Protections 2016 Ft. Collins, Colorado, USA, 7-9 September 2016
2nd International Seminar on
Dam Protection Against Overtopping
ISBN: 978-1-1889143-27-9 DOI:

Soil-Cement for High-Velocity Spillway Flow Applications

Korey J. Kadrmas[1], P.E., Project Manager, and Robert J. Huzjak[2], P.E., President,
[1]RJH Consultants, Inc.
9800 Mt. Pyramid Court, Suite 330
Englewood, CO 80112
[2]RJH Consultants, Inc.
9800 Mt. Pyramid Court, Suite 330
Englewood, CO 80112
Email: kkadrmas@rjh-consultants.com

ABSTRACT

Although soil-cement has been used on many dams for slope erosion protection for over 50 years, soil-cement has had limited use as an overtopping liner protection for spillways. The application of soil-cement for a spillway liner was researched and modeled to establish performance criteria to support design of an auxiliary spillway for a new large, high hazard dam in Colorado. Case studies were researched and hydraulic performance tests were conducted at the Hydraulics Laboratory at the Engineering Research Center of Colorado State University (CSU) to establish design criteria for soil-cement lined spillways subject to high-velocity flows.

The purpose of this paper is to supplement the existing base of research regarding the suitability of soil-cement for hard protection channel lining applications subject to high-velocity flow. Information in this paper was developed from a special application testing program developed for an emergency spillway for a dam in Colorado. The paper will include the methods and procedures of batching and placing the soil-cement specimens, a summary of data collected, results, and conclusions for the soil-cement performance testing program.

Keywords: *Soil-cement, high-velocity, spillway, overtopping, protection.*

1. INTRODUCTION

There are several hardened protection materials currently employed for providing overtopping protection for dam, levee, and flood protection projects including: reinforced concrete, roller-compacted concrete (RCC), engineered blocks, etc. The selection criteria for the required overtopping material are dependent on the characteristics of the design flow, composition and performance of the protection material, and the risk tolerance of the owner. Recent research and advancements in engineering and construction methods have provided alternate hardened concrete options. This paper focuses on presenting engineering data and design thresholds to support the use of soil-cement as an acceptable protection material for spillways.

Although soil-cement has been used on many dams for slope erosion protection for over 50 years, soil-cement has had limited use as the hardened material (liner) for spillways. The application of soil-cement for a spillway liner was researched and modeled to establish performance criteria to support design of an emergency spillway for a new large, high hazard dam in Colorado. Case studies were researched and hydraulic performance tests were conducted at the Hydraulics Laboratory at the Engineering Research Center of CSU to establish design criteria for soil-cement lined spillways subject to high-velocity flows.

The performance of soil-cement (i.e., durability, strength, erosion resistance, etc.) is a function of its specific properties and can vary significantly based on a) the gradation of the base soil, b) the amount of cement, and c) the compressive strength of the soil-cement. Performance and design criteria are published for use of soil-cement for erosion protection; however, for soil-cement subject to high velocity flows, limited data is available and design procedures are not well established. Based on existing literature, previous hydraulic modeling, and data gathered from existing research and projects, there is reasonable information to conclude that properly mixed and placed soil-cement can have acceptable performance for flow velocities up to about 20 fps (6.1 m/s). However, the peak flow velocity through spillways can often exceed 20 fps (6.1 m/s) and the flow durations can occur over several hours to several weeks.

A specific hydraulic performance testing program was developed and performed to evaluate permissible design limits and to support design of the soil-cement lined spillway channel. Varied soil-cement test specimens were batched and placed under controlled measures in steel boxes that were constructed specifically for this evaluation, and were installed in CSU's outdoor hydraulic flume. Tests were conducted at velocities of 17 fps, 25 fps, and 32 fps (5.2 m/s, 7.6 m/s, and 9.8 m/s) for soil-cement mixes with three different cement contents for a similar base soil gradation. The test objectives were:

- Evaluate the performance and erosion of soil-cement for a range of cement contents subject to different high velocity flows for extended flow durations.
- Select a cement content for the soil-cement spillway liner that balances performance, safety, reliability, and costs.

1.1. Background

The use of soil-cement for slope protection on dams first began in the United States with an experimental test section constructed in 1951 by the U.S. Bureau of Reclamation (USBR) at Bonny Dam located in eastern Colorado (NTIS, 1984) at a site that experienced "maximum destructive exposure." The facing was inspected frequently and after 10 years of evaluation, soil-cement was added to the USBR specifications as an alternative to riprap for upstream slope protection (Holtz and Walker, 1962). The first three dams to use soil-cement for upstream slope protection were Ute Dam in New Mexico (built in 1962), Merritt Dam in Nebraska (built in 1963), and Cheney Dam in Kansas (built in 1964). The first documented use of soil-cement in spillways in the United States was at Broad Canyon Dam in Radium Springs, NM in 1969 (Ken Hansen, P.E., personal communication, 2009). Significant data is available related to the performance of soil-cement for upstream slope protection; however, there is limited research and documented performance data available regarding the performance of soil-cement lining subject to high velocity flows in spillway channels.

Four publications that investigated soil-cement for channel lining applications are described in this paper. The soil-cement type presented in this study is categorized as "cement-treated base" as defined by the Portland Cement Association (PCA). Based on a review of these publications, it is the authors' opinion that the current literature verifies that soil-cement for channel lining applications will perform effectively for maximum flow velocities on the order of 25 fps (7.6 m/s) and that the performance of soil-cement for channel lining applications for these high velocity flows is a function of strength and aggregate size.

1.2. Literature Review and Definitions

A literature review was performed to identify previous research regarding soil-cement subject to high velocity flows. This search identified four publications that are discussed herein. To facilitate an understanding of this research, definitions for key terminology are as follows:

- **Soil-Cement:** Soil-cement is a highly compacted mixture of soil, Portland cement, and water. Soil-cement referenced in the research publications is generally in the "cement-treated base" category of soil-cement, as defined by the PCA. Cement-treated base types of soil-cement consist of mixtures of soil and aggregate with measured amounts of Portland cement and water.
- **Course-Grained Soils:** More than 50 percent retained in a 0.075 mm (No. 200) sieve.
- **Sand:** Material passing a 4.75 mm (no. 4) sieve and retained on a 0.075 mm (No. 200) sieve.
- **Cement:** Portland Type I/II.

Previous research regarding soil-cement subject to high velocity flows included publications by PCA (PCA and Hansen, 2002); L.L. Litton and R.A. Lohnes (Litton and Lohnes, 1982); R.P. Bass (Bass 1999); and Simons, Li &

Associates (Simons Li, 1988). The cement content of tested soil-cement samples ranged from 5 to 13 percent. Important findings from the literature review are as follows:

- L.L. Litton, and R.A. Lohnes (Litton and Lohnes, 1982) present results for a range of soil-cement samples that were tested with varying soil compositions (alluvium, sand, and sand-alluvium mixtures) with the cement contents ranging from 5 to 13 percent by weight. Test results showed that velocities could exceed 25 fps (7.6 m/s) without causing substantial erosion for certain mix designs and that there is a decrease in weight loss (i.e., erosion) with increases of sand content and cement content.

