EC, and that higher EC always occurs with a higher slurry application rate and at higher soil layers near the top. For the plots with 10 ton/acre and 20 ton/acre of slurry, EC is reduced after one year. The dissolved salts in slurry can explain the increase in EC after application of CGR (DeSutter, et al., 2011; Mamo, et al., 2015). From the perspective of vegetation growth, high EC may have negative impacts because higher osmotic pressure around roots decreases the ability of a plant to absorb water (Warrence et al., 2002). All measured EC values are below 4 dS/m, meaning that the plants can grow without limitations (Waskom, et al., 2014). In summary, although the slurry can significantly change soil EC, this change is still acceptable in terms of vegetative growth.

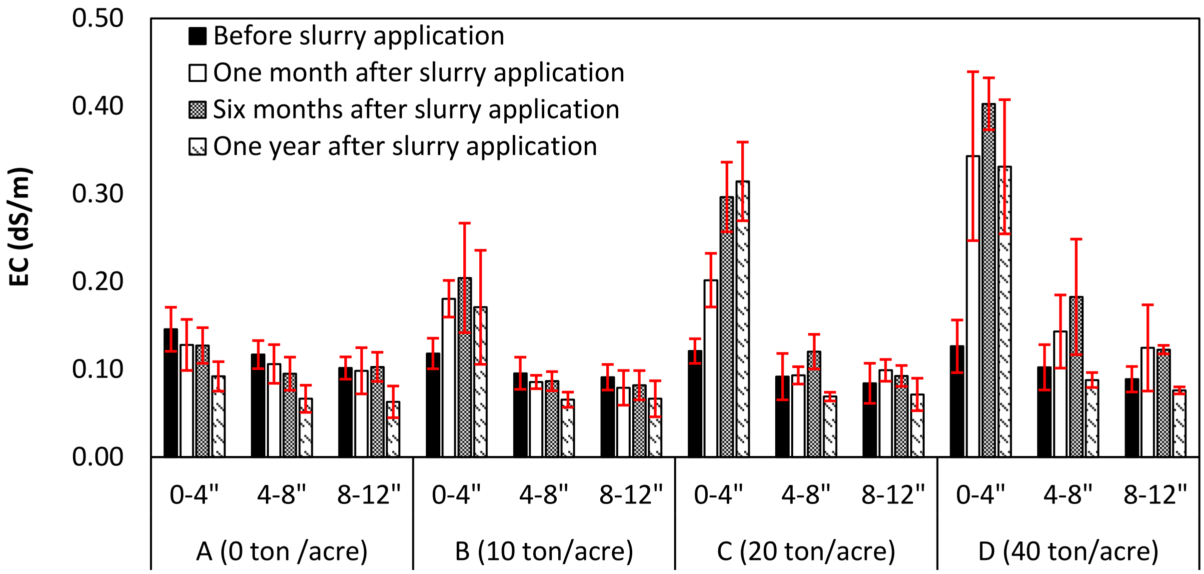


Figure 17. The results of EC at the Kelly Farm.

The ANOVA EC results for the Kelly Farm are presented in

Table 16. Treatment, depth, and their interaction significantly influenced soil EC after the different treatment times listed in

Table 16.

Table 16. The ANOVA results of EC at the Kelly Farm.

Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		<.0001	<.0001	<.0001
Depth	<.0001	<.0001	<.0001	<.0001
Treatment × Depth		0.0005	<.0001	<.0001

4.3.1.3 Alkalinity

Alkalinity is an important property used to measure the soil's ability to neutralize acidic pollution from rainfall or wastewater.

Figure 18 shows the results of alkalinity measurements with Std at the Kelly Farm using the titration method. These results indicate that application of slurry significantly increases alkalinity, and the trend of increase is similar to that of soil pH and EC. The alkalinity of topsoil with more slurry and longer treatment time is higher than for other soils. As a waste material from concrete products, CGR retains strong alkalinity from constituents such as CaO and MgO, and the addition of CGR can cause higher soil alkalinity. Scott (1985) and Scott (1986) indicate that the application of CGR can mitigate the effects of acidity within soil and improve the growth of plant species.

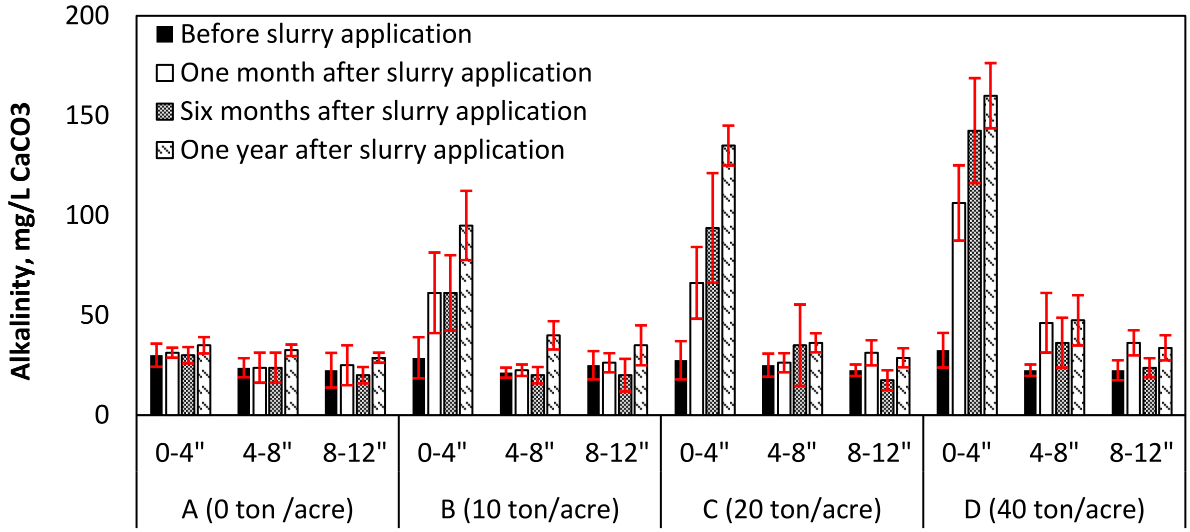


Figure 18. The results of alkalinity at the Kelly Farm.

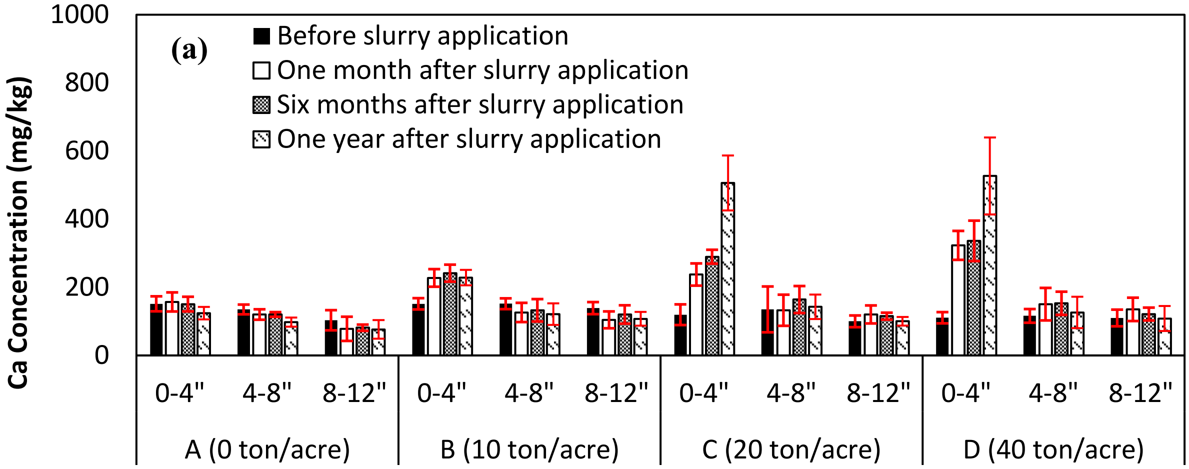
The results of ANOVA analysis are shown in Table 17, and they indicate that treatment and depth and their interaction contribute to a significant difference in soil alkalinity.

