August 14, 2013

Ms. Nicki Danielson-Bartelt
Minnesota Department of Transportation
3485 Hadley Avenue North, Mail Stop 610
Oakdale, Minnesota 55128-3307

Re: Matrix Riprap Implementation, MnDOT Contract No. 99136
(Ayres Associates Project No. 32-1679.00)

Dear Ms. Danielson:

Ayres Associates has completed the above-referenced research project on implementation of Matrix Riprap per MnDOT contract No. 99136 (including Amendments 1 and 2). This letter report provides a description of the demonstration installation (including one-half day training) and subsequent grout mix design and testing performed under this contract.

1. EXECUTIVE SUMMARY:

The Minnesota Department of Transportation (MnDOT) provided funding under Contract No. 99136 to perform a demonstration of Matrix Riprap installation as a scour countermeasure at an existing bridge abutment in Milaca, Minnesota. The installation was conducted by MnDOT District 3 maintenance personnel on May 16, 2012 under the guidance of Mr. Paul Clopper, P.E. of Ayres Associates. In addition to observing the demonstration installation, the approximately 30 MnDOT personnel in attendance also received one-half day of classroom training on the applications, design, and installation of this material.

Subsequent to the installation in Milaca, seven grout mix designs were batched and tested at Colorado State University under the direction of Mr. Clopper. The flowability of each batch was tested using standard American test equipment and compared to the results from the European Flow Table test, which has been used as the standard QA/QC test for the grout component of Matrix Riprap. Of all the standard American devices investigated, the results from the American slump cone test (ASTM C143) exhibited the best correlation to the European Flow Table results.

2. BACKGROUND:

The Minnesota Department of Transportation (MnDOT) has identified Matrix Riprap as a countermeasure to provide erosion resistance for minimizing scour and erosion in open channel flow. In particular, there is an interest in using this countermeasure as a cost-effective alternative to more traditional armoring treatments to protect bridge abutments from scour during flood events. The materials and application methods are presented in the Federal Highway Administration (FHWA) guidance document, Hydraulic Engineering Circular No. 23 (HEC-23), and in that document the system is termed Partially Grouted Riprap (Lagasse et al. 2009).

Matrix Riprap consists of relatively uniformly-sized angular riprap to which a Portland cement based grout is applied to "glue" the individual particles together. A median particle diameter of 9 to 15 inches is suitable for this purpose. The grout is <u>not</u> used to completely fill the voids between the particles. Therefore the resulting matrix remains porous and permeable. It also maintains flexibility under conditions of differential settlement and/or frost heave by cracking into conglomerate particles, where each conglomerate is composed of multiple rocks which remain glued together. **Figure 2.1** provides photographs of the material and its placement at a coastal site in northern Germany.

	
a. Placement in the dry	b. Close-up showing grout penetration into void spaces with porosity being maintained

Figure 2.1. Partially grouted riprap ("matrix riprap"). From HEC-23, 3rd Edition.

3. DEMONSTRATION SITE AND PILOT INSTALLATION:

3.1. Site Description:

A demonstration site was identified by MnDOT personnel for the application of Matrix Riprap at an existing bridge abutment (Bridge # 48030, Hwy 23 over Rum River in Milaca, MN). Although not originally designed for Matrix Riprap, the bridge abutments have existing riprap of a size generally suited for this treatment. The existing riprap at this site was rounded, whereas ideally the riprap should be angular to sub-angular; however, the partially grouted technique can be applied to any riprap as long as the d_{50} of the riprap ranges from 9 to 15 inches. Also, at this site, in some areas the rock gradation was not very uniform, with some very large rocks surrounded with much smaller rocks which led to small-sized voids. In some areas, sediment and soil had washed into the voids of the original riprap, thus decreasing the amount of open void area available for grout penetration. **Figure 3.1** provides a photo of the abutment and riprap prior to the grout installation.

Figure 3.1. Photo of Bridge 48030 left abutment prior to grout installation.

3.2. Grout mix and Testing:

The target grout mix presented in HEC-23 for partially grouted riprap is:

For 1.0 Cubic Yard:

Portland cement:	750 lb
Fine aggregate (sand):	1,190 lb
Coarse aggregate (pea gravel):	1,190 lb
Water:	435 lb
Entrained air:	5 to 7 %

To ensure the correct grout flowability, the European Flow Table test target spread of the grout for placement in the dry should be:

34 to 38 cm	(no taps)	(13.4 to 15.0 inches)
50 to 54 cm	(after 15 taps of the hinged table)	(19.7 to 21.3 inches)

Figure 3.2 shows the European flow table with the grout spread after 15 taps of the hinged table.

a. European Flow Table and cone

b. Grout spread after 15 taps of the hinged table

Figure 3.2. European Flow Table test. From HEC-23, 3rd Edition.