  Based on the PCA limiting criterion of 7 percent weight loss, the following relationship in Table 1 between cement content, percent sand, and maximum allowable velocities were proposed by Litton and Lohnes (1982):

Table 1. Maximum Allowable Velocity (fps)

Soil Mixture	Cement Content		
	5 Percent	**7 Percent**	**9 Percent**
Alluvium – 25 percent Sand	9.8 (3.0 m/s)	17.0 (5.2 m/s)	>25.0 (7.6 m/s)
Alluvium – 40 percent Sand	13.5 (4.1 m/s)	>25.0 (7.6 m/s)	>25.0 (7.6 m/s)
Alluvium – 55 percent Sand	21.3 (6.5 m/s)	>25.0 (7.6 m/s)	>25.0 (7.6 m/s)

- Simons, Li & Associates (Simons Li, 1988) discusses the hydraulic performance testing of soil-cement on a downstream embankment slope exposed to overtopping flows. The slopes were at 3 horizontal to 1 vertical (3H:1V) and 2H:1V and subject to 1 foot to 4 feet (0.3 m to 1.2 m) of overtopping flow, and the soil-cement was placed in horizontal lifts. The cement content was 8 percent by weight. Results from the study showed that properly designed soil-cement can withstand the flow of clean water up to a velocity of 20 fps (6.1 m/s) with little erosional damage. The qualitative description of damage was described as “rounding off” of the edge of each stairstep. Also noted for this test program was that cold joints between the lifts did not affect stability.
- Bass (Bass, 1999) discusses the development of soil-cement used for bank protection and drop structures and presents examples to demonstrate recent projects with channel velocities exceeding 25 fps (7.6 m/s).
- PCA (PCA and Hansen, 2002) references earlier PCA research (PCA, 1943). This paper presents results from a series of hydraulic performance tests investigating the use of soil-cement as a lining option for open flumes. Results from the study showed that after 6 days, no appreciable erosion was observed for a flow velocity of 28 fps (8.5 m/s) on a 4 1/2-inch-thick (11.4 cm) soil-cement lining consisting of 60 percent sand and 40 percent silt/clay stabilized with 8 percent cement. The document states that properly designed soil-cement can withstand the flow of clean water up to a velocity of 20 fps (6.1 m/s) with little erosional damage. For higher flow velocities or abrasion erosion conditions, the compressive strength of soil-cement needs to be increased by either:
    - Modification to the mixture proportions.
    - Increased degree of compaction.
    - Extending the curing period.

1.3. Design Criteria

The intent of this research was to develop design criteria for hard overtopping protection on spillways that is in accordance with State of Colorado dam safety regulations. Hydrologic modeling of the anticipated inflow floods greater than the 100-year event, up to and including the inflow design flood (IDF), was performed to evaluate the anticipated peak flow velocities in the spillway.

Flow depths on the soil-cement lining for the 100 percent IDF were predicted to range from about 2 to 6 feet (0.6 to 1.8 m) and velocities were predicted to generally range from about 20 to 28 fps (6.1 to 8.5 m/s). Flow depths on the soil-cement lining for the 50 percent IDF were predicted to range from about 1 to 3 feet (0.3 to 0.9 m) and velocities were predicted to generally range from about 13 to 16 fps (4.0 to 4.9 m/s). Flow depths on the soil-cement lining for the 25 percent IDF were predicted to range from about 0.5 to 2.3 feet (0.2 m to 0.7 m) and velocities were predicted to generally range from about 10 to 14 fps (3.0 to 4.3 m/s).

Based on the results of the hydraulic models, the spillway overtopping protection would be designed for peak flow velocities of 28 fps (8.5 m/s) and routine flow velocities ranging from 10 to 20 fps (3.0 to 6.1 m/s). Based on the reviewed research referenced above and the results of the hydraulic modeling, the design team developed the following conclusions:

- Erosion of the soil-cement during the design event will occur because predicted velocities exceed 20 fps (6.1 m/s) but the amount of erosion is difficult to predict.
- The ability of soil-cement to resist erosion from high velocity flows is a function of the specific properties of the selected material and cement content.
- Adequate data was not available to design the soil-cement mix and predict the performance of the spillway lining for the referenced project. Procedures for soil-cement design based on erosion from high velocity flow are not well established and additional research and testing is required.
- A hydraulic model study was needed to evaluate the erosion resistance of the proposed soil-cement material for a range of cement contents. The cement content selected for the mix that will be constructed will be based in part on the results of the model study.

2. TEST PROGRAM DEVELOPMENT

RJH Consultants, Inc. (RJH) developed hydraulic performance test (i.e., model study) procedures and methodology to evaluate the performance of soil-cement lining subject to high velocity flows for a range of cement contents. The testing program generally consisted of the following:

- Developing soil-cement mix designs and specifications.
- Constructing the soil-cement test specimens.
- Performing materials testing of the soil-cement.
- Performing the hydraulic performance tests in a controlled environment.

The hydraulic performance tests were performed at the Hydraulics Laboratory at the Engineering Research Center at CSU in Fort Collins, Colorado (CSU Hydraulics Laboratory).

2.1. Mix Designs and Specifications

The source material for the soil-cement consists of excavated materials from the subject dam site and is geologically classified as the Upper Dawson Formation, which is generally a poorly cemented fine to coarse grained sandstone. The base material was processed by mining the sandstone and passing the material through a 2-inch (5.1 cm) screen to remove oversized particles. This is the same material used for the soil-cement slope protection on the upstream slope of the dam. The specifications for this project required the base soil to meet the following criteria:

- Free from organic material with no lumps of clay larger than 1 inch (2.5 cm).
- Sulfate content less than 0.2 percent.
- Plasticity index of 6 or less.
- Meet the gradation band shown on Figure 1.
- Moisture density relations in accordance with ASTM D 558.
- Compressive strength in accordance with ASTM D 1633 with minimum compressive strengths of 600 pounds per square inch (psi) (42.2 kg/cm²) at 56 days.
- Freeze-Thaw durability tests in accordance with ASTM with a maximum loss of 8 percent.
- Wet-Dry durability tests in accordance with ASTM D 559 with a maximum loss of 6 percent.

The soil-cement was to be placed in the testing apparatus "specimens" as follows:

- In compacted finished lifts of not more than 4 inches (10.2 cm).

- Compact each lift to a minimum of 96 percent of maximum dry density as determined by ASTM D 558. The average of all tests shall not be less than 98 percent of the maximum dry density.
- Compaction moisture content between optimum moisture content and 1.5 percent above optimum moisture content.

The testing criteria for the hydraulic performance tests were developed based on the above specification and mix designs that were developed by RJH for the upstream slope protection at the subject dam. The design criteria was developed based on recommendations from PCA and USBR, and required a freeze-thaw maximum loss of 8 percent and a wet-dry maximum loss of 6 percent. RJH evaluated the laboratory mix design test results for soil-cement mixed at 6-, 7-, 9-, 10-, 11-, 12-, 13-, and 14-percent ("dry weight") cement contents against the design criteria established above and plotted the test results for wet-dry durability (Figure 2), freeze-thaw durability (Figure 3), and compressive strength (Figure 4) as shown below.