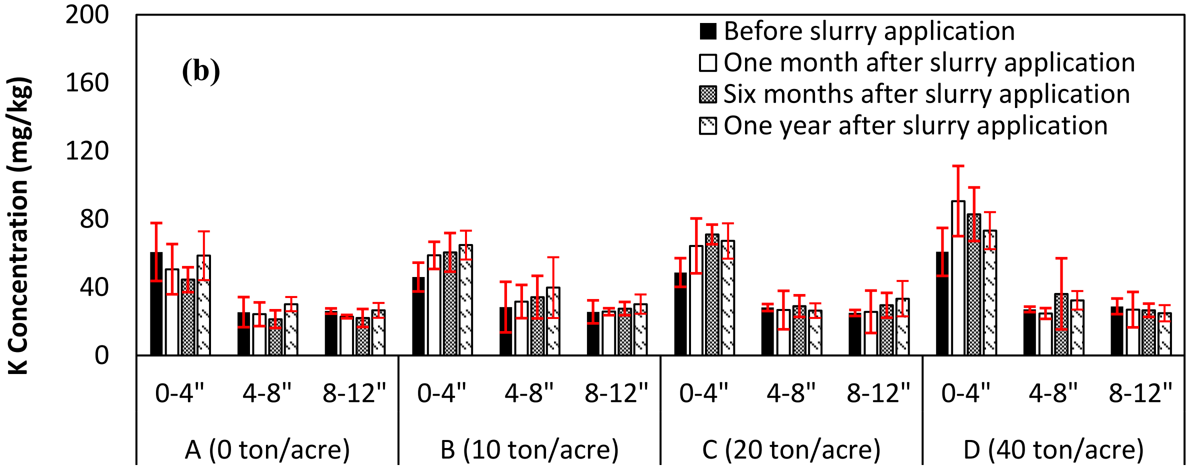
Table 17. The ANOVA results of alkalinity at the Kelly Farm.

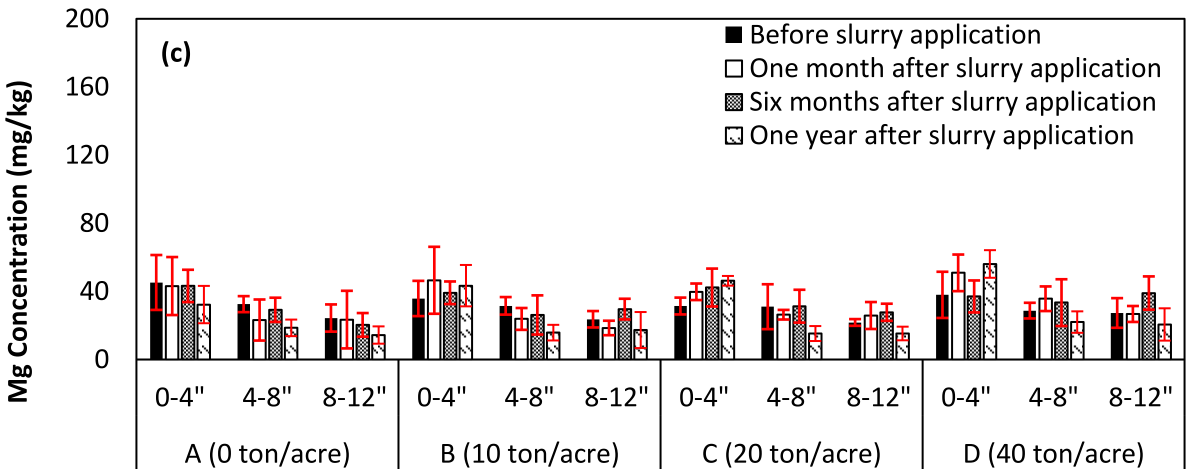
Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		<.0001	<.0001	<.0001
Depth	0.0047	<.0001	<.0001	<.0001
Treatment × Depth		0.0002	<.0001	<.0001

4.3.1.4 Concentration of Metals

Portland concrete production can introduce concentrations of metals such as Ca, K, Mg, Na, Fe, Al, and others that have the ability to leach into deep soil and groundwater and cause environmental contamination. The primary exchangeable metals Ca, K, Mg and Na, also known as the basic nutrient metals for plants, are measured in this study under the specified leaching conditions. The measured concentrations of four primary exchangeable metals with Std, presented in Figure 19, show that while the content of metals at the soil top increase after the application of slurry, this influence at middle and bottom soil levels is limited. Among these metals, the increases in the concentration of K and Mg are relatively lower than for Ca and Na because their content in the slurry is lower. In addition, one year after slurry application, the soils treated with 20 ton/acre and 40 ton/acre slurry exhibit the highest concentration of Ca, indicating that slurry leach more Ca over longer treatment times. The increases in exchangeable metals in soil at the Kelly Farm are due to the addition of CGR (DeSutter, et al., 2011; Mamo, et al., 2015), but this effect is limited below a depth of 4 in. from the top surface.







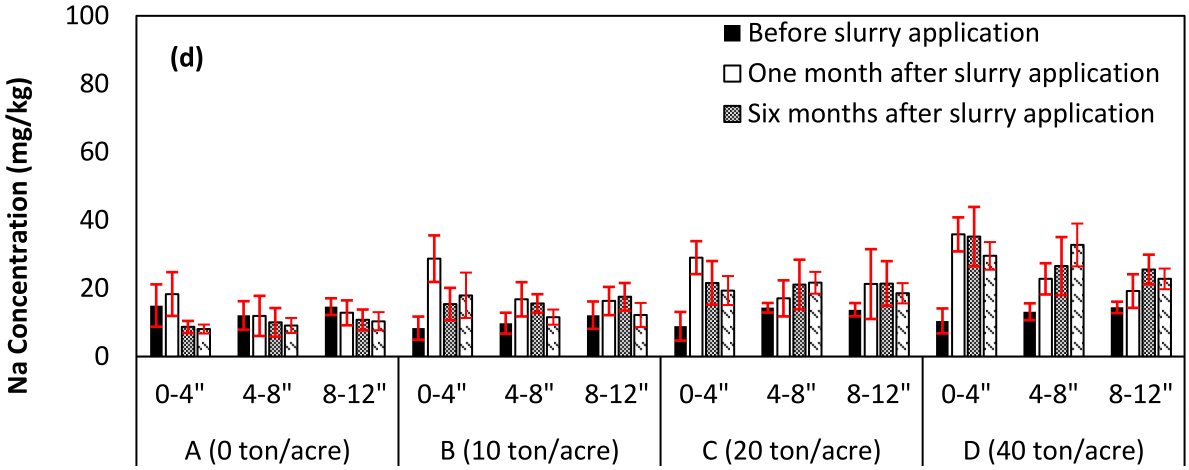


Figure 19. The concentrations of leached metals at the Kelly Farm: (a) Ca; (b) K; (c) Mg; and (d) Na.

Table 18 summarizes the statistical results from measurement of concentration of exchangeable metals at the Kelly Farm. At the initial stage, the concentrations of K and Mg are significantly different at different depths, and after slurry application, CGR becomes an important factor, producing significant Ca and Na effects at all stages. Depth significantly influences the concentrations of Ca, K, and Mg after slurry application, and its interaction with slurry is particularly significant with respect to Ca. For Mg, interaction between slurry and depth has no significant influence.

Table 18. The ANOVA results of concentrations of leached metals at the Kelly Farm.