On May 15, 2012, Ms. Nicole Danielson-Bartelt of MnDOT and Mr. Paul Clopper of Ayres Associates coordinated with the Knife River concrete batch plant in Milaca to test the grout mix design. A first trial batch of 3.0 cubic yards was prepared and tested. The first batch consisted of the following components (on a 1.0 cubic yard basis):

Milaca Trial Batch #1 (for 1.0 Cubic Yard):

Portland cement:	750 lb
Fine aggregate (sand):	1,230 lb
Coarse aggregate (pea gravel):	1,200 lb
Water:	479 lb
Air entrainment additive:	7.6 oz
Water reducer additive:	30.0 oz

The results of various tests of Trial Batch #1 are as follows:

European Flow Table test:

- 34.5 cm (no taps) (13.6 inches)
- 65.0 cm (after 15 taps) (25.6 inches)

American slump test:

- 8.75 inches vertical slump

Entrained air:

- 15 %

Based on the excessive spread of the grout after 15 taps of the European flow table (65 cm vs. 54 cm maximum recommended spread), the mix was adjusted and a second trial batch of 3.0 cubic yards was prepared. No water reducing agent was incorporated in the second batch, and less water was used. The second batch consisted of the following components (on a 1.0 cubic yard basis):

Milaca Trial Batch #2 (for 1.0 Cubic Yard):

Portland cement:	750 lb
Fine aggregate (sand):	1,230 lb
Coarse aggregate (pea gravel):	1,200 lb
Water:	423 lb
Air entrainment additive:	5.7 oz
Water reducer additive:	none

The results of various tests of Trial Batch #2 are as follows:

European Flow Table test:

- 34.0 cm (no taps) (13.4 inches)
- 57.0 cm (after 15 taps) (22.4 inches)

American slump test:

- 7.5 inches vertical slump

Entrained air:

- 9 %

Even though Trial Batch #2 was slightly over the maximum recommended grout spread after 15 taps of the European flow table (57 cm vs. 54 cm), this mix design was deemed adequate for installation at the demonstration bridge site. **Figure 3.3** provides photos of the European flow table and American slump cone tests of Trial Batch #2 at the Knife River batch plant in Milaca, MN.

	
a. European flow table and cone. Note 34 cm diameter spread after no taps of the table.	b. American slump cone test with 7.5 inch vertical slump.

Figure 3.3. Grout tests of Trial Batch #2 in Milaca, MN.

3.3. Grout Placement at Bridge Abutment:

Setup: On May 16, 2012, MnDOT District 3 traffic and maintenance personnel provided traffic control on the bridge and installed the approved grout on the existing abutment riprap at Bridge #48030. Note that only the left (east) abutment received the Matrix Riprap treatment; the right (west) abutment was left alone during this project. The intent of MnDOT is to monitor, over time, the performance of the Matrix Riprap on the left (east) abutment and compare its performance to that of the existing loose riprap on the right (west) abutment.

The District 3 maintenance personnel provided a Bobcat™ dual-stroke grout pump to deliver the grout from a staging area on the bridge deck to the abutment riprap below. **Figure 3.4** provides photos of the setup prior to grouting.

	
a. MnDOT crew setting up for partial grout installation.	b. Bobcat™ grout pump ready to receive grout from concrete truck.

Figure 3.4. Grout pump setup for Matrix Riprap installation in Milaca, MN.

A sufficient length of 2.5 inch diameter flexible grout hose was available to hang from the bridge deck and reach all the way underneath the bridge, thereby avoiding the need to move the grout pump from one side to the other. The hose had a 2 inch diameter nozzle. While the hose was being deployed, a final check on the grout flowability was made with the European flow table to ensure the batch as delivered to the site had the proper consistency. **Figure 3.5** illustrates the setup.

	
a. Flexible grout hose deployed from bridge deck.	b. Checking grout spread on site. Note 57 cm spread after 15 taps of the hinged table.

Figure 3.5. Matrix Riprap grout installation setup in Milaca, MN.

Grout placement: For proper installation of Matrix Riprap, the intent of the grout placement operation is to "glue" individual stones together by placing the grout at the contact point between one stone and the next. With the proper consistency and flowability, the grout will penetrate down through the voids and glue the rocks together in the lower portion of the riprap blanket as well, while maintaining approximately 50% of the void space open. This achieves the desired final result, producing a system that is porous and permeable. *<u>The natural tendency of a grout operator to place the grout nozzle directly into the voids and fill them up is to be avoided at all costs.</u>*

As grouting commenced at Bridge #48030, the biggest problem was the inability to throttle the flow rate low enough to place the grout accurately. The pump delivered the grout in pulses, with each pulse delivering a large volume of grout in a short period of time (2-3 seconds). This forced the person on the end of the hose to "shoot" the grout at the desired location from a distance of 3 to 4 feet away, instead of placing the grout at a manageable rate from a couple inches above the surface of the riprap. In many areas, the person on the end of the hose was not able to move fast enough to distribute the grout uniformly around the stones. This resulted in excessive "splash" on the surface of the stones. **Figure 3.6** shows the grouting process in action. **Figure 3.7** provides photos of the finished installation.

