Freeze-thaw performance of granular roads stabilized with optimized gradation and clay slurry

Ziqiang Xue

Graduate Research Assistant, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

Jeramy C. Ashlock

Richard L. Handy Associate Professor, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

Bora Cetin

Associate Professor, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, USA

Sajjad Satvati

Graduate Research Assistant, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

Halil Ceylan

Professor, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

Yijun Wu

Graduate Research Assistant, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA

Cheng Li

Assistant Professor, School of Highway, Changan University, Xi'an, Shanxi Province, China

ABSTRACT: A recently-developed granular road stabilization method was applied to four test sections in different Iowa counties. This new method uses an optimized target gradation achieved by blending existing surface materials with two to three fresh aggregate types to achieve the tightest possible particle packing. A clay slurry is also incorporated into the top two inches during mixing of the surface aggregates to increase the plasticity and binding characteristics to reduce material loss. The performance of the test sections was measured using field dynamic cone penetrometer (DCP) tests, falling weight deflectometer (FWD) tests, and nuclear density gauge tests. The test results are compared to those of adjacent control sections as well as test sections stabilized using Portland cement and steel slag. Among the stabilization methods applied in the test sections, the Optimized Gradation with Clay Slurry stabilization method and the cement-treated 4" surface course was the most costeffective.

Keywords: Stabilization, granular roadway, elastic modulus, falling weight deflectometer, shear strength, dynamic cone penetrometer

1 INTRODUCTION

Granular-surfaced roads commonly provide access between rural and urban areas for hauling agricultural products to market, but high traffic loads and large numbers of freeze-thaw cycles in seasonally cold regions can damage the road surface, especially during springtime. Water present in the near-surface layers experiences phase changes due to the freezing and thawing [1]–[3], resulting in aggregate deterioration and various distresses such as loss of crown, washboarding, potholes, rutting, and raveling. Moreover, the mechanical properties of the surface layers, including gradation, shear strength, and stiffness, are altered due to the material property changes. Regular maintenance is therefore required to maintain road serviceability, which can be costly for DOTs or secondary roads agencies.

Stiffness and strength, the main factors in road design, depend on the quality, shape, aggregate size, thickness, and density of the surface layer [4]–[6]. Environmental conditions and traffic loads alter the surface elastic modulus and shear strength, and knowledge of such mechanistic factors can help in evaluating road performance. Previous studies have shown the significant effects of freeze-thaw cycles on degrading the mechanical properties of granular layers [7]–[11]. Stabilization of granular roadways with quarry fines byproducts has been proven to improve these properties by increasing plasticity and providing tighter bonding between aggregates [12]–[14]. Quarry fines are typically found in one of three distinct formats: screenings, pond fines, and baghouse fines, all of which are waste products of rock-crushing processes [15].

This study investigates the effects of utilizing a clay slurry quarry fines byproduct to provide improved binding between surface aggregates in four granular-surface road test sections. FWD and DCP tests were conducted on test sections and control sections to monitor the elastic modulus and shear strength of the surface aggregate layers subjected to seasonal freezing and thawing cycles. Nuclear gauge density tests were also conducted to compare the density and moisture content of the granular surface layers. The performance of sections stabilized with the clay slurry and an optimized gradation was compared with that of adjacent test sections stabilized with Portland cement and steel slag, as well as control sections.

2 MATERIALS

To cover a wide range of the state's climate conditions, subgrade types, and aggregate sources, the test sections were constructed in Cherokee, Hamilton, Howard, and Washington counties distributed across Iowa (Figure 1). The test sections were constructed by stabilizing the top 4" of the granular surface layers. For the Optimized Gradation with Clay Slurry (OGCS) sections constructed in all four counties, the top 4" of surface course materials were blended in optimized proportions, after which clay slurry was sprayed and mixed into the top 2". The 4"-thick steel slag sections were constructed in Howard and Cherokee counties using conventional granular roadway construction methods, and a 4" thick cement-treated surface course was constructed in Washington County using the county's wheel-loader mounted milling machine.