Metals	Factor	*p-value*			
		Initial	One-month	Six-month	One-year
Ca	Treatment	0.0846	<.0001	<.0001	<.0001
	Depth		<.0001	<.0001	<.0001
	Treatment × Depth		0.0139	0.0001	<.0001
K	Treatment	<.0001	0.0241	0.0004	0.3795
	Depth		<.0001	<.0001	<.0001
	Treatment × Depth		0.0125	0.0487	0.2572
Mg	Treatment	0.0004	0.2329	0.4558	0.0084
	Depth		<.0001	0.0020	<.0001
	Treatment × Depth		0.8714	0.2522	0.1567
Na	Treatment	0.0690	0.0002	<.0001	<.0001
	Depth		<.0001	0.6170	0.0762
	Treatment × Depth		0.5284	0.3674	0.0218

4.3.1.5 Cation Exchange Capacity

The soil CEC with Std at the Kelly Farm is shown in Figure 20. The plots treated with CGR exhibit higher CEC than at their initial stage, indicating that the application of slurry can increase soil CEC, and especially significantly influence the top layer. The main contribution for the increase in CEC results from the presence of CGR. CGR has a large fraction of fine particles (DeSutter, et al., 2011; Mamo, et al., 2015; Kluge, et al., 2018), particularly in a relatively high specific area of CGR. Consideration of the high surface charge density of concrete fines (Labbez, et al., 2006; Elakneswaran, 2009) suggests that CGR has ability to hold cations and increase soil CEC. Another reasonable cause of increases in soil CEC after CGR treatment is the increase in pH from the liming effect of CGR (Sonon, et al., 2014). The CEC of soil at middle and bottom layers is lower than at the top layer, and after the application of slurry it still does not significantly increase because exchangeable metals find it difficult to penetrate into deeper soil. With an increase in treatment time, soils receiving 20 and 40 ton/acre exhibit increased CEC, indicating that the slurry leaches exchangeable metals continuously in one year, with most of them trapped in the top soil. In the consideration of these influences, the addition of CGR on soil has a potential for increasing the CEC of the soil matrix. Thus, this practice can be beneficial for vegetation growth since it can hold nutrients in the soil due to increases in CEC.

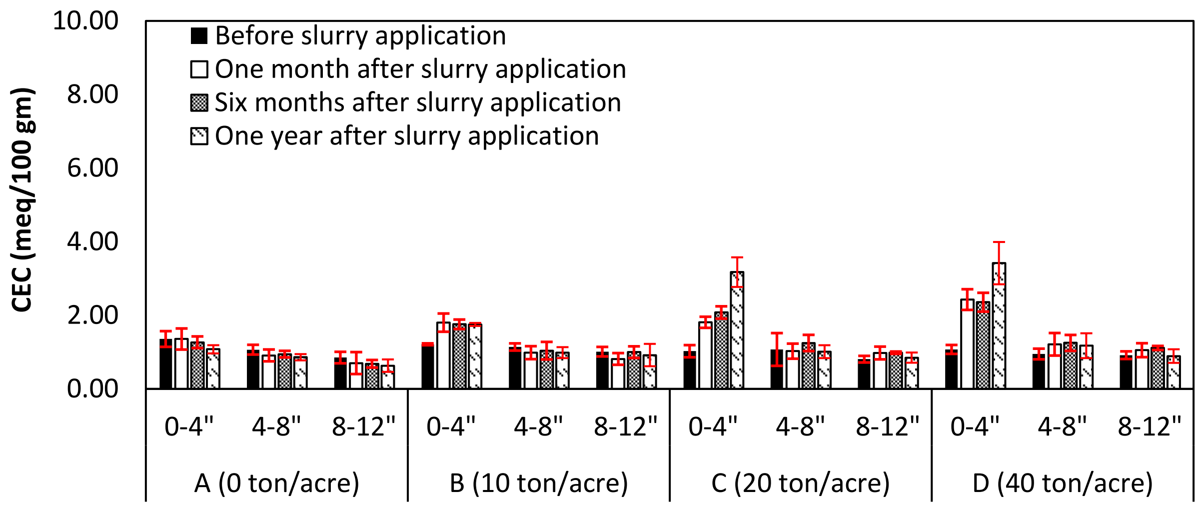


Figure 20. The results of CEC at the Kelly Farm.

The calculated p values are summarized in Table 19. Treatment, depth, and their interaction exhibit p values greater than 0.05 at all stages, indicating that CEC can be significantly influenced by these factors.

Table 19. The ANOVA results of CEC at the Kelly Farm.

Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		<.0001	<.0001	<.0001
Depth	0.0010	<.0001	<.0001	<.0001
Treatment × Depth		0.0360	0.0009	<.0001

4.3.1.6 Exchangeable Sodium Percentage

ESP results at the Kelly Farm are shown in Figure 21. They indicate that while the proportion of Na in CEC is particularly increases in CGR-treated soil and the concentration of domain cations increases after the application of slurry, the higher application rate of CGR does not exhibit higher ESP at the one-month stage. The ESP of middle and bottom soil is higher than for top soil because of the high content of Ca in the top layer, and after the one-month stage the surface layer ESP decreases, because more Ca than Na leached from slurry. The soil with high ESP can be defined as a sodic soil, which may have negative impacts on plant growth due to the poor water infiltration (Warrence et al., 2002).In this study, the increase in soil ESP did not change soil into a sodic condition, because the increased ESP did not exceed the threshold of 20% (Shainberg and Letey, 1984).

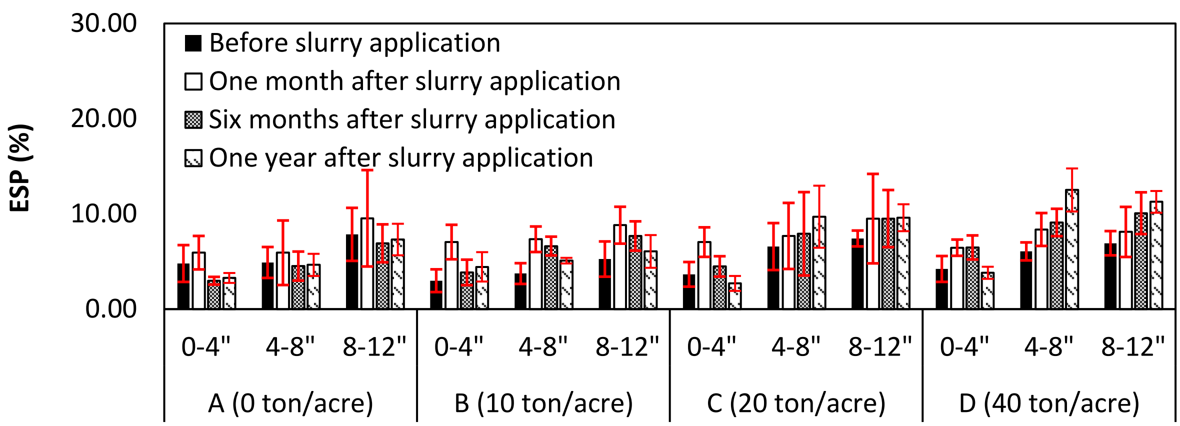


Figure 21. The results of ESP at the Kelly Farm.

Statistical ESP results are shown in Table 20. While at the one-month stage, no factors show a significant effect on ESP, treatment and depth become significant factors at the six-month stage, and their interaction becomes significant after one year. This seems reasonable because a longer treatment time results in more metals being leaching from slurry to change the soil ESP.

Table 20. The ANOVA results of ESP at the Kelly Farm.

Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		0.8752	0.0005	<.0001
Depth	0.0001	0.0642	<.0001	<.0001
Treatment × Depth		0.9130	0.9630	0.0001

4.3.1.7 Percent Base Saturation

Calculated PBS results at the Kelly Farm are displayed in Figure 22. The PBS of soil does not change significantly after the application of slurry. At the surface layer, PBS of soil is higher than for middle and bottom layers. At middle and bottom layers, PBS is reduced, with the increase in time due to the relatively higher content of Na in the soil. In general, higher PBS indicates more fertile soil since it reflects less content of acidic cations such as Al, higher pH (5.5 to 7.0), and more nutrient cations (Sonon et al., 2014). Therefore, the addition of CGR will not cause a significant reduction of PBS in soil to make soil less fertile.