Observations and recommendations: At the conclusion of the pilot installation, the following observations and recommendations are made:

1. The original riprap installation was not designed as a Matrix Riprap system, but instead was "retrofitted." Ideally, the stones should be more angular instead of rounded, and should be more uniform in size; however, this demonstration site will provide valuable information on the performance of matrix riprap where rounded stones were used. In places at this site, smaller stones and soil in and around the larger riprap particles resulted in very small void spaces which the grout could not penetrate. In these local areas, the grout simply puddled on the surface.

a. Note distance from nozzle to riprap and resulting splash.

b. Managing the grout hose requires several people working on an uneven surface.

Figure 3.6. Placement of grout at Bridge # 48030.

a. Note the excessive amount of grout on the surface of the stones in many places.

b. In this area, the distribution of grout is appropriate. Note open void spaces.

Figure 3.7. Final condition of Matrix Riprap at Bridge # 48030.

2. The rate of grout delivery was too great for accurate placement of the grout, resulting in excessive splash on the surface of the stones. This in itself is not detrimental to the performance of the system, but is not ideal from an aesthetic point of view. Ideally, the grout should be placed with the nozzle close to the riprap surface so that the grout glues the stones together just at their contact points.

   Although the author has had good experience with dual-piston grout pumps on other projects, consideration might be given to the use of a screw-type pump (for example, Bunker model B100) to deliver a more manageable flow rate and eliminate the pulsing effect we experienced at this project site.

3. The overall installation achieved its objective of demonstrating the technique and familiarizing MnDOT personnel with the equipment, testing, and logistical requirements involved in proper Matrix Riprap implementation.

4. Monitoring the installation and comparing it to the condition of the loose (ungrouted) riprap on the right abutment should be conducted annually. Ideally, monitoring (including photo documentation) could be done after the ice breakup each spring to determine the resistance of the Matrix Riprap to ice loading, and again after the runoff season has peaked to determine its performance under hydraulic loading. Any maintenance required on either the left or right abutment should be documented and added to the file for this research project.

4. CORRELATION BETWEEN EUROPEAN FLOW TABLE AND STANDARD AMERICAN TESTS:

4.1 Purpose and Background:

At the time of this study, the European flow table is that was used in these tests were unavailable for purchase in the United States; however, we understand that U.S. suppliers can now obtain and provide these units, but at a considerable price considering the shipping price from Europe. The MnDOT Bridge Office owns one unit that was purchased and shipped from the United Kingdom. The Bridge Office acknowledges that it would be difficult to coordinate the lending out of this piece of equipment for every project where Matrix Riprap was desired. In addition, many MnDOT participants at the demonstration site in Milaca indicated that they would be much more interested in implementing Matrix Riprap if they could use standard American testing equipment instead of this unique European device.

Therefore, following the demonstration installation in Milaca, MnDOT Contract No. 99136 was amended to include an investigation of standard American tests of concrete and grout to determine if a correlation to the European Flow Table test with American practices could be established. The investigation was subsequently conducted at Colorado State University's Hydraulics Laboratory under the direction of Mr. Paul Clopper of Ayres Associates, as described below.

Seven grout mix designs were produced, each with varying proportions of cement, sand, pea gravel, and water. Each batch was made with a target weight of approximately 200 pounds, or about 1.5 cubic feet. Each component of the mix was measured to the nearest one-half pound. Some mixes were intentionally produced to achieve a grout that was too "thin," and others that were too "thick." Each mix was then tested (three replicates for each mix, for each test) in accordance with the following procedures:

1. European Flow Table test (as described in HEC-23 and implemented at the Milaca site)

2. ASTM C143, "Standard Test Method for Slump of Hydraulic-Cement Concrete"

3. ASTM C1362, "Standard Test Method for Flow of Freshly-Mixed Hydraulic-Cement Concrete" (This test is also referred to as the "K-Slump Test")

4. ASTM D6449 "Standard Test Method for Flow of Fine Aggregate Concrete for Fabric Formed Concrete (Flow Cone Method)"

Figure 4.1 presents the grain size distributions for the fine aggregate (sand) and coarse aggregate (pea gravel) used in the mix design at Colorado State University. **Figures 4.2 through 4.5** show the standard American grout tests (using ASTM standards) performed at Colorado State University. The European Flow Table test was also performed on each of the seven trial mixes (three replicates), as previously shown in Figure 3.2.