For the OGCS test sections, an optimized gradation using existing surface materials and locally available fresh aggregates was first determined using the spreadsheet tool published along with the TR-685 project report [25]. A predetermined depth of existing aggregates was first ripped using a motor grader, after which fresh aggregates were spread and blade-mixed in several passes to achieve a uniform gradation. To improve upon a previous study that used powdered bentonite for plasticity, a newly available clay-slurry quarry product was applied to the optimized gradation mixture during construction of the OGCS test sections in all four counties. The clay slurry was sprayed onto the aggregate mixtures using a self-unloading tanker truck, then blade-mixed into the top 2" of aggregates using numerous motor grader passes until the material had

somewhat dried out. The surface was then shaped, and a few compaction passes were applied using rubber-tire rollers to accommodate the wet mixture that tended to stick to smooth-drum vibratory rollers. To achieve an immediately drivable surface, a light covering of fresh surface aggregates (approximately two 13-ton truckloads for each 500-ft long test section) were spread over the top and pressed in with the rubber-tired roller. While the resulting surfaces were very wet immediately following construction, they were passable by traffic and typically dried up within 24-48 hours.

Figure 1. Locations of the test sections in four Iowa counties (Red dots show locations of the actual test sections).

2.1 Steel slag surface

Steel slag (SS) is an industrial byproduct commonly used as a stabilizer or amendment in roadway systems. Under compaction and road traffic, SS usually evolves into a high strength material with the capability for self-stabilization. In this study, the SS material was collected from Phoenix Services, LLC, in Wilton, IA. The full depth of the existing surface aggregate was first ripped down to the subgrade and hauled away and the slag then dumped in thin lifts sprayed with water and bladed. After shaping the surface, at least four passes of a rubber-tire roller were made, followed by a few passes of a vibratory smooth-drum roller.

2.2 Cement treated aggregate surface course

In this study, 7% Portland cement by dry weight was blended into a 4-in. (101.6-mm) thick surface aggregate course in Washington County without treating the subgrade. The cement was first spread over the test section, then mixed full-depth using a 60-in. wide RoadHog milling machine which was mounted on a Caterpillar 938M Wheel Loader and attached to a water feeder truck by a hose system. After mixing, additional water was sprayed with

a water truck and the surface was shaped with a grader. The surface was compacted with four passes of a rubber tire roller immediately followed by a smooth-drum vibratory roller to reduce the compaction delay time.

2.3 *Laboratory testing of construction materials*

After construction, laboratory tests were performed on samples from both the control sections and the stabilized sections. Sieve and hydrometer analyses were performed according to ASTM Methods D6913 and D7928 respectively, along with Atterberg limits tests (ASTM D4318) with classification by the AASHTO and USCS systems (ASTM D3282 & D2487). The index properties and USCS classifications of the materials sampled from the field sections summarized in Table 1 show that, despite the addition of clay-sized particles, the OGCS sections all had lower fines contents than their nearby control sections that contained aggregates abraded and broken down by traffic loading. The control section materials in Cherokee county were non-plastic, i.e., sandy river gravel was the primary source of surfacing material there, while in the other counties crushed limestone having fines with some plasticity was typically used. The slag sections also had very little fines contents from the slag source discussed in this paper. All sections were constructed on a relatively stiff subgrade layer.

3 TESTING METHODOLOGY AND RESULTS

To determine freezing and thawing effects, field tests were performed at five points on each section during winter 2018 and spring 2019. FWD and DCP tests were conducted to evaluate the elastic modulus and shear strength, respectively, of the granular surface and subgrade layers, and nuclear-density gauge tests were performed to determine moisture content and density of each test section. The test methods and results are described in the following sections.