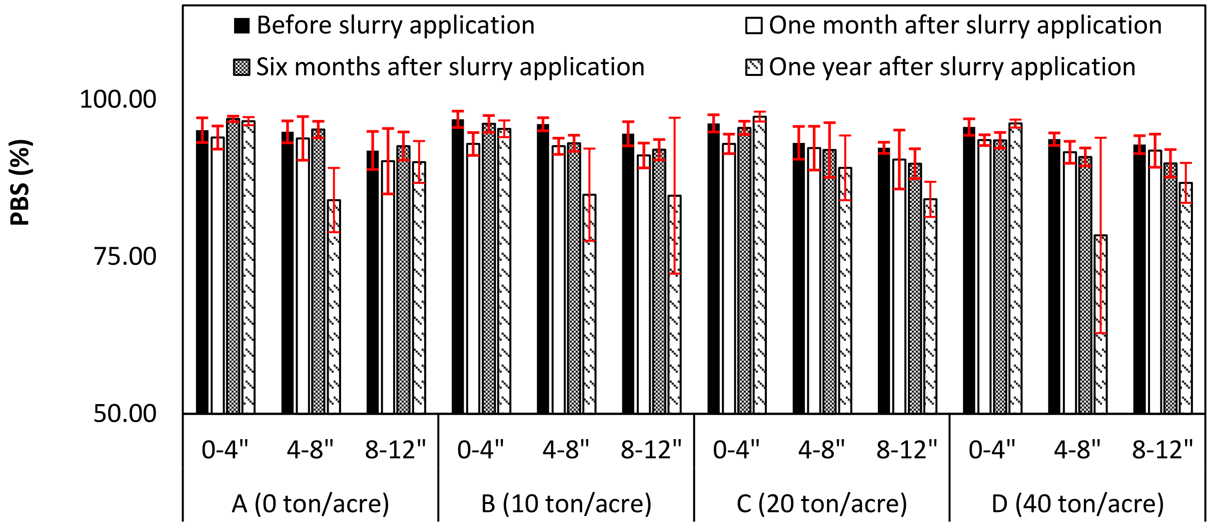


Figure 22. The results of PBS at the Kelly Farm.

The PBS ANOVA results for the Kelly Farm are summarized in Table 21, showing that treatment is significant only at the six-month stage. As another factor in this model, depth has a significant effect only at the one-month stage. Since the PBS can be affected differently by several metals in the soil, the properties and composition of the CGR source are important to soil PBS.

Table 21. The ANOVA results of PBS at the Kelly Farm.

Factor	*p-value*			
	Initial	One-month	Six-month	One-year
Treatment		0.9306	0.0007	0.6038
Depth	0.0001	0.0615	<.0001	<.0001
Treatment × Depth		0.9161	0.9043	0.4923

4.3.2 Soil Chemical Measurements at the Minnesota Roadsides

4.3.2.1 pH

The pH results with Std at the MN sites are shown in Figure 23. For both of these sites, the pH results exhibit a small difference at the top surface layer with respect to the CGR area, the non-CGR area, and the control area. At the MN sites, the CGR areas did not display higher pH than of the areas without

CGR. Many factors such as carbonation, Al and S from CGR, different CGR offloading rate along roadside, and rain and snow effects can cause the lower pH values (DeSutter, et al., 2011; Townsend, 2016).

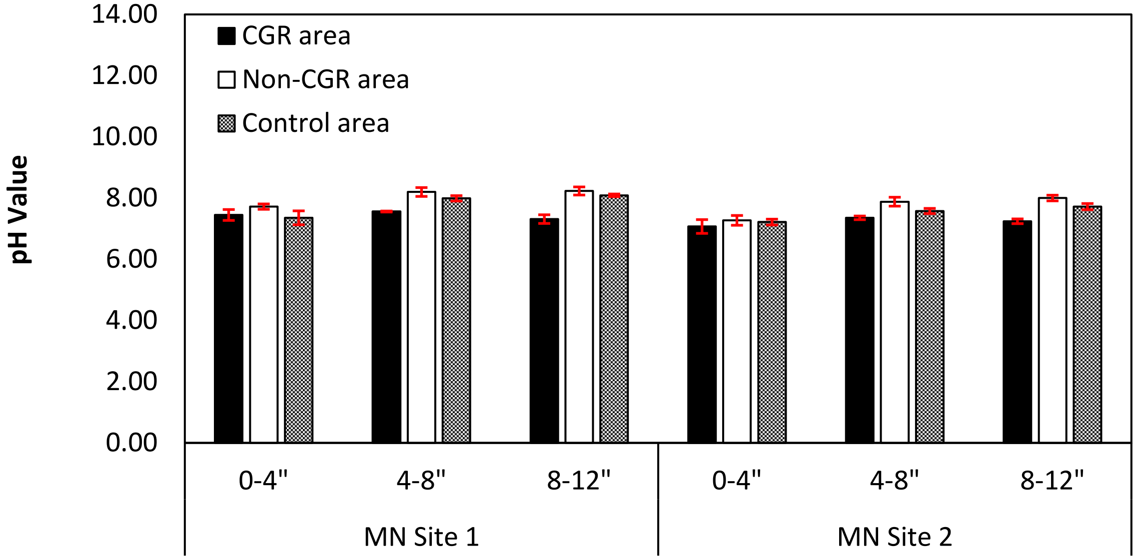


Figure 23. The results of pH at the Minnesota roadsides.

The statistical pH analyses at the MN sites are shown in Table 22. For site 1, the single factor of CGR does not significantly affect pH, but at site 2 it is a significant factor on soil pH, with the significant difference caused by the relatively high pH in the middle and bottom layer at areas without CGR. This results from the different soil types in different layers where different colors of soil are observed. The different results at these two sites can have been caused by many factors like different CGR source, discharge rate, and sliding of deicing agent.

Table 22. The ANOVA results of pH at the Minnesota roadsides.

Group	Factors	*p-value*	
		pH at Site 1	*pH at Site 2*
Group 1	CGR	0.0553	0.0433
	Depth	0.1249	0.0420
CGR area and Control area	CGR × Depth	0.0691	0.7716
Group 2	Slope	0.1057	0.1103
	Depth	0.0089	<.0001
Non-CGR area and Control area	Slope × Depth	0.2563	0.9087
Group 3	CGR × Slope	0.0002	0.0116
	Depth	0.2025	0.0390
CGR area and Non-CGR area	CGR × Slope × Depth	0.1246	0.8289

4.3.2.2 Electrical Conductivity

The EC results with Std at the MN sites are shown in Figure 24. The area with CGR exhibits the highest EC values, with the surface layer EC higher than for the two deeper layers. The results are similar to those from the Kelly Farm, i.e., the presence of slurry can introduce dissolved salts to increase soil EC although not above 4 dS/m. In addition to that, automotive emission and road maintenance activities such as the use of deicing additives are other reasons to elevate EC in the areas close to road.

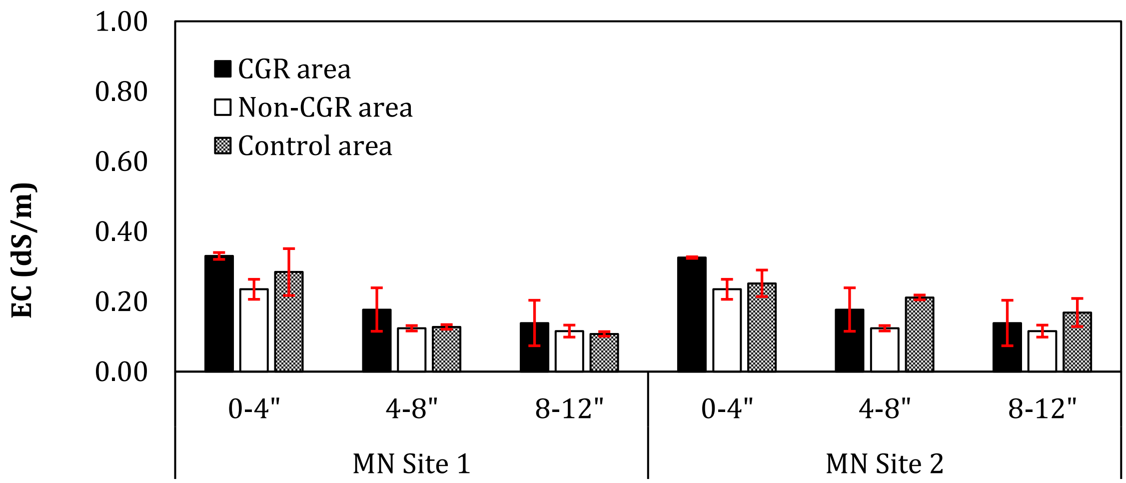


Figure 24. The results of EC at the Minnesota roadsides.