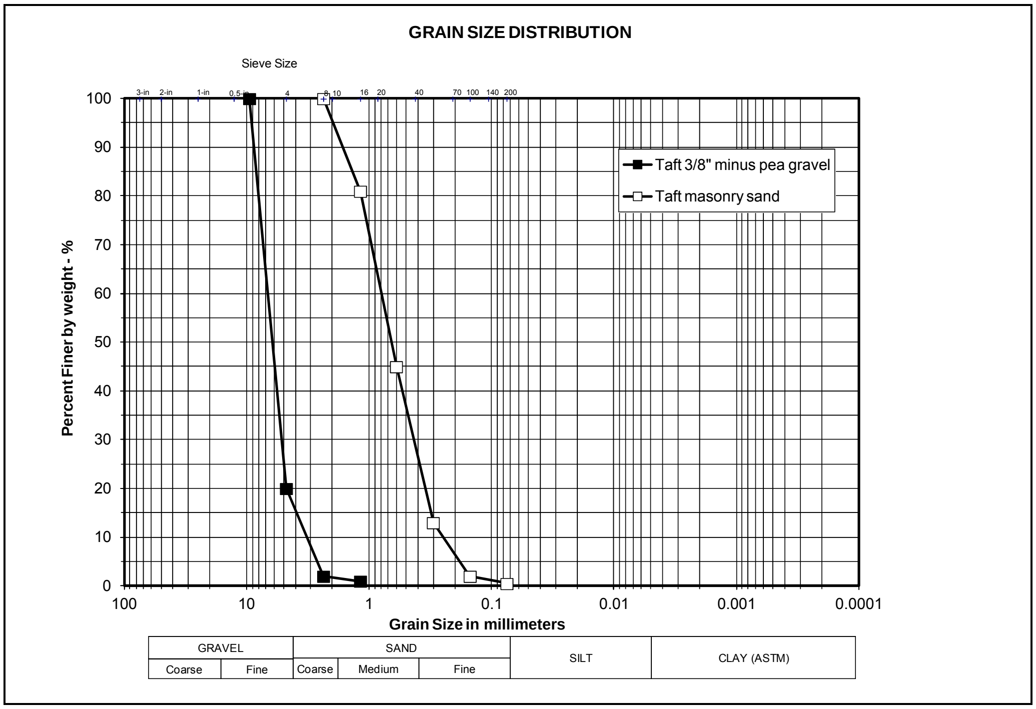


Figure 4.1. Grain size distributions used in CSU grout correlation investigations.

a. Components of each grout mix were measured to an accuracy of 0.5 pounds.

b. A small (3 cubic feet) portable concrete mixer was used in the CSU tests.

Figure 4.2. Grout mix tests at Colorado State University.

	
a. American slump cone in foreground. Compare to European cone on table in background.	b. American slump is measured vertically.

Figure 4.3. ASTM C143, standard American slump test.

	
a. Penetration of the piston is measured after 60 seconds of immersion in the grout.	b. Position of the piston is recorded immediately after extraction.

Figure 4.4. ASTM C1362, K-slump test device.

	
a. The flow cone is filled with grout to a prescribed volume.	b. The time it takes for the grout to flow out of a specified nozzle diameter is recorded.

Figure 4.5. ASTM D6449, flow cone test device.

4.2. Results:

The following discussion presents a summary of the findings from the correlation study tests conducted at CSU. In general, the investigation focused on the correlation of standard American tests as compared to the European Flow Table tests after 15 taps, as that measurement represents the flowability of the grout under the vibration and placement conditions of the grout. Detailed information regarding the grout mix designs and test results are provided in **Appendix A** of this report.

1. European Flow Table Test - No taps vs. 15 taps:

As a first approach, our research team felt it was important to determine whether the European Flow Table test yielded consistent results with the grout spread measurements obtained after no taps compared to the measurements after 15 taps. Because three replicates were performed on each batch, the average result and the individual results were both analyzed. Therefore, the results present 21 data points representing the individual test results, as well as 7 data points that represent the average of the 3 replicates for each test.

The results for all seven trial batches are shown in **Figure 4.6**. The spread (diameter) of the grout after no taps compared to the spread after 15 taps (which represents the effect of vibration during grout placement) was quite good, with an R-squared regression value of about 0.90.

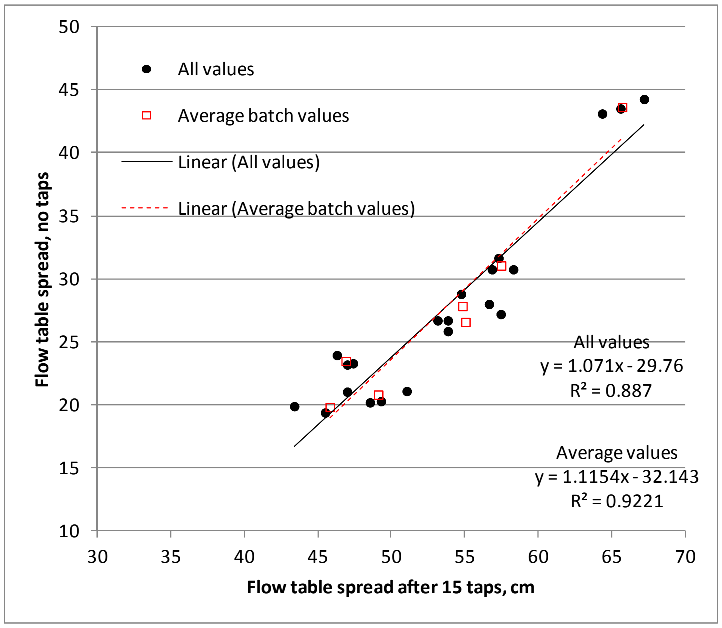


Figure 4.6. European Flow Table test results: No taps vs. 15 taps.