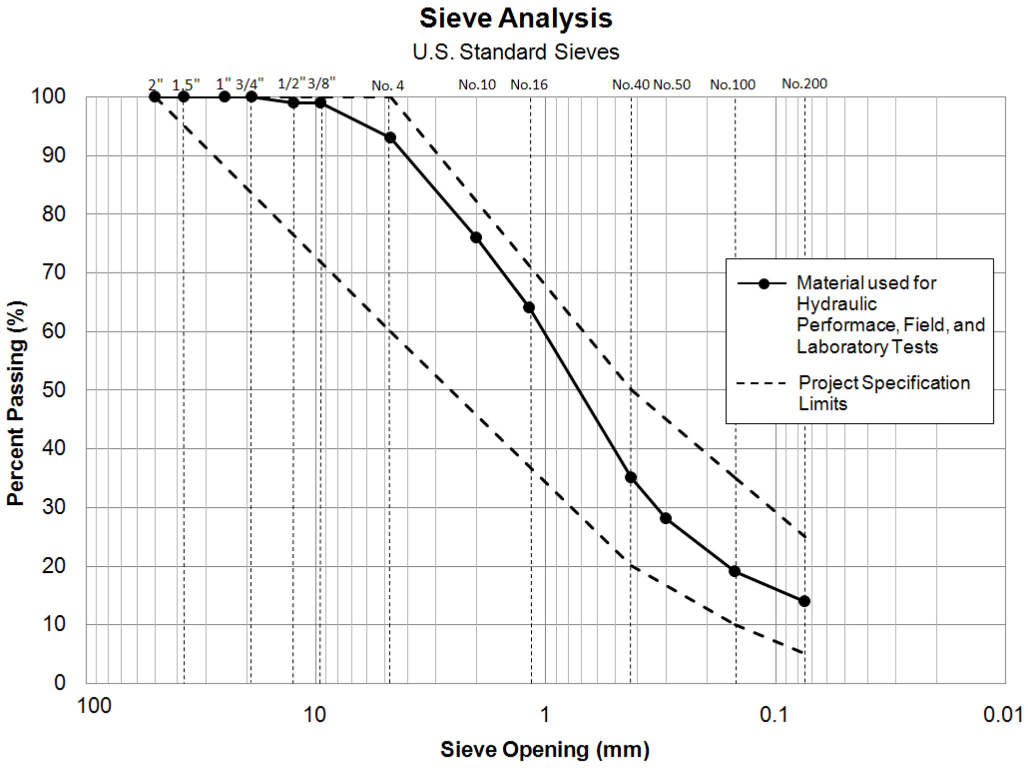


Figure 1. Base Soil Gradation Band

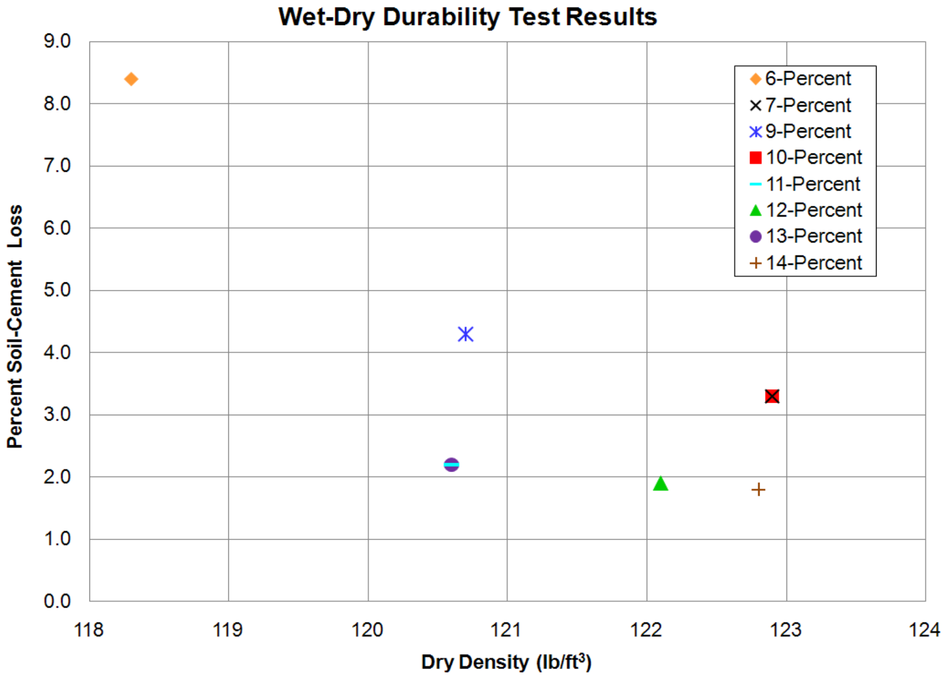


Figure 2. Wet-Dry Durability Test Results

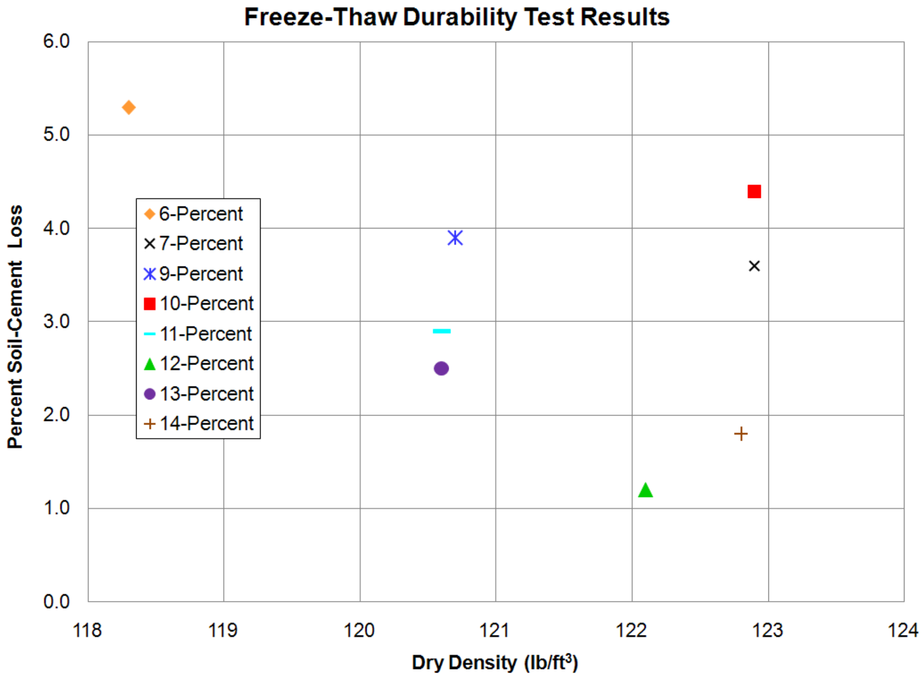


Figure 3. Freeze-Thaw Durability Test

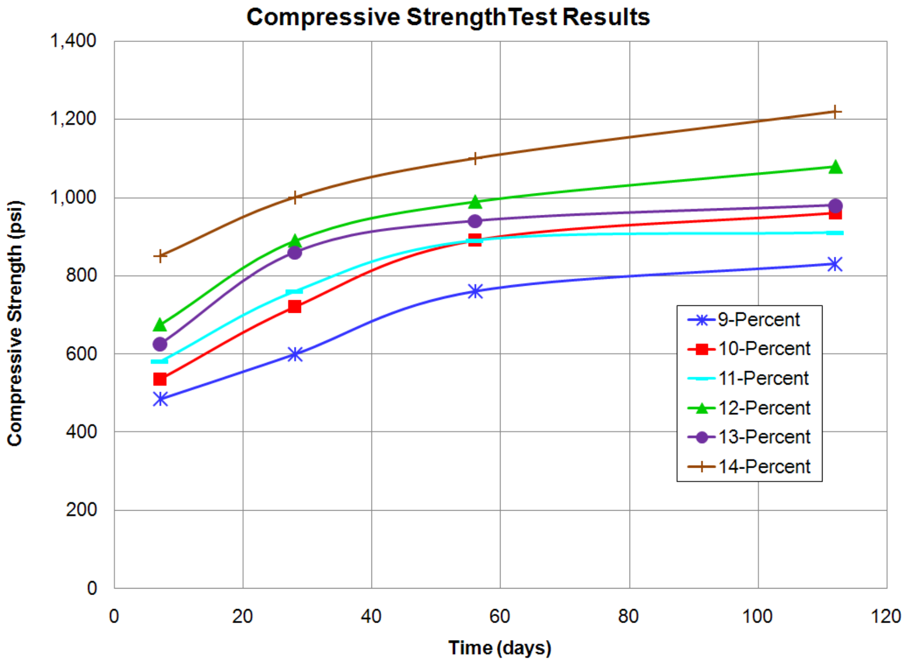


Figure 4. Compressive Strength Test

The above test results demonstrate that all the mix designs meet the compressive strength and freeze-thaw durability requirements. However, a minimum cement content of about 7 percent was required to meet the wet-dry durability design criteria. In addition to meeting the above strength and durability requirements, the soil-cement intended for use on the spillway needed to resist significant erosion from high velocity flows. Based on these findings, the soil-cement with cement contents of 8, 10, and 12 percent was selected for the hydraulic performance test.

Soil-cement samples were prepared in the laboratory to establish the target density for preparation of the field test specimens. The gradation of the base material used for these laboratory density tests is shown as the solid line on Figure 1.

Results from the laboratory standard Proctor test are provided in Table 2.

Table 2. Test Target Density and Moisture Content

Mix Design (by dry-weight cement content)	**Maximum Dry Density (lb/ft^3)**	**Optimum Moisture Content (%)**
8 percent	122.8 (1967.1 kg/m^3)	10.8
10 percent	122.5 (1962.3 kg/m^3)	11.2
12 percent	122.1 (1955.9 kg/m^3)	11.1

2.2. Construction of Test Specimens

Steel test boxes were constructed specifically for this evaluation. The soil-cement test boxes had nominal interior length, width, and depth dimensions of 30 feet, 3 feet, and 8 inches (9.1 m, 0.9 m and 0.2 m), respectively. A soil-cement test box is shown in Photograph 1.

The soil-cement test specimens were constructed at the CSU Hydraulics Laboratory under the direction of RJH on November 17 and 18, 2009. Dr. Christopher Thornton led the work that was performed by CSU. Steel I-beams were placed transverse along the bottom of the test boxes to provide rigidity and support. The test boxes were placed on the ground to be filled with the soil-cement mixture. Wooden 4- by 4-inch (10.2 cm by 10.2 cm) boards were placed uniformly underneath the test boxes, between the steel I-beams, to add support and reduce vibration and movement during compaction of the soil-cement mixture.

Three soil-cement test specimens were constructed with cement contents of 8, 10, and 12 percent cement content by weight. Prior to placement in the test boxes, the Portland cement, soil, and water mixture were mixed using ready-mix truck as a volumetric cement mixer. The mixer contained a system of hoppers (two), sprayers, conveyor belt, chute, and auger, as shown in Photograph 2.

Photograph 1. Soil-Cement Test Box

Photograph 2. Volumetric Cement Mixer (Ready-Mix Truck)

Provisions followed to prepare the soil-cement mixture included: First the soil was weighed and loaded into the large hopper. The cement was then weighed and loaded into the small hopper. The soil and cement were then released from their respective hoppers onto a conveyor belt at designated rates to ensure the mix was consistent with the mix design. Water was then sprayed as shown in Photograph 3 onto the soil and cement at a designated rate to ensure the mix was consistent with the mix design.