3.1 *Dynamic Cone Penetration (DCP) tests*

DCP tests were conducted to track relative changes in shear-strength profiles in terms of correlated California bearing-ratio (CBR) values. The road system profile was treated as a two-layered system consisting of an aggregate surface layer over a subgrade layer. The thicknesses of the surface layers were estimated based on the DCP data by determining the point at which the plot of cumulative depth versus the number of cumulative blows exhibited a sudden change in slope [1]. The correlated CBR values (denoted DCP-CBR) were then averaged over the depth of the aggregate surface layer for both winter 2018 and spring 2019 field tests.

As shown in Figure 2, the DCP-CBR values for both the OGCS and control sections in Washington County increased from winter to spring, while the values for the 4" cement-treated section were erratic but mostly decreased. In Howard County, the OGCS, control, and 4" slag sections all experienced decreases in DCP-CBR values from winter to spring, with the strength loss generally being smallest in the OGCS section and greatest in the control section. In Hamilton County, the OGCS section exhibited higher DCP-CBR values in the spring, while those of the control section did not change much. In Cherokee County, the OGCS section exhibited a significant decrease in DCP-CBR values (but still greater than the control section's), while both the control and slag sections exhibited little change.

The primary difference setting Cherokee apart from the other three counties is that Cherokee have a continuous thick layer of sandy gravel grading to sand and finally transitioning to silt at a depth of a few feet, while the other three counties have a stiff clay subgrade directly below the 4" surface aggregate layers. Also, 13% of the optimized gradation in Cherokee

Table 1. Soil index properties of the surface materials sampled from control sections and after-constructed stabilized sections.

County	Hamilton			Washington			Howard			Cherokee			
Stabilization method	OGCS	Control	OGCS	4" Cement	Control	OGCS	4" Slag	Control	OGCS	4" Slag	Control		
Particle-size Distribution Results (ASTM D6913/D6913M-17/D4318-17)													
Gravel content (%)	60	20.4	56	69.5	32.9	71	78	43.5	54.9	52.5	25.9		
Sand content (%)	24	56.3	24	27	29.4	15	22	37.6	31.8	44.6	58.4		
Silt content (%)	9	12.7	11	3	23.0	11	0	12.7	6.3	1.7	9.9		
Clay content (%)	7	10.6	9	0.5	14.7	3	0	6.2	7.0	1.2	5.8		
Coefficient of uniformity, C_u	685	313	1536	4	1,064	425	5.4	449	563	11	121		
Coefficient of curvature, C_c	18	5	39	1	0.2	92	1.6	1	7	1	2		
Atterberg Limits Test Results (ASTM D4318-17e1)													
Liquid limit	23	19	27	NP	26	26	NP	18	28	NP	NP		
Plastic limit	13	14	14	NP	16	17	NP	13	14	NP	NP		
AASHTO and USCS soil classification (ASTM D3282-15 & ASTM D2487-17e1)													
USCS Classification	GC	SC-SM	GC	GP	GC	GC	GW	SC-SM	GC	GW	SM		
AASHTO Classification	A-2-4	A-1-b	A-2-6	A-1-a	A-4	A-2-4	A-1-a	A-1-b	A-2-6	A-1-a	A-1-b

Figure 2. Results of shear strength for surface layers (five points evenly distributed in each section).

consisted of river rock, the most common surfacing material in that county, while the other counties typically used crushed limestone. Based on the data shown in Figure 2, different subgrade support conditions and inclusion of river rock can reduce the strength of the OGCS method over time, while the subgrade and surfacing materials in Washington and Hamilton counties lead to strength increases for this method.

3.2 Falling-Weight Deflectometer (FWD) tests

The FWD tests were conducted using a JILS model SN121 FWD with a two-piece segmented loading plate. The FWD model used nine sensors with horizontal spacings between 6 and 12 inches (152.4 to 304.8 mm) to measure deflections on the road surface and provide a measured deflection basin. Three different target dynamic pressures of 250, 275, and 300 kPa were applied on the plate. The upper limit of 300 kPa was necessary to avoid over-ranging the deflection sensors for the relatively compliant unpaved road surface. The combined Boussinesq-Odemark solution was utilized to obtain stresses, strains, and deformations at each given depth and radii for a homogeneous, linear-elastic half-space model [16]. In conformance with this combined theory, back-calculation was performed based on dynamic loads and peak deflections observed under the geophones in the two-layered system [17]–[22].