2. ASTM C143, "American slump" vs. European Flow Table test:

Of the three ASTM tests investigated, the standard American slump test (ASTM C143) correlated best with the European flow table test results after 15 taps. The acceptable tolerance of the European flow table spread for grout (placed in the dry) correlates well with a slump of about 5 to 8 inches, with an R-squared value of about 0.89. The results are shown in **Figure 4.7**.

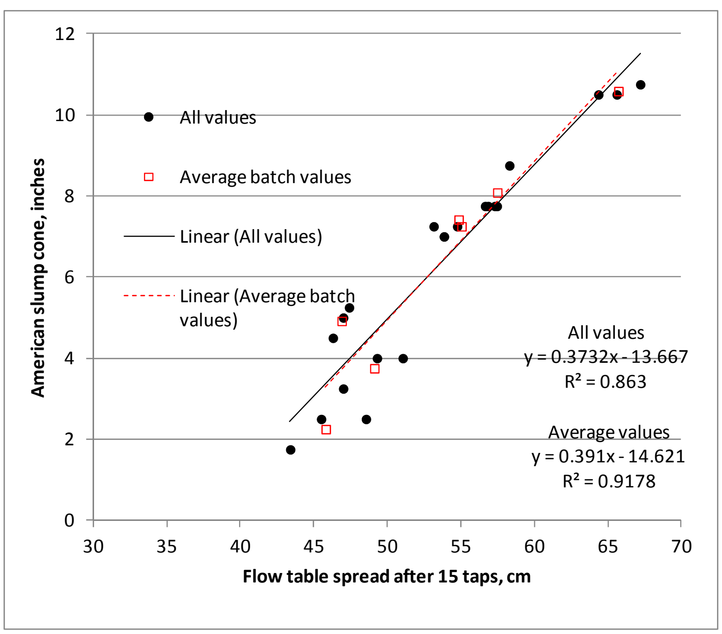
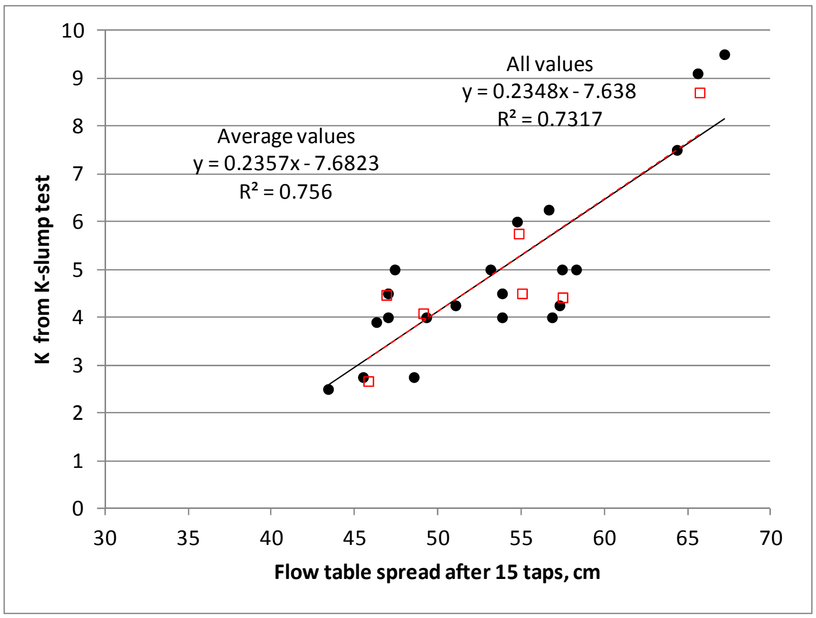


Figure 4.7. American slump values vs. European Flow Table test after 15 taps.

3. ASTM C1362, "K-slump" vs. European Flow Table test:

The K-slump test offers a quick and easy way to measure the flowability of a concrete grout. Unfortunately, the presence of larger aggregate (pea gravel) sizes in all the test mixes appeared to limit the repeatability of test results from this device. The within-test variability was relatively large, resulting in a determination that this test is not appropriate for assessing the suitability of grout for Matrix Riprap implementation. The overall R-squared value compared to the European Flow Table test was about 0.74, but the test values in the range of acceptable European Flow Table values showed an unacceptably wide range. The results are shown in **Figure 4.8**.



4. ASTM D6449, "Flow Cone" vs. European Flow Table test:

This test turned out to be a complete disappointment to the Ayres research team. The presence of coarse aggregate ("pea gravel") material in all the test batches resulted in clogging of the flow cone nozzle. This was not expected, given that the maximum nozzle diameter of 0.75 inch was twice as large as the largest particle size in the pea gravel. Clearly, this test is designed for "neat cement grout" which contains no particles larger than sand size. We obtained no data from this test, as even the mixes which contained a small percentage of pea gravel were still able to clog the 0.75 inch orifice.