The combined materials were then conveyed into a half-pipe chute where a rotating auger mixed the materials. Soil-cement was placed in two lifts and compacted using a vibratory plate compactor to achieve a compacted thickness of 4 inches (10.2 cm) per lift. The first lift of the soil-cement mixture was placed uniformly into the soil-cement test boxes as shown in Photograph 4. After compaction of the first soil-cement lift, the surface was scarified with a rake prior to placement of the second lift as shown in Photograph 5.

Photograph 3. Water Applicator and Chute

Photograph 4. First Lift Placement

Photograph 5. Scarification between Lifts

Photograph 6. Lift Compaction

Photograph 7. Soil-cement Test Box

Compaction of the final second lift for one of the test boxes is shown in Photograph 6. In the corners of the test boxes, the soil-cement was compacted using hand tampers to create a uniform and consistent top appearance to the soil-cement in the test boxes. Field density tests were completed at random following each 4-inch (10.2 cm) lift placement and were performed in general accordance with ASTM D 2992 to record the density of the placed materials.

The finished surfaces of the soil-cement in the test boxes were touched up by hand to fill or smooth any surface defects. A completed soil-cement test box prior to curing is shown in Photograph 7.

Field testing density and moisture results for each of the test mix designs are summarized in Table 3.

Table 3. Field Testing Density and Moisture Results

Mix Design (by cement content)	**Summary of Field Testing Results**	
	Density	**Moisture**
8 percent	• All eight tests had a compaction above 96 percent of the maximum dry density. • The average compaction was 96.9 percent of the maximum dry density.	• Five tests were below the optimum moisture content, ranging from 2.3 percent to 0.4 percent below • Three tests were within the specified range.
10 percent	• All six tests had a compaction above 96 percent of the maximum dry density. • The average compaction was 96.7 percent of the maximum dry density.	• One test was 4.4 percent below the optimum moisture content. • Five tests were within the specified range.
12 percent	• All six tests had a compaction above 96 percent of the maximum dry density. • The average compaction was 97.2 percent of the maximum dry density.	• Four tests were below the optimum moisture content, ranging from 4.7 percent to 1.2 percent below. • One test was within the specified range. • One test was above the specified range at 1.9 percent above optimum moisture content.

Based on the density test results of the soil-cement in the test boxes, the compaction was above 96 percent of the maximum dry density; however, the average in-situ compaction was less than 98 percent of the maximum dry density for all three test specimens. Also, the moisture content of ten out of the 20 tests was below optimum moisture content and one test was more than 1.5 percent above optimum moisture content. The soil-cement material placed in the test boxes did not meet the requirements of the project specifications because:

- The average density was 96.9 percent of Proctor maximum (specifications require an average of 98 percent).
- The moisture content of half of the tests was below optimum moisture content.