Figure 3 shows the surface elastic modulus (termed E_{FWD}) determined from FWD tests performed at five points in each section during winter 2018 and spring 2019. In Washington County, E_{FWD} for the OGCS and control sections did not exhibit any statistically significant changes from winter to spring (one point in each section was stiffer in spring). However, in the 4" Cement section the modulus underwent a considerable decrease from winter to spring. In Howard and Cherokee Counties, the maximum change of E_{FWD} occurred as decreases in the OGCS section in Howard County and the OGCS and 4" slag sections in Cherokee county. The maximum decrease in E_{FWD} among all sections was in the OGCS section in Hamilton County; this section exhibited the highest average initial E_{FWD} (~18,000 MPa) compared to all sections during winter 2018 (due to the frozen ground in accordance with the weather information that day). The modulus for this section decreased significantly during spring 2019, becoming similar to that of the other sections (~1,300 MPa). The E_{FWD} for the control section also decreased slightly from winter 2018 to summer 2019 in Hamilton.

Figure 3. Elastic modulus of granular surface layers determined from FWD tests (five points evenly distributed in each section).

3.3 Nuclear gauge & result summary

Nuclear-gauge tests were conducted in the four counties to monitor changes in water content (ω) and dry density (γ_d) of the surface aggregates. The average results for ω and γ_d are shown in Table 2, along with the average values of E_{FWD} and DCP-CBR for all sections.

Based on the average values reported in Table 2, the cement-stabilized surface section in Washington County, the control sections in Howard and Cherokee counties, and the steel slag section in Howard County all exhibited significant decreases in CBR, indicating that these sections lost shear strength during spring thawing. The OGCS and control sections in Hamilton, Howard, and Cherokee counties, as well as all slag and cement sections, experienced significant decreases in elastic modulus during the spring thaw as well. However, the average strength and stiffness for all OGCS and cement-stabilized sections were higher than those of the corresponding control sections in all four counties after the spring thaw. The moisture

Table 2. Test result summary for Winter 2018 and Spring 2019 (average values for five tests in each section).

Section		Avg. DCP-CBR (%)		Avg. E_{FWD} (MPa)		Avg. γ_d (kN/m ³)		Avg. ω (%)	
		F ¹	S ²	F	S	F	S	F	S
Washington	OGCS	29.7	114.9	683.9	1,672.3	21.6	21.5	6.0	5.8
	Cement	169.9	115.1	6,547.6	846.7	20.3	20.0	9.2	8.2
	Control	33.9	70.9	645.4	1,162.6	20.2	20.5	7.9	6.3
Howard	OGCS	66.6	44.4	1,728.6	984.4	19.8	19.3	7.4	6.3
	Slag	77.1	43.4	555.8	363.6	26.4	25.3	4.3	3.5
	Control	116.7	39.7	691.9	426.3	20.8	18.9	7.8	6.7
Hamilton	OGCS	48.9	126.7	17,882.7	1,316.5	20.7	22.1	5.7	3.7
	Control	26.0	109.9	1,356.4	189.05	20.2	20.0	9.5	9.1
	OGCS	114.4	21.2	1,666.2	388.4	21.1	21.1	7.1	5.2
Cherokee	Slag	24.7	23.9	1,363.7	257.1	25.04	26.3	3.6	2.4
	Control	23.6	5.2	284.9	120.9	20.5	20.7	9.9	5.4

1 Fall 2018, ²Spring 2019

contents of all the control sections were found to be slightly higher than all other sections, with the exception of the cement-stabilized surface.