4.3. Conclusions:

1. Based on the results of the correlation studies, we conclude that the standard American slump test (ASTM C143) can be used, with caution, as a surrogate for the European Flow Table test. Although more study is necessary, our opinion is that a slump of no less than 6.5 inches and no more than 7.5 inches will yield a grout mix that exhibits the proper consistency and flowability for use in Matrix Riprap applications. This is an extremely encouraging result, but must be noted that it is still preliminary in nature and much work remains to be done to ensure this test result produces a suitable grout. In the interim, when Matrix Riprap installations are performed, we encourage the measurement of both European Flow Table and American slump tests are made and recorded for future study. Ayres Associates can and will maintain a database of such studies and measurements to enhance the understanding of this technology, provided that the data is made available to us.

2. An additional comment can be made at this point: Our research team noted that these various mixes showed a marked difference in flowability depending upon the ratio of fine to coarse aggregate in the mix; the greater the ratio, the less flowability was observed. This is because the sand particles tend to bind the water more closely than the pea gravel, resulting in a "thicker" grout, even though the total amount of (sand + pea gravel) as a ratio to water remains the same.

3. As a result of observation #2 above, we recommend that more tests be performed with a grout that has little or no coarse aggregate (pea gravel), and uses a slightly greater amount of water to compensate to achieve the desired flowability. We believe that the ultimate performance of a "neat cement" grout for Matrix Riprap application would compare favorably with the current mix design that uses an equal amount of fine and coarse aggregates. This change might well result in similar performance of Matrix Riprap, while alleviating the concern of clogging the grout pump as expressed by MnDOT District 3 maintenance personnel.

5. COMMENTS ON CURRENT MNDOT SPECIAL PROVISION 2511 FOR MATRIX RIPRAP:

Appendix B provides the most current version of the MnDOT special provision 2511 for Matrix Riprap implementation. Ayres Associates research team's comments and observations regarding the MnDOT special provision 2511 document, in its current form, are provided in this section.

1. In general, MnDOT special provision 2511, in our opinion, should prove suitable for implementation of Matrix Riprap for scour and erosion protection. We note that the test requirements are specific to the European Flow Table test. We have suggested alternative language based on the results of the grout correlation studies described in this report.

2. **3601.2.A2e Matrix Riprap:** MnDOT riprap specifications indicate that, "The specification of Class III , IV or V riprap shall be used for matrix riprap." These specifications ensure that these classes refer to d_{50} values of 9", 12", and 15" as specified in HEC-23; we note that in HEC-23, these classes are referred to as Class II, III, and IV. Also, a uniformity coefficient $C_u = d_{85}/d_{15}$ should be specified such that C_u is less than or equal to 2.5.

3. **2511.2.C:** Delete the reference to "consistency of toothpaste." Add a reference to the European Flow Table test to "Consistency (Slump) test procedure" to make sure this requirement indicates that the European flow table is the standard. The Ayres Associates research team can support, at this time, an addition to this section that indicates that a standard American slump test, in accordance with ASTM C143 could be added to this section as an additional test, with a vertical slump tolerance of 6.5 to 7.5 inches.

4. **2511.3.D:** Same comment as in item #2 above. We note that the current MnDOT riprap classes III, IV, and V are the same as HEC-23 classes II, III, and IV.

5. The MnDOT requirement of a "test pad" is greatly appreciated. In this section, we believe it would be appropriate to discuss the grout delivery rate and the fact a continuous flow of grout at the rate of no more than 10 gal/min (0.6 l/s) is optimal for placing the grout in a manageable manner to achieve the objective of "gluing" the individual stones together at their contact points. Please refer to the discussion in Section 3.3 regarding grout pump selection and application rates.

I trust that this documentation meets your needs and expectations. It has been a pleasure working with you on this project. Please let me know if you have any questions or need additional information.

Sincerely,

Ayres Associates Inc

Director, Applied Technology

PEC:sp

Enclosure

APPENDIX A

SUMMARY OF COLORADO STATE UNIVERSITY (CSU) TEST DATA ON GROUT MIX DESIGN AND TESTING

Performed by: CSU AND AYRES ASSOCIATES INC

On behalf of:

MINNESOTA DEPARTMENT OF TRANSPORTATION

MATRIX RIPRAP IMPLEMENTATION
CONTRACT NO. 99136

A.1: TRIAL BATCH MIX DESIGNS

Batch 1 measured 03/29/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	41.5	41.5	0.0	0.24	0.21			
sand	67.0	65.8	1.2	0.38	0.34			
gravel	67.0	66.6	0.4	0.38	0.34			
water	22.5	0.0	22.5	0.13	0.11			
SUM	198	173.9	24.1	1.13	1.00	0.581	0.225	0.139

Batch 2 measured 03/29/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	41.5	41.5	0.0	0.24	0.22			
sand	67.0	65.8	1.2	0.38	0.35			
gravel	67.0	66.6	0.4	0.38	0.35			
water	17.5	0.0	17.5	0.10	0.09			
SUM	193	173.9	19.1	1.10	1.00	0.461	0.178	0.110

Batch 3 measured 04/01/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	41.5	41.5	0.0	0.24	0.21			
sand	67.0	65.8	1.2	0.38	0.34			
gravel	67.0	66.6	0.4	0.38	0.34			
water	19	0.0	19.0	0.11	0.10			
SUM	194.5	173.9	20.6	1.11	1.00	0.497	0.192	0.119