However, the use of these test specimens was deemed appropriate for hydraulic performance testing because a) the overall objective of the hydraulic performance testing could be achieved, b) the field tests may not accurately represent the in-place conditions because of the reliability of using a nuclear density gauge to test a thin layer of material in a steel box, and c) the hydraulic performance tests would provide conservative estimates of the scour potential of the soil-cement lining for the project.

Pucks (“samples”) were prepared from the materials used for each test specimen for subsequent laboratory testing. The pucks were developed according to ASTM D 558 using 4-inch-diameter (10.2-cm-diameter) steel molds about 4.6 inches (11.7 cm) deep and in three lifts. The materials were compacted using a 5.5 lb. (2.5 kg) hammer, falling 12 inches (30.5 cm), with 25 blows per each of the three lifts as shown in Photograph 8.

The curing procedures of the test specimens were developed to best produce soil-cement material that is similar to expected field conditions. The CSU Hydraulics Laboratory is heated and the completed test specimens were moved inside to maintain the temperature above 40°F (4.4°C) for curing. The exposed soil-cement surfaces were covered with burlap and wetted four times a day for 7 days to maintain a saturated surface. Prior to performance testing, the 8, 10, and 12 percent cement content test specimens were cured for 171 days, 205 days, and 219 days, respectively.

A few hairline cracks were observed on the surface of the test specimens following transport to the testing facility. These cracks were the result of transporting the test boxes. The objective of the testing was to evaluate the erosion performance of the soil-cement and not the effect of joints or cracks. The cracks were sealed using a high-strength, structural epoxy paste (Sikadur 31, Hi-Mod Gel) as shown in Photograph 9 so the cracks would not impact the test results. The epoxy paste was applied to seal the cracks and provide a smooth surface to reduce the potential for impacting hydraulic flow velocities and to provide a test specimen without defective locations. The evaluation of the test specimens focused on locations outside the limits of the cracks.

Photograph 8. Puck Preparation

Photograph 9. Epoxy Paste Crack Repair

2.3. Laboratory Materials Testing

Laboratory testing was performed on the test pucks from the constructed test boxes to ensure the mix meets the strength and durability design requirements. The laboratory testing of the test pucks included:

- ASTM D 559 – Wet-Dry Durability Test.
- ASTM D 560 – Freeze-Thaw Durability Test.
- ASTM D1633 – Compressive Strength Test.
- ASTM D 2937 – Dry Density.

A summary of the laboratory tests are as follows:

Dry density ranged from 123 to 125 pcf (1970.3 to 2002.3 kg/m^3), freeze-thaw loss was generally about 1 to 2 percent, and wet-dry durability loss ranged from 0.5 to 1.5 percent. The results met the project specifications for the upstream slope protection material. However, no reliable trend was identified between the test results and cement content. The average 56 day compressive strength was 700 psi, 800 psi, and 800 psi (49.2 kg/cm^2, 56.2 kg/cm^2, and 56.2 kg/cm^2) for the pucks at 8, 10, and 12 percent cement content, respectively. The reason for the lack of strength gain between the 10 and 12 percent specimens is unknown. The laboratory materials test resulted in compressive strengths greater than the project specified 600 psi (42.2 kg/cm^2), so these were considered acceptable results. RJH recommended accepting the test puck results and advancing to the hydraulic performance testing.

2.4. Hydraulic Performance Testing

2.4.1. Test Facility

The hydraulic flume at the CSU Hydraulics Laboratory was used for the hydraulic performance testing of the soil-cement test specimens. A schematic profile of the hydraulic flume is illustrated on Figure 5. The testing apparatus consisted of a flume that is 5 feet wide and 100 feet long (1.5 m wide and 30.5 m long) with a 2H:1V slope. The upper portion of the flume was modified to seamlessly accommodate the 3-foot-wide by 30-foot-long (0.9 m wide by 9.1 m long) test boxes. The test boxes were placed within the modified flume section using a crane and attached with steel angle irons and bolts. Transition sections were added to ensure uniform velocity profiles across the upstream and downstream ends of the test boxes. A seamless transition was accomplished on the upstream end with steel flushing and the surface of the sheet metal was modified by using a spray-on texturing to give a surface roughness similar to the soil-cement. A perforated toe plate as added to the downstream end to ensure exit discharge conditions that would not provide a premature scour location that would propagate upstream and influence the hydraulic test results.

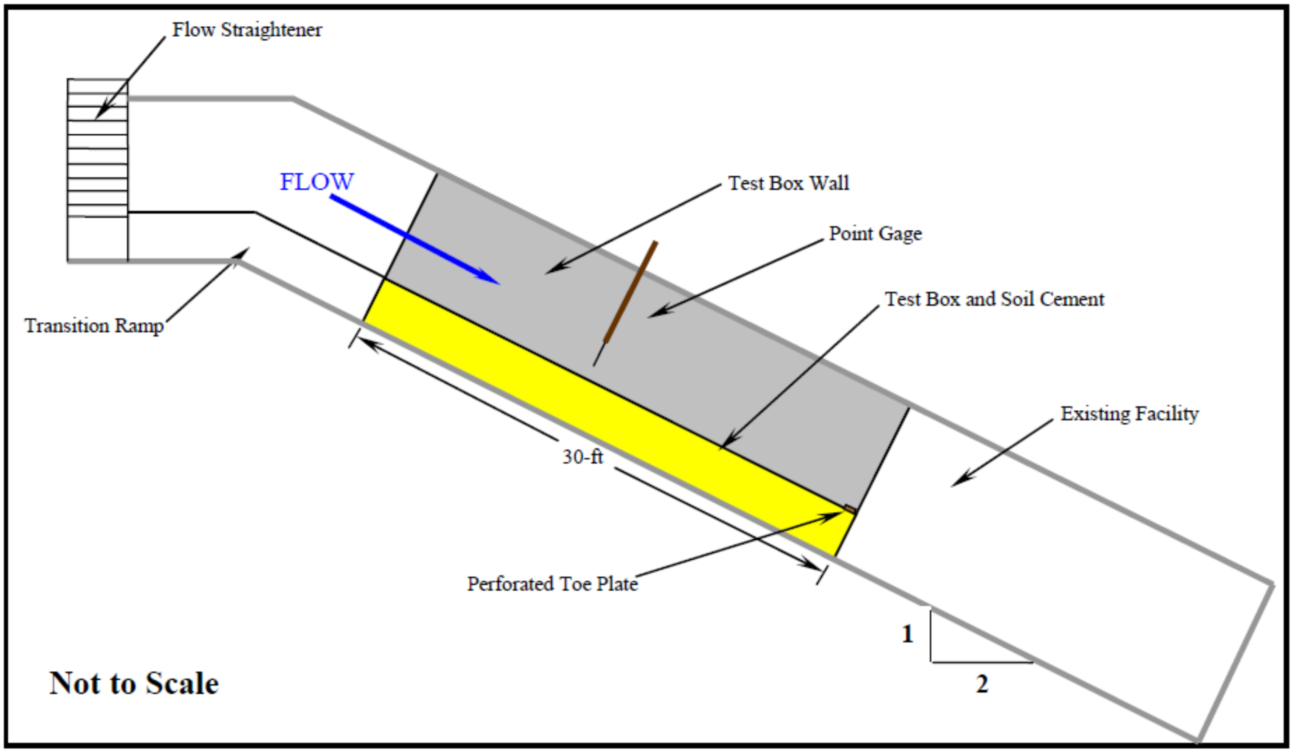


Figure 5. Hydraulic Flume Schematic

2.4.2. Test Procedures

A series of nine hydraulic tests were performed on different days between May 6 and June 29, 2010. The nine tests consisted of three separate hydraulic tests for each of the three soil-cement test specimens at targeted velocities of 17, 25, and 32 fps (5.2, 7.6, and 9.8 m/s). These velocities corresponded to flow rates of 20 cubic feet per second (cfs), 40 cfs, and 100 cfs (0.6 m^3/s, 1.1 m^3/s, 2.8 m^3/s), respectively.