3.4 Cost comparison

For all the test sections, the construction and maintenance costs were tracked over the duration of the project. Figure 4 shows a summary of the construction costs.

Figure 4. Construction and maintenance costs (\$/sq.yd.) for stabilized sections in all four counties.

According to Figure 4, the two steel slag sections had relatively high costs compared to the other sections. The hauling cost was the most significant component for the slag sections, but this cost could be significantly lower for counties located close to a slag source. The cost for Portland cement materials comprised approximately 80% of the construction costs for the cement-stabilized section, and it should be noted that a rental cost was not incurred for the milling machine as it was owned by Washington County. Construction costs for the OGCS sections included hauling costs which depend on distance from the supplier on the eastern border of the state, and several hours of blade-mixing and rolling. The aggregate materials used in the OGCS sections came from the local quarries in each county.

After construction was finished, maintenance records including cost summaries were recorded by county engineers. Details of maintenance costs during the first year incurred by blading and spreading fresh aggregate over the test sections as needed are given in Table 3 (information from Cherokee County was not available). Maintenance costs in each section were minor compared to construction costs. In Hamilton county, the entire cumulative length of test sections was bladed instead of treating them separately. The control section in Howard county had a maintenance cost greater than four times that of the stabilized sections.

Beyond having a reasonable construction cost, to be cost-effective a stabilization method should have relatively good strength and binding properties that can be maintained for a reasonable length of time. The corresponding construction method should be easily achievable using readily-available equipment and materials. Because hauling costs will depend on distance from the stabilizer source, their contribution to the overall construction and maintenance costs should be carefully considered by secondary-road agencies.

Table 3. Construction costs for the four counties (2018-2019).

County	Detail	Section Name	Material Cost (\$)	Equipment Cost (\$)	Labor Cost (\$)	Cost (\$/sq. yd.)
Howard	1.42hrs blading	OGCS	NA	99.49	51.37	0.073
	1.9hrs blading	Control	497.60	133.01	68.68	0.340
	0.75hrs blading	4" Phoenix Slag	NA	52.48	27.10	0.077
Washington	3hrs blading	Entire 1 mile	NA	228.45	123.69	0.030
Hamilton	8hrs blading	Entire 1 mile	NA	609.20	254.88	0.060

4 CONCLUSIONS

While most of the stabilized test sections lost surface and subgrade strength and exhibited a decrease in elastic modulus due to effects of freezing and thawing, according to the test results not all counties lost strength after the winter season. The main conclusions with respect to the stabilization methods examined in this paper are as follows:

- The OGCS method exhibited good average strength that actually increased after the spring thaws in Howard and Washington counties, but decreased after spring thawing in Cherokee and Hamilton counties. The method was therefore found to be more effective in counties with clayey subgrades, and experienced significant strength loss in the county with a sandy subgrade. However, in all four counties the average strength and stiffness in the OGCS sections after the spring thaw were greater than those of the nearby control sections. The construction and maintenance costs for this method were also relatively low compared to the other two stabilization methods examined. Overall, while the OGCS method appears to be a cost-effective stabilization alternative easily achievable in Iowa, further observation is required to evaluate this method's long-term performance.
- While the steel slag sections exhibited good strength in both Howard County and Cherokee County, the cost of hauling steel slag can be significant depending on distance from available sources.
- The cement-stabilized surface course treatment exhibited a large increase in average strength that decreased after the spring thaw but remained higher than that of the control section. The stiffness was greatly improved after construction but fell below that of the control section after spring. Based on these conclusions, the 4" cement-stabilized surface is also recommended as a cost-effective alternative.

According to the test results, maintenance logs, and survey photos of the test sections, not all sections suffered from a significant strength decrease after the spring thaw. Based on cost and performance comparisons, the optimized gradation with clay slurry and 4" cement-stabilized surface methods appear to be the most cost-effective alternatives among those examined in this study.

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