Batch 4 measured 04/01/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	41.5	41.5	0.0	0.24	0.21			
sand	89.5	87.9	1.6	0.51	0.46			
gravel	44.5	44.2	0.3	0.25	0.23			
water	19	0.0	19.0	0.11	0.10			
SUM	194.5	173.6	20.9	1.11	1.00	0.503	0.161	0.120

Batch 5 measured 04/01/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	41.5	41.5	0.0	0.24	0.21			
sand	45.0	44.2	0.8	0.25	0.23			
gravel	89.0	88.4	0.6	0.51	0.46			
water	19	0.0	19.0	0.11	0.10			
SUM	194.5	174.1	20.4	1.11	1.00	0.491	0.238	0.117

Batch 6 measured 04/05/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	45.5	45.5	0.0	0.26	0.23			
sand	67.0	65.8	1.2	0.38	0.34			
gravel	67.0	66.6	0.4	0.38	0.34			
water	19	0.0	19.0	0.11	0.10			
SUM	198.5	177.9	20.6	1.13	1.00	0.453	0.185	0.116

Batch 7 measured 04/05/2013						Ratios		
Component	Moist aggregate	Dry weight	Total water	Percent by dry weight	Percent by wet weight	Water: cement	Water: (cement + fine agg)	Water: (cement + fine + coarse agg)
	lb	lb	lbs	decimal	decimal	decimal	decimal	decimal
cement	37.5	37.5	0.0	0.22	0.20			
sand	67.0	65.8	1.2	0.38	0.35			
gravel	67.0	66.6	0.4	0.38	0.35			
water	19	0.0	19.0	0.11	0.10			
SUM	190.5	169.9	20.6	1.09	1.00	0.550	0.200	0.121

A.2: TRIAL BATCH TEST RESULTS : RAW DATA

CSU Grout Mix		European Flow Table per HEC-23		American slump, C143	K-slump device, ASTM C1362			Flow cone, ASTM D6449
Batch no.	Replicate	Dia, cm (0 taps)	Dia, cm (15taps)	Slump, in	K reading	W reading	K-W	Time, seconds
1	a	44.25	67.20	10.75	9.50	1.20	8.30	n/a, ¾" nozzle clogged
	c	43.50	65.60	10.50	9.10	0.10	9.00	
	b	43.10	64.35	10.50	7.50	2.00	5.50	
2	c	23.30	47.40	5.25	5.00	1.25	3.75	n/a, ¾" nozzle clogged
	b	23.20	47.00	5.00	4.50	3.00	1.50	
	a	23.95	46.30	4.50	3.90	2.75	1.15	
3	b	27.20	57.45	7.75	5.00	3.75	1.25	n/a, ¾" nozzle clogged
	a	25.85	53.85	7.00	4.50	2.75	1.75	
	c	26.70	53.85	7.00	4.00	2.25	1.75	
4	a	21.10	51.05	4.00	4.25	2.50	1.75	n/a, ¾" nozzle clogged
	b	20.30	49.30	4.00	4.00	2.50	1.50	
	c	21.05	47.00	3.25	4.00	2.00	2.00	
5	a	28.00	56.65	7.75	6.25	1.50	4.75	n/a, ¾" nozzle clogged
	b	28.80	54.75	7.25	6.00	1.25	4.75	
	c	26.70	53.15	7.25	5.00	2.50	2.50	
6	c	20.20	48.55	2.50	2.75	1.25	1.50	n/a, ¾" nozzle clogged
	b	19.40	45.50	2.50	2.75	1.00	1.75	
	a	19.90	43.40	1.75	2.50	0.75	1.75	
7	b	30.75	58.30	8.75	5.00	2.25	2.75	n/a, ¾" nozzle clogged
	c	31.65	57.30	7.75	4.25	2.00	2.25	
	a	30.75	56.85	7.75	4.00	2.25	1.75	

APPENDIX B

MnDOT SPECIAL PROVISION 2511:

MATRIX RIPRAP IMPLEMENTATION

S-1 **<u>(2511) RANDOM RIPRAP SPECIAL – MATRIX RIPRAP</u>**

Mn/DOT 2511 is hereby modified and/or supplemented with the following:

S-1.1 2511.1 Description

This work consists of constructing matrix riprap (formerly called Partially Grouted Riprap) in accordance with the Mn/DOT Standard Specification 2511 and the following:

Matrix riprap construction involves furnishing and placing stone riprap, at the locations shown in the Plans or ordered by the Engineer, as a protective covering on earth slopes, piers, abutments, walls, or other structures, where the soil is susceptible to erosion. The voids of the riprap matrix are then partially filled with a Portland cement based grout by hose or tremie. The final configuration results in an armor layer that retains approximately 50% of the void space of the original riprap. All matrix riprap applications will be made "in the dry," with no installation of matrix riprap underwater. Riprap shall be placed on a filter layer consisting of granular material or geotextile material as specified in the plans or by the Engineer.