Each hydraulic performance test consisted of a continuous 6-hour flow over the soil-cement test specimen with uniform flow discharge. The test specimen was considered successful where the surface of the soil-cement endured the first 6-hour test without exceeding the defined performance threshold. Following confirmation of a successful first 6-hour test, the procedure was repeated at the next higher discharge. The performance threshold for the soil-cement test specimens was defined as the point at which significant erosion (several inches) deformation or obvious system failure occurred. This was qualitatively evaluated based on visual assessments of the soil-cement test specimens at the conclusion of each performance test and documented with point gage measurements at pre-designated locations, random scour depth measurements, and video camera and photograph documentation.

Prior to the start of each test, the hydraulic flume was primed with a flow of about 5 cfs (0.1 m^3/s). Flow in the flume was measured with an in-line sonic flowmeter located on the inflow pipe before discharging into the flume. The in-line sonic flowmeter is accurate to about ± 3 percent. The flow rate was then slowly increased until the desired flow rate and corresponding flow velocity were achieved. The test time did not begin until the desired flow rate/velocity was achieved. Hourly measurements of water surface elevations were made using the point gage at 1-foot (0.3 m) intervals (stations) along the centerline, and 1-foot (0.3 m) to the left and right of the centerline.

Elevations along the surface of the test specimens were recorded prior to and after termination of each test at the same locations as the “test in progress” water surface readings. Elevations were recorded to the nearest +/- 0.01 foot (0.3 cm) using an elevated point gage and survey level on a rail assembly over the flume. The flow rate along the test specimen was measured in the flume independently of flowmeter measurements using the point gage to record flow depths during the 6-hour test and convert the measurements to flow velocities. The point gage measurement system is shown in Photograph 10.

Photograph 10. Point Gage Measurement System

At the conclusion of each test, the soil-cement test specimen was inspected for overall system integrity and photographs and video were documented.

2.4.3. Test Results

General

Table 4 presents a text matrix of the hydraulic performance tests. The results of each test are described in the following sections.

Table 4. Hydraulic Performance Test Specimen Matrix

Test ID	Target Flow Rate (cfs)	Target Velocity (ft/s)	Test Duration (hrs)
8, 10 and 12 Percent Cement			
1	20 (0.6 m³/s)	17 (5.2 m/s)	6
2	40 (1.1 m³/s)	25 (7.6 m/s)	6
3	100 (2.8 m³/s)	32 (9.8 m/s)	6

Following the hydraulic performance testing, water surface profiles were developed from the data collected during testing and were evaluated using a standard step theoretical hydraulic model in general accordance with ASTM Standard D7276. The theoretical hydraulic models were developed for all nine tests with varying Manning’s n values to identify the best-fit Manning’s roughness determined from maximizing the coefficient of determination (R^2). Based on the best-fit profiles, the Manning’s n coefficient was determined to be 0.016. The theoretical water surface profiles were used to compute flow velocity and boundary shear stress values at generally 1-foot increments along the test specimens. Table 5 provides a summary of the actual computed velocities and shear stress along the test specimen for each hydraulic performance test.

Table 5. Summary of Hydraulic Performance Test Results

Performance Test	**Discharge (cfs)**	**Manning's n**	**Target Velocity (ft/s)**	**Average Velocity (ft/s)**	**Maximum Velocity (ft/s)**	**Average Shear Stress (psf)**	**Maximum Shear Stress (psf)**	**Cumulative Material Lost(1) (ft)**	**Stable Y/N**
8 Percent Cement									
1	20 (0.6 m^3/s)	0.016	17 (5.2 m/s)	20.5 (6.2 m/s)	24.5 (7.5 m/s)	4.1 (20.0 kg/m^2)	5.8 (28.3 kg/m^2)	0.03 (0.9 cm)	Y
2	40 (1.1 m^3/s)	0.016	25 (7.6 m/s)	24.1 (7.3 m/s)	28.9 (8.8 m/s)	4.6 (22.5 kg/m^2)	6.8 (33.2 kg/m^2)	0.03 (0.9 cm)	Y
3	100 (2.8 m^3/s)	0.016	32 (9.8 m/s)	26.5 (8.1 m/s)	32.5 (9.9 m/s)	4.3 (21.0 kg/m^2)	6.6 (32.2 kg/m^2)	0.03 (0.9 cm)	Y
10 Percent Cement									
1	20 (0.6 m^3/s)	0.016	17 (5.2 m/s)	21.1 (6.4 m/s)	24.7 (7.5 m/s)	4.3 (21.0 kg/m^2)	5.9 (28.8 kg/m^2)	0.05 (1.5 cm)	Y
2	40 (1.1 m^3/s)	0.016	25 (7.6 m/s)	24.7 (7.5 m/s)	29.3 (8.9 m/s)	4.9 (23.9 kg/m^2)	7.0 (34.2 kg/m^2)	0.05 (1.5 cm)	Y
3	100 (2.8 m^3/s)	0.016	32 (9.8 m/s)	26.5 (8.1 m/s)	32.6 (9.9 m/s)	4.3 (21.0 kg/m^2)	6.6 (32.2 kg/m^2)	0.05 (1.5 cm)	Y
12 Percent Cement									
1	20 (0.6 m^3/s)	0.016	17 (5.2 m/s)	21.4 (6.5 m/s)	24.7 (7.5 m/s)	4.4 (21.5 kg/m^2)	6.0 (29.3 kg/m^2)	0.05 (1.5 cm)	Y
2	40 (1.1 m^3/s)	0.016	25 (7.6 m/s)	24.4 (7.4 m/s)	29.1 (8.9 m/s)	4.8 (23.4 kg/m^2)	6.9 (33.7 kg/m^2)	0.04 (1.2 cm)	Y
3	100 (2.8 m^3/s)	0.016	32 (9.8 m/s)	26.8 (8.2 m/s)	32.8 (10.0 m/s)	4.4 (21.5 kg/m^2)	6.7 (32.7 kg/m^2)	0.04 (1.2 cm)	Y

Note:

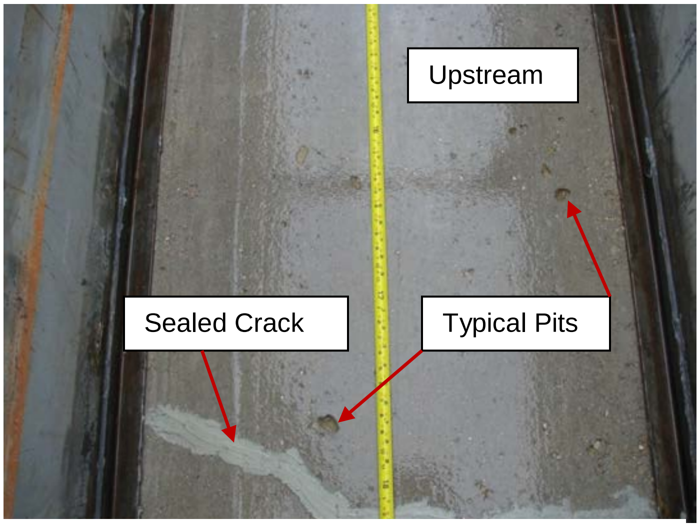
1. Cumulative material lost defined as average depth of “pits” on surface of specimen.

8 Percent Cement Content Test

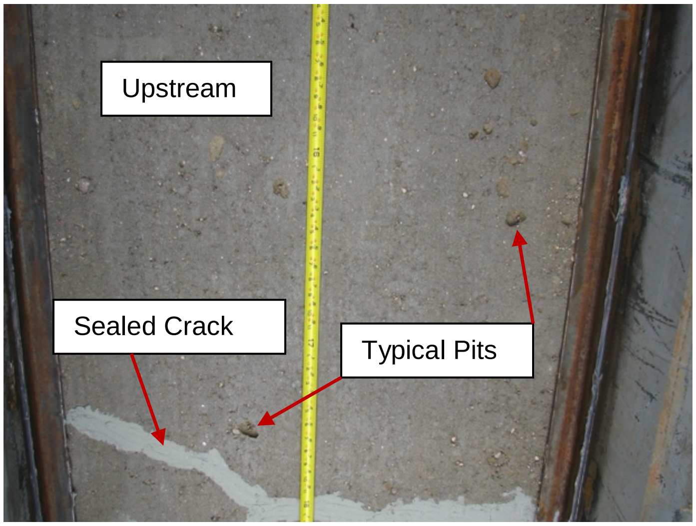
After the initial test (Test 1) with an average velocity of about 20.5 fps (6.2 m/s) and a maximum velocity of 24.5 fps (7.5 m/s), multiple "pits" (i.e., small areas of localized loss of material) were observed at randomly spaced locations along the test specimen. The largest pit was about 2 inches (5 cm) in diameter, and less than 1/4 inch (0.6 cm) deep. The remaining pits were generally less than 1 inch (2.5 cm) in diameter, and about 1/8 inch to 1/4 inch (0.3 to 0.6 cm) deep. No qualifying surface erosion of the soil-cement was observed.

Test 2 had an average velocity of about 24.1 fps (7.3 m/s) and a maximum velocity of 28.9 fps (8.8 m/s). The existing pits developed during Test 1 did not appear to increase in diameter during Test 2. There was a very slight increase in depth, generally less than about 1/8 inch (0.3 cm) at the documented location of the Test 1 pits. Also, an increase in the number of small pits that were less than 1 inch (2.5 cm) in diameter and less than 1/4 inch (0.6 cm) in depth were observed. No qualifying surface erosion of the soil-cement was observed.

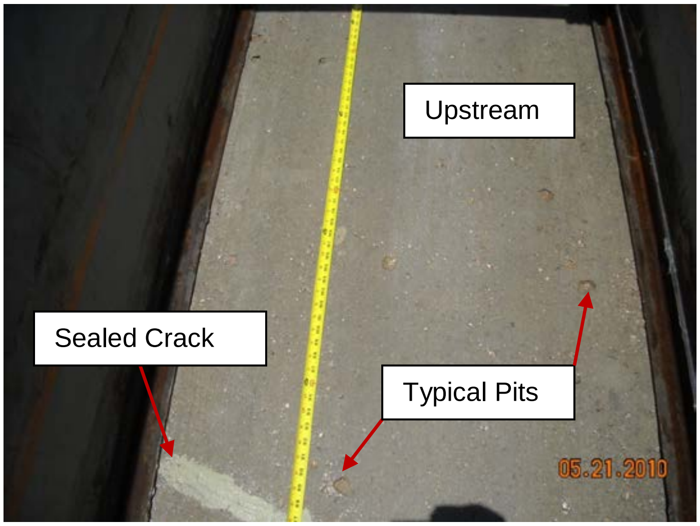
Test 3 had an average velocity of about 26.5 fps (8.1 m/s) and a maximum velocity of 32.5 fps (9.9 m/s). The existing pits from Tests 1 and 2 did not appear to increase significantly during Test 3 in diameter or depth; depth increase was less than a 1/4 inch (0.6 cm). Examples of the observed surface of the soil-cement at generally the same documented location following each test are shown in Photographs 11 through 13.



Photograph 11. Test 1 – 8 percent at 20 cfs



Photograph 12. Test 2 – 8 percent at 40 cfs



Photograph 13. Test 3 – 8 percent at 100 cfs

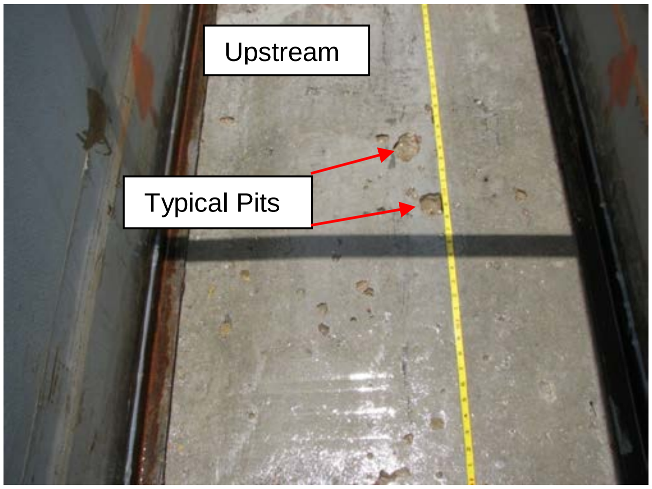
10 Percent Cement Content Test

Consistent with Test 1 at 8 percent cement, multiple pits were observed at randomly spaced locations along the test specimen after Test 1 at 10 percent cement. The largest pit was about 5 inches (12.7 cm) in diameter, and about 1 inch (2.5 cm) deep. Four to five pits were observed to be about 3 inches (7.6 cm) in diameter, and less than 3/4 inch (1.9 cm) deep. The remaining pits were less than 1 inch (2.5 cm) in diameter, and were about 1/4 inch (0.6 cm) deep to about 1/2 inch (1.3 cm) deep. Very minor erosion of the soil-cement surface was observed.