The *p*-values for different factors are shown in Table 23. While depth is an important factor significantly influencing EC in each group, interactions between different factors except CGR and slope have no significant differences other than for soil EC. The results from the ANOVA model in group 1 indicated that CGR had no significant effect, and it is hypothesized that effects of slurry on EC are significantly reduced due to some environmental activities after long-term offloading of slurry, although the CGR area still has the highest EC.

Table 23. The ANOVA results of EC at the Minnesota roadsides.

Group	Factors	*p-value*	
		EC at Site 1	*EC at Site 2*
Group 1	CGR	0.0753	0.8848
CGR area and Control area	Depth	<.0001	0.0005
	CGR × Depth	0.9351	0.0874
Group 2	Slope	0.3236	0.0012
Non-CGR area and Control area	Depth	<.0001	0.0001
	Slope × Depth	0.2762	0.1116
Group 3	CGR × Slope	0.0095	0.0108
CGR area and Non-CGR area	Depth	<.0001	<.0001
	CGR × Slope × Depth	0.3180	0.3610

4.3.2.3 Alkalinity

The alkalinity results with Std at the MN sites are shown in Figure 25, demonstrating that the control area exhibit the highest alkalinity at both roadsides, and the CGR areas have the lowest alkalinity except for the top soil at MN Site 1. In addition, the top layer has higher alkalinity than others for all areas at the MN sites. These results indicate that CGR does not increase alkalinity of soil after long-term roadside slurry offloading. The different weather effects (i.e., rain, snow and wind) and human activities (i.e., automotive emission and road maintenance) contribute to the lower alkalinity in CGR areas.

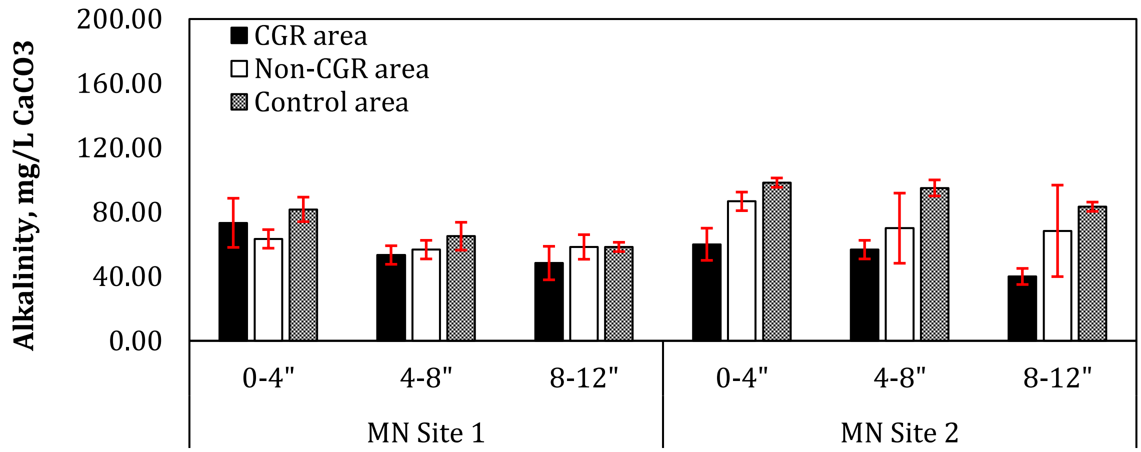


Figure 25. The results of alkalinity at the Minnesota roadsides.

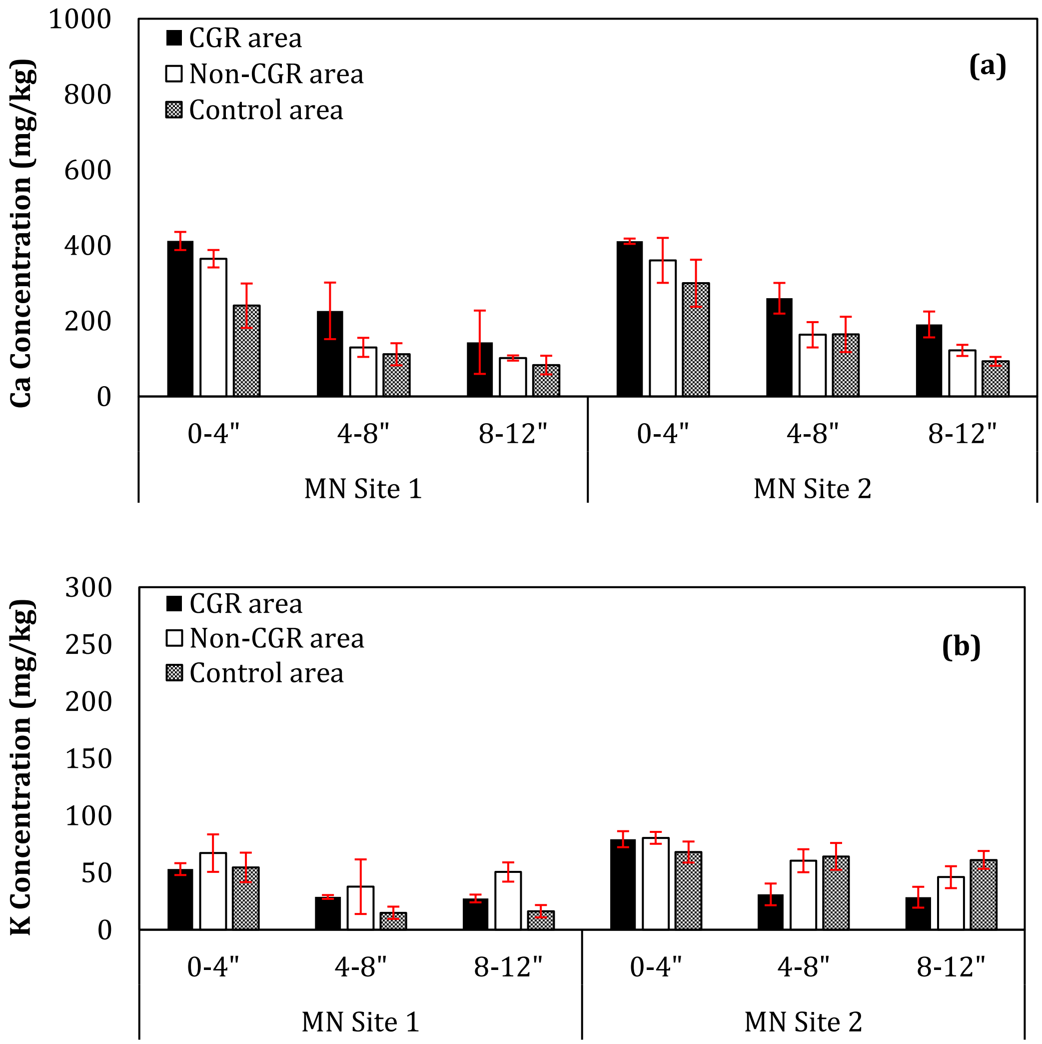
Table 24 shows the statistical results for alkalinity at the MN sites. For these two sites, CGR has a significant effect on alkalinity but the difference results from the higher alkalinity of the control area. The higher alkalinity at the control area is hypothesized to be related to soil composition and environmental activities. For other factors in different groups, Site 1 and Site 2 produce different conclusions due to different soil compositions, CGR sources, and environmental conditions.

Table 24. The ANOVA results of alkalinity at the Minnesota roadsides.