S-1.2 2511.2 Materials

All materials shall satisfy the requirements of 2511.2 except as modified below.

Modify 3601.2 Riprap Materials by adding section 3601.2.A2e

3601.2.A2e Matrix Riprap

The contractor shall furnish stones that meet the requirements of Table 3606-1. The class of riprap (size) required shall be as specified on the plans, or by the Engineer. Only Class III , IV or V riprap shall be used for matrix riprap.

Modify 2511.2.C Riprap Stone as follows:

2511.2.C Replace the material requirements of 3A-Grout with the following:

The approximate mix design for the grout required for one cubic yard of mix is shown in Table 1 below. The applicable materials specifications are listed next to each material in the grout mix. Contractor Mix design is required before placement of the matrix riprap. The wet grout density must be within the range of 120 to 140 lbs/ft^3. The wet density shall be determined by the Engineer using the air content pot, at a rate of once per pour. The grout mix should be approximately the consistency of toothpaste. Gradation and quality of the crusher chips and sand shall be checked at the rate of once per pour or whenever new material is brought onto the project.

Table 1: Approximate Mix Design for Grout (one cubic yard of mix)

Material	Material Specification	Quantity (lbs)
Portland Cement	3101	740 to 760
Fine aggregate (sand), dry	3126	1180 to 1200
¼" Crusher chips, dry	3137 CA-80	1180 to 1200
Water	3906	420 to 450
Air entrainment	3113	8 to 12%

Quality Assurance Requirements:

The Engineer will perform a Consistency (Slump) Test on the grout mix using a specialized slump cone and table developed for grout material used in matrix riprap applications. The specialized test equipment must be obtained from the Bridge Hydraulics Unit before the placement of the matrix riprap. The slump test shall be performed a minimum of 2 times per day or whenever new materials are brought onto the project.

Consistency (Slump) test procedure:

Place the slump cone on the table, the surface should be completely dry. Fill the cone with the grout mixture in two layers, rodding each layer 25 times. Use the rod to smooth off the top of the grout so it is flush with the cone. Pick the slump cone straight up off the table, allowing the grout to spread out on the table. Measure the diameter of the grout mix on the table and record. Tap the table up and down 15 times. Measure the diameter and record. Grout shall meet requirements before it is allowed to be placed.

The target values for the grout consistency (slump) test are as follows:
34 to 38 cm (13.4 to 15 inches) diameter, no tapping of the table
50 to 54 cm (19.7 to 21.25 inches) diameter, 15 taps of the table

S-1.3 2511.3 Construction Requirements

All construction methods shall satisfy the construction requirements of 2511.3 except as modified below.

Modify 2511.3.A General as follows:

2511.3.A General Change the second paragraph to read:

The contractor shall place riprap on a filter material, to the thickness and extents specified in the plans or by the Engineer.

Modify 2511.3.C Riprap Stone by adding section 2511.3.C4:

2511.3.C4 Matrix Riprap

Matrix riprap stones shall be placed as specified for random riprap.

Modify 2511.3.D Grouting as follows:

2511.3.D Grouting Replace the section with the following:

Test section:

Before application of the grout on the entire riprap installation, a test section shall be completed by the contractor and observed by the Engineer. This section shall be of the same thickness as the standard riprap section, and have minimum dimensions of 10 ft by 10 ft. The Engineer will visually observe the application of the grout, inspect the final grout configuration in the test section, and approve of the method/application. Once approved, the same method/application used in the test section shall be reproduced for the rest of the matrix riprap installation.

Grouting Method/Application:

Table 2 below presents the recommended values for quantity of grouting material as a function of the class (size) of the riprap. Care shall be taken by the contractor so that the application quantities are not exceeded, as too much grout can create an impermeable layer on the surface of the armor layer or on the filter at the bottom of the riprap. Before placing the grout, wet the riprap so it is clean and will bond to the grout.

Table 2: Grouting Material Quantities

Riprap Size Class	Application Quantity of Grout (ft3/yd2)
Class III	2.0 – 2.2
Class IV	2.7 – 3.2
Class V	3.4 – 4.1

Grout shall be dispensed from flexible hose or tremie attached to a boom on a concrete pump truck. The recommended hose diameter size is 2-3 inches, to allow a 1-man grouting operation. Grout shall be supplied to the pump truck from a standard concrete mixer truck. The grout shall be applied by hand using the hose or tremie using one of two grouting procedures: line-by-line or spot-by-spot. Either procedure is acceptable, and shall be approved by the Engineer during the test section application

After application of the grout on the riprap matrix, approximately 50% of the original void space in the riprap will be retained. The upper half of the riprap layer should have approximately two-thirds of the voids filled with grout, and the lower half of the riprap layer should have approximately one-third of the voids filled with grout.

S-1.4 2511.5 Measurement and Payment

Measurement will be made by volume, computed on the basis of surface area and thickness of the Class XXX Riprap. Payment will be made under Item 2511.607 (Random Riprap Special) at the Contract bid price per cubic yard, which shall be payment in full for all costs involved, including the riprap, grout, labor and equipment.