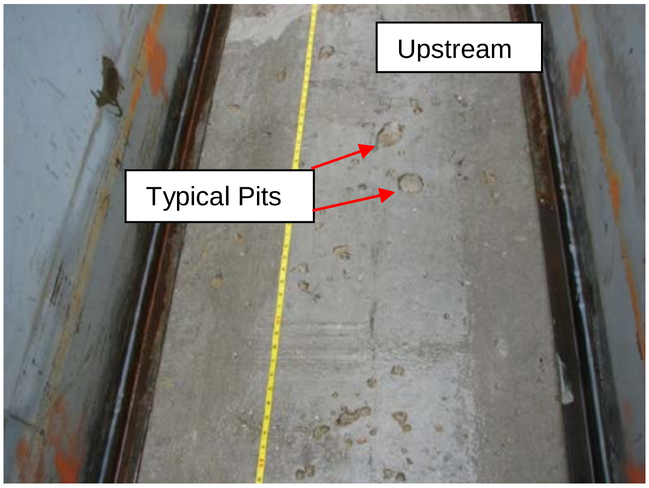
After Test 2, the existing pits from Test 1 did not appear to increase in diameter or depth. An increase in the number of small pits less than 1 inch (2.5 cm) in diameter and less than 1/4 inch (0.6 cm) in depth was observed. The minor amount of localized erosion appeared to increase slightly.

After Test 3, the existing pits from Test 2 did not appear to increase significantly in diameter or depth. The largest pit, about 5 inches (12.7 cm) in diameter, deepened to a total of about 1 1/4 inches (3.2 cm). The 3-inch-diameter (7.6 cm diameter) pits appeared to remain about 3 inches (7.6 cm) in diameter, and deepened to a total depth of about 1 inch (2.5 cm). The remaining pits did not appear to increase in diameter or depth. An increase in the number of small pits less than 1 inch (2.5 cm) in diameter and less than 1/4 inch (0.6 cm) in depth was observed. The minor amount of localized erosion appeared to increase slightly.

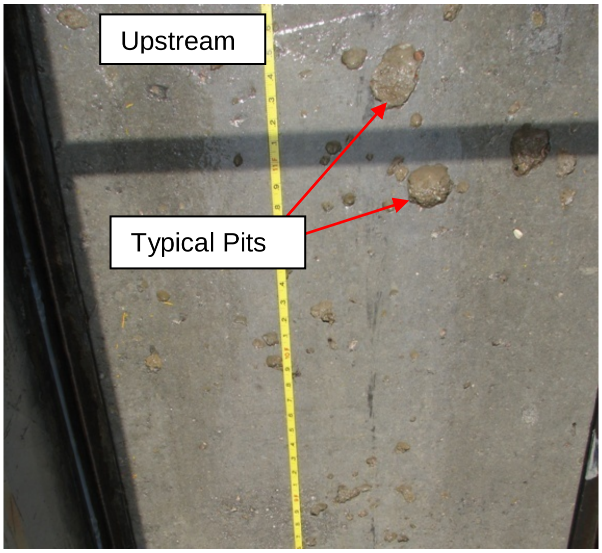
Examples of the surface of the soil-cement for each test are shown below.



Photograph 14. Test 1 – 10 percent at 20 cfs



Photograph 15. Test 2 – 10 percent at 40 cfs



Photograph 16. Test 3 – 10 percent at 100 cfs

Photograph 17. Close Up – Erosion area after Test 3 – 10 Percent at 100 cfs

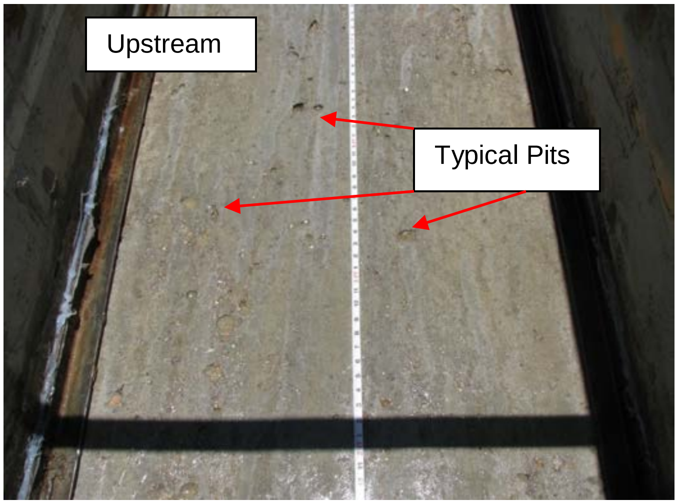
12 Percent Cement Content Test

Consistent with the tests at the other cement contents, multiple pits were observed at randomly spaced locations along the test specimen after Test 1. The deepest pit was about 3 inches (7.6 cm) in diameter, and about 1 3/4 inches (4.4 cm) deep. There were between 15 and 20 pits that were 2 to 4 inches (5.1 to 10.2 cm) in diameter, and about 1/4 inch (0.6 cm) deep. The remaining pits were less than 1 inch (2.5 cm) in diameter, and were about 1/4 inch (0.6 cm) deep, but there were many. Very minor erosion of the soil-cement surface was observed.

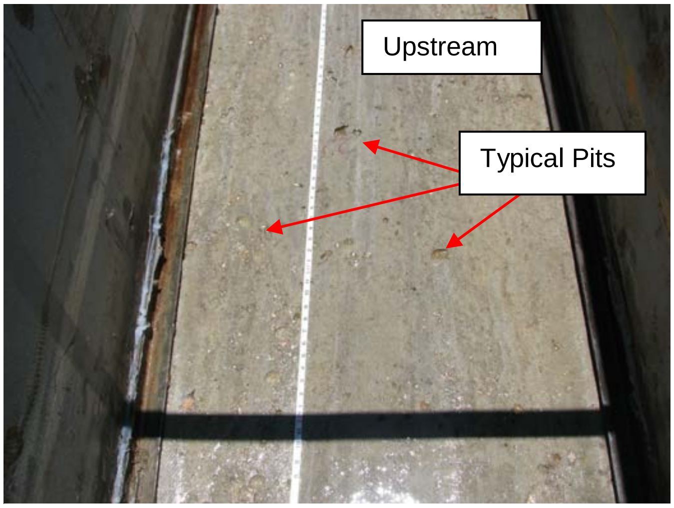
After Test 2, the existing deepest pit from Test 1, about 3 inches in diameter, did not appear to notably increase in diameter, but increased in depth to about 2 inches (5.1 cm). The remaining existing pits did not appear to notably increase in diameter, but the depths of many pits deepened to about 1/2 inch (1.3 cm). An increase in the number of small pits less than 1 inch (2.5 cm) in diameter and less than 1/4inch (0.6 cm) in depth was observed. The minor amount of localized erosion appeared to increase slightly.

After Test 3, the existing deepest pits from Test 2, which were about 3 inches (7.6 cm) in diameter, did not appear to notably increase in diameter, but increased in depth to about 2 1/4 inches (5.7 cm). The remaining existing pits did not appear to notably increase in diameter, but the depths of many pits deepened to about 1/2 inch to 3/4 inch (1.3 cm to 1.9 cm). An increase in the number of small pits less than 1 inch (2.5 cm) in diameter and less than 1/4 inch (0.6 cm) in depth was observed. The minor amount of localized erosion appeared to increase slightly.