Group	Factors	*p-value*	
		Alkalinity at Site 1	*Alkalinity at Site 2*
Group 1 CGR area and Control area	CGR	0.0412	<.0001
	Depth	0.0019	0.0005
	CGR × Depth	0.9529	0.6951
Group 2 Non-CGR area and Control area	Slope	0.0152	0.0318
	Depth	0.0070	0.1971
	Slope × Depth	0.0975	0.7328
Group 3 CGR area and Non-CGR area	CGR × Slope	0.8006	0.0095
	Depth	0.0283	0.1487
	CGR × Slope × Depth	0.1969	0.6711

4.3.2.4 Concentration of Metals

Figure 26 shows the results with Std of exchangeable metals at the two MN sites. In Figure 26, the CGR area has the highest content of Ca, while for the other metals K, Mg, and Na, Site 1 and Site 2 produce different results due to different soil compositions and CGR sources. The exchangeable metals other than Na also have their higher concentrations in the upper soil layers. In the non-CGR area, level of K exhibits a higher concentration than that in the control area, and one reasonable hypothesis for this is that the non-CGR area may have received some slurry in the past from the CGR area through effects of gravity and rainwater. Since several factors (weather, traffic volume and maintenance frequency) can control quality of roadside soil, the levels of metals at roadside soil exhibit the different results from the soil at the Kelly Farm.



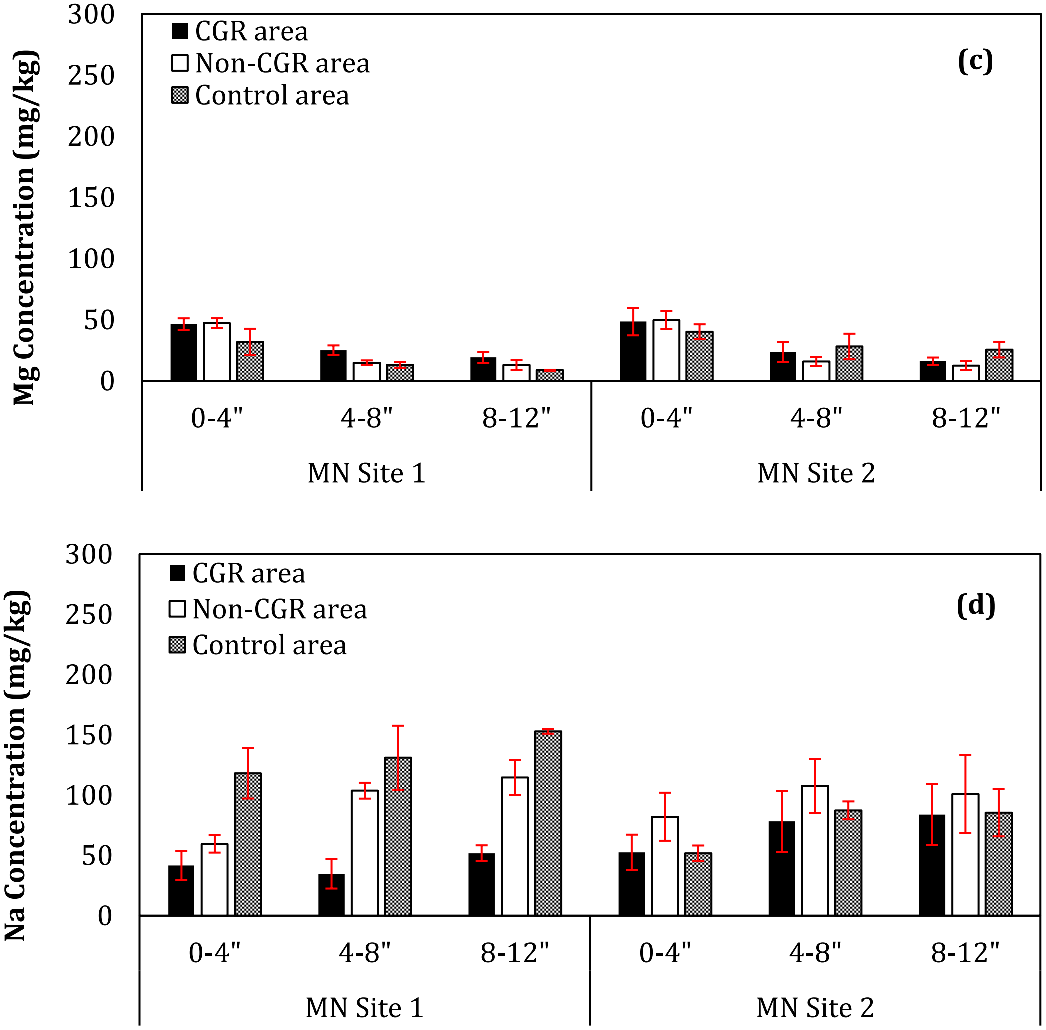


Figure 26. The concentrations of leached metals at the Minnesota roadsides: (a) Ca; (b) K; (c) Mg; and (d) Na.

Table 25. The ANOVA results of concentrations of leached metals at the Minnesota roadsides.

Group	Factors	*p-value*							
		Site 1				*Site 2*			
		Ca	*K*	*Mg*	*Na*	*Ca*	*K*	*Mg*	*Na*
Group 1	CGR	<.0001	0.0279	0.0004	<.0001	<.0001	0.0012	0.6225	0.7102
	Depth	<.0001	<.0001	<.0001	0.0588	<.0001	0.0002	0.0007	0.0150
	CGR × Depth	0.0071	0.1450	0.8079	0.3871	0.4380	0.0016	0.1865	0.8865
Group 2	Slope	0.0040	0.0038	0.0126	0.0001	0.0055	0.6253	0.1198	0.0383
	Depth	<.0001	0.0023	<.0001	0.0010	<.0001	0.0072	<.0001	0.0448
	Slope × Depth	0.0135	0.4151	0.0904	0.2511	0.0067	0.0666	0.0198	0.8107
Group 3	CGR × Slope	0.0006	0.0237	0.0157	<.0001	0.0005	0.0019	0.3187	0.0445
	Depth	<.0001	0.0075	<.0001	0.0005	<.0001	<.0001	<.0001	0.1482
	CGR × Slope × Depth	0.2399	0.6256	0.0884	0.0021	0.1229	0.0441	0.5419	0.8754

Table 25 presents the ANOVA analysis of exchangeable metals at the MN sites. At Site 1, CGR, depth, and slope show significant effects on concentration of metals, although some interactions do not result in significant differences. At Site 2, only Ca is significantly affected by the CGR and depth and no other interactions, while for other metals the different groups produce different statistical results. Differences between the two sites might result from the different soil compositions, CGR sources, and environmental conditions. In summary, at the CGR area only Ca shows a higher concentration than for other areas without slurry.

4.3.2.5 Cation Exchange Capacity

The soil CEC measurements with Std at the MN sites are presented in Figure 27. Both the CGR area and the non-CGR area exhibit higher CEC than for the control area, and the CEC of the middle and bottom layers is also lower than that for the surface layer. CGR is a source of rich exchangeable metals, and its presence can cause the higher CEC values in soil. CEC of the non-CGR area is higher than for the control area, perhaps due to CGR received in the past through effects of gravity and rainwater.

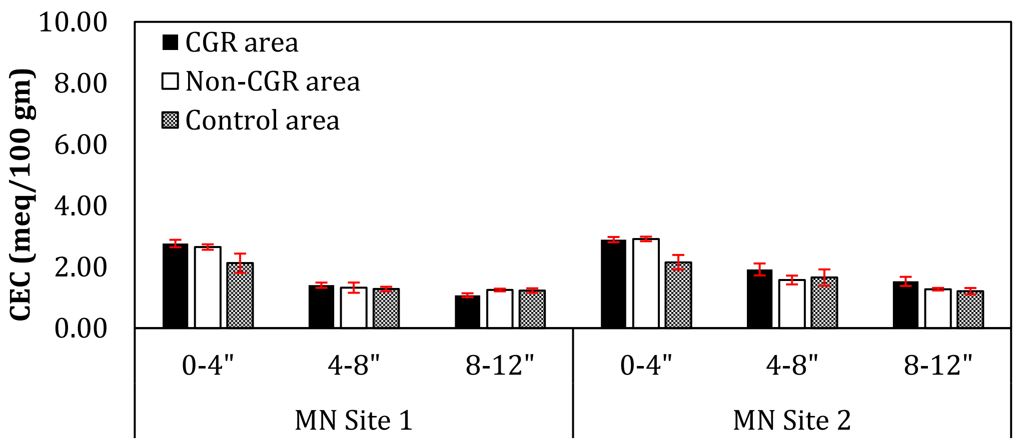


Figure 27. The results of CEC at the Minnesota roadsides.

Table 26. The ANOVA results of CEC at the Minnesota roadsides.

Group	Factors	*p-value*	
		CEC at Site 1	*CEC at Site 2*
Group 1 CGR area and Control area	CGR	0.0138	0.0003
	Depth	<.0001	<.0001
	CGR × Depth	0.0020	0.0907
Group 2 Non-CGR area and Control area	Slope	0.0206	0.0081
	Depth	<.0001	<.0001
	Slope × Depth	0.0261	0.0020
Group 3 CGR area and Non-CGR area	CGR × Slope	0.8813	0.0072
	Depth	<.0001	<.0001
	CGR × Slope × Depth	0.0674	0.0665

Table 26 shows the ANOVA results of CEC at the two MN roadsides. In this table, CGR, depth, and slope can cause significant differences, as reflected in their p values greater than 0.05. For the effects of interactions, Site 1 and Site 2 produce different conclusions because their soil compositions, CGR sources, and environmental conditions are different.

4.3.2.6 Exchangeable Sodium Percentage

Figure 28 shows that the control area exhibited the highest ESP value at Site 1, but at Site 2 the non-CGR area has a higher ESP than the other areas. Soil depth also influences ESP, with the deepest layer exhibiting the highest ESP, a result similar to that at the Kelly Farm.

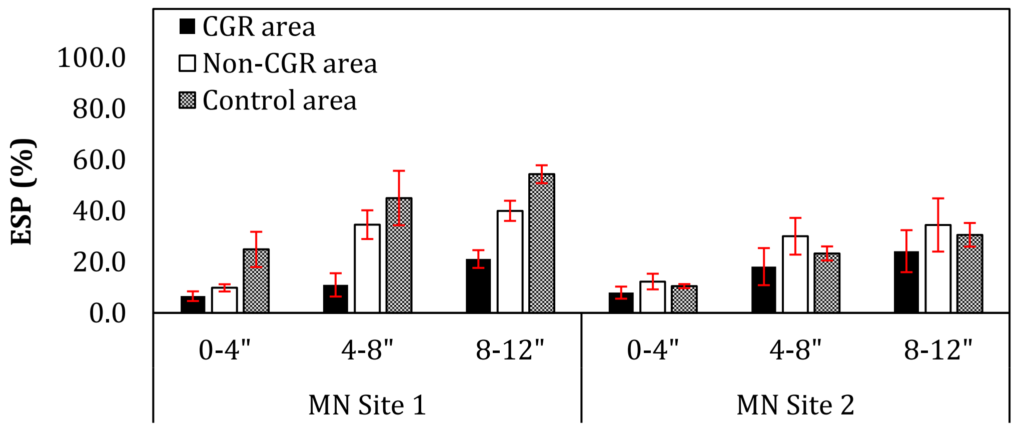


Figure 28. The results of ESP at the Minnesota roadsides.

Table 27 presents the results of ANOVA model for ESP at MN sites. Depth is a significant factor because the deeper layer exhibits the highest ESP values. At Site 1 CGR and slope significantly influence ESP. but opposite to that at Site 2. Different soil composition, CGR source, and environmental condition can cause these differences.

Table 27. The ANOVA results of ESP at the Minnesota roadsides.

Group	Factors	*p-value*	
		ESP at Site 1	*ESP at Site 2*
Group 1 CGR area and Control area	CGR	<.0001	0.0738
	Depth	0.0001	0.0002
	CGR × Depth	0.0697	0.8022
Group 2 Non-CGR area and Control area	Slope	0.0006	0.1547
	Depth	<.0001	0.0001
	Slope × Depth	0.7837	0.7627
Group 3 CGR area and Non-CGR area	CGR × Slope	<.0001	0.0204
	Depth	<.0001	0.0014
	CGR × Slope × Depth	0.0014	0.6298

4.3.2.7 Percent Base Saturation

The PBS results with Std from the MN sites are presented in Figure 29. At MN Site 1, the CGR area exhibit higher PBS than both the control area and the non-CGR area. At MN Site 2, the non-CGR area has a lower PBS than the others. In addition, the surface layer PBS is higher than for other layers, indicating that the CGR area has relatively more Ca, K, and Mg than non-CGR and control areas.

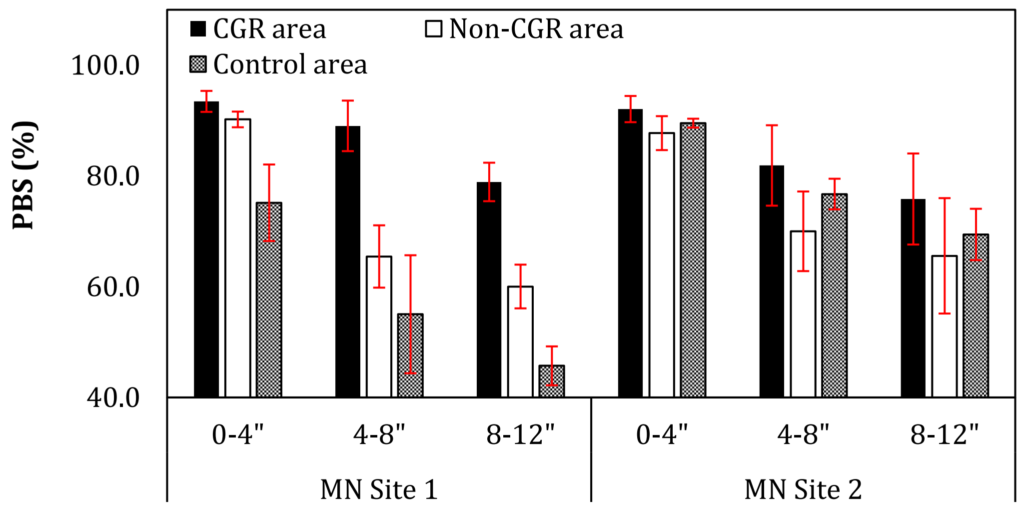


Figure 29. The results of PBS at the Minnesota roadsides.

Table 28 displays the statistical results of PBS at the MN sites. In Table 28, CGR in Group 1, slope in Group 2, and three-way interaction in Group 3 significantly affect PBS at Site 1 but not at Site 2, indicating that while the effect of CGR on PBS is not consistent with the results for the Kelly Farm, the two-way interaction of CGR and depth displays consistent results at both the MN sites and the Kelly Farm. Since PBS is determined by the concentration of metals and CEC, the difference in statistical results can be caused by the different soil composition, CGR source, and environmental activities.

Table 28. The ANOVA results of PBS at the Minnesota roadsides.

Group	Factors	*p-value*	
		PBS at Site 1	*PBS at Site 2*
Group 1	CGR	<.0001	0.0738
CGR area and Control area	Depth	0.0001	0.0002
	CGR × Depth	0.0697	0.8022
Group 2	Slope	0.0006	0.1547
Non-CGR area and Control area	Depth	<.0001	0.0001
	Slope × Depth	0.7837	0.7627
Group 3	CGR × Slope	<.0001	0.0204
CGR area and Non-CGR area	Depth	<.0001	0.0014
	CGR × Slope × Depth	0.0014	0.6298

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 KEY FINDINGS FROM CONTROLLED FIELD EXPERIMENTS AT KELLY FARM

Based on tests conducted at Kelly Farm to evaluate the effects of concrete grinding residue on physical and chemical properties of soil, key findings can be summarized as follows:

- The application of CGR did not induce statistically significant effects on the plant biomass at the Kelly Farm.
- The application of CGR had mixed effects on plant coverage percentages. Although plant growth of some species was sometimes inhibited by the CGR, at 10 and 20 ton/acre levels of CGR, plant growth for the warm-seasoned grasses and the legumes was promoted (but not a significant difference).
- The CGR did not significantly affect soil bulk density. The variation coefficient (relative standard deviation) of soil bulk density was as low as 0.05, indicating that soil bulk density was a relatively stable property.
- While the CGR did not significantly influence the saturated hydraulic conductivity values, one year after the application of 40 ton/acre CGR, saturated hydraulic conductivity tended to be smaller than it was for the other treatments.
- The CGR did not significantly influence soil infiltration.
- Soil pH measurements at the Kelly Farm showed that an increase in CGR application rate increased pH. This influence decreased with increasing soil depth, and this effect did not persist after one month.
- For EC measurement, the higher CGR application rates exhibited higher EC, with the top surface EC being much higher than that of deeper layers, and this effect still persisted after one year.
- With respect to alkalinity, the plots with highest CGR application rates exhibited the highest alkalinity, with the surface layer having a higher value than the other layers. In addition, CGR continued to increase soil alkalinity after one year.
- At the Kelly Farm, the higher application rate of CGR increased the concentrations of Ca, K, Mg, and Na, and the concentrations decreased with an increase in soil depth, although for K and Na, this effect did not persist after one year.
- CEC values increased with the application of CGR at the Kelly Farm, with surface soil exhibiting higher CEC, in general, and the effect of CGR on increasing CEC persisted after one year.
- ESP values increased with an increase in application rate of CGR at the Kelly Farm at the six-month and one-year stages. At the Kelly Farm sites, the deeper soil layers in general had higher ESP than the top surface soil. Since increased ESP may cause a reduction in soil water infiltration, CGR should not be discharged to soil with high sodicity.
- The application of slurry decreased PBS slightly at the Kelly Farm at the one-month stage.

- The effects of CGR on increases in pH and alkalinity can be beneficial to acidic soil due to liming effect. Moreover, based on the findings CGR can supply nutrients (Ca, Mg and K) to plants and increase CEC (soil fertility), and appropriate application rate of CGR have potential to promote plant growth. In this study, the promoted growth of the warm-seasoned grasses and the legumes was observed after application of 10 and 20 ton/acre CGR.

This results of field study at the Kelly farm control site indicated that the application of CGR up to 40 dry ton/acre did not significantly affect soil physical properties and plant biomass, however, the plant coverage percent of warm-seasoned grasses and the legumes were promoted and the chemical properties of soil were significantly influenced. The changed chemical properties of soil after addition of CGR were due to the rich content of metallic compounds (CaO, MgO, etc.) in CGR, but changes such as elevated pH, alkalinity, contents of nutrients and CEC are beneficial for vegetation from the perspective of improvements on plant growth and soil quality, especially for acidic soils. In consideration of the mitigated effects of CGR with soil depth and time, the discharge of CGR at 40 dry ton/acre is not a concern to groundwater and roadside environment if placements are kept away from sensitive areas such as water bodies. Additionally, the higher application rate (over 40 ton/acre) of CGR and longer evaluation period (over 12 months) are recommended in the future studies.

5.2 KEY FINDINGS FROM ROADSIDE EXPERIMENTS AT MINNESOTA SITES

Based on tests conducted at two sites (where CGR was previously offloaded) along I-90 near Austin, MN, to evaluate the effects of concrete grinding residue on physical and chemical properties of soil, key findings can be summarized as follows:

- There was no significant difference in bulk density values for the CGR affected area and the non-CGR affected area at Site 1. For Site 2, the bulk density values in the CGR-affected areas were significantly smaller than those in the non-CGR affected area.
- The saturated hydraulic conductivity values of the CGR affected area at Site 1 were not significantly different from the saturated hydraulic conductivity values of the non-CGR area, although at Site 2 the saturated hydraulic conductivity values of the CGR affected area were significantly smaller than the values of the non-CGR area.
- The CGR did not significantly affect soil infiltration.
- While the CGR did not significantly affect the roadside plant biomass, at Site 2, the plant biomass of the CGR affected area tended to be smaller than the plant biomass of the non-CGR area.
- The area receiving CGR slurry exhibited lower pH than areas that did not receive CGR.
- The CGR area exhibited the highest EC, and EC decreased with soil depth.
    - The surface layer of the control area exhibited the highest alkalinity at the Minnesota sites.
- The concentration of Ca was higher at the CGR area for both sites, but for other metals (K, Mg and Na), Sites 1 and 2 exhibited different trends.
- CGR areas exhibited higher CEC values, and the CEC of topsoil was higher than for other layers.

- The CGR area at the Minnesota sites exhibited the lowest ESP values, and the deeper soil layers had higher ESP than top surface soil in general.
- The CGR area exhibited higher PBS values than the other areas at the Minnesota sites, and deeper soil layers exhibited lower PBS values.

The study of two Minnesota roadsides investigated the long-term effects of CGR on roadside soil physical and chemical properties and plant biomass. The results for Site 1 showed that CGR did not affect soil physical properties and plant biomass significantly, but influenced alkalinity, CEC, ESP and PBS significantly. For Site 2, the results differed from those of Site 1, indicating that CGR significantly influenced soil bulk density and hydraulic conductivity, alkalinity and CEC. Multiple factors contributed to the differing results for Sites 1 and 2, including the deicing agents used on road surface, vehicle emission, CGR composition, CGR discharge rate, and time after spreading. Because the changed properties due to spreading of CGR did not indicate reductions in soil quality and plant growth, CGR was not found to be a long-term concern to roadside environments.

5.3 RECOMMENDATIONS FOR FUTURE STUDIES

5.3.1 Fate and Transport of CGR Particles in the Field and Its Modelling

The current research report investigated the change in pH, electrical conductivity (EC), alkalinity, cation exchange capacity (CEC), exchangeable sodium percentage (ESP), and percent base saturation (PBS), and element concentrations (e.g. Ca, Mg, Cr, Cu) in soil at different depths with different CGR loads for 2 years. The current report provides quantifiable data regarding the impact of CGR on soil at different depths but it does not provide any information regarding the fate and transports of CGR particles and leached elements through soil. Moreover, the current study investigated the changes in soil characteristics only in the vertical direction (1-D only). However, fate and transport of these elements will be in all three directions in real field conditions. Furthermore, it is expected that the fate and transport of elements and CGR particles will be faster with surface run off and as a result of this movement of CGR particles and elements will be more critical in the horizontal direction than in the vertical direction. Therefore, a field study along with fate and transport modelling analyses should be conducted as the next phase of this project. It is recommended that a field site along the highway be selected and CGR applied after this selection process. The recommended data collection should be at least 2 years.

5.3.2 Reuse of CGR with Other Stabilizers

CGR materials can be recycled in soils as a companion stabilizing agent. While CGR itself possesses high potential to be used for a stabilizing agent, it can also improve the soil strength when used with other conventional stabilizers such as cement, class C fly ash, lime, and commercial liquid stabilizers. CGR is a slurry material and can minimize the use of required water for soil stabilization with conventional stabilizers in addition to its own binding capacity. While this would cause a cost reduction during the construction process, it would also increase the sustainability and life-cycle cost of the chemical stabilization applications due to use of less water and less chemical stabilizers. The main goal of this project is to determine the optimum moisture and conventional stabilizer content that are used with different soil types. The optimum design will be determined per laboratory strength tests. This research will include extensive geotechnical engineering laboratory tests, and life-cycle cost and cost-benefit analyses.

5.3.3 Determine CGR Effects on Soil Thermal Properties and Soil Temperature

Based on the controlled field study at the Kelly Farm, a relatively thick surface CGR layer remained one and half years after the CGR application. The applied CGR has a light color, which may alter the surface radiation partitioning and surface energy balance. The CGR may also reduce soil water evaporation. Both processes could alter the soil temperature. Therefore, a possible future topic is to determine how CGR affects soil thermal properties and soil temperature distribution.

5.3.4 Perform a CGR Controlled Field Study on Compacted Soil

The controlled field study at the Kelly Farm was based on natural soil. However, along the roadside, the soil is usually compacted. Therefore, performing a controlled field study on compacted soil could better reflect CGR effects on roadside conditions. Measurements could include soil bulk density, saturated hydraulic conductivity, soil infiltrability, and plant germination and growth.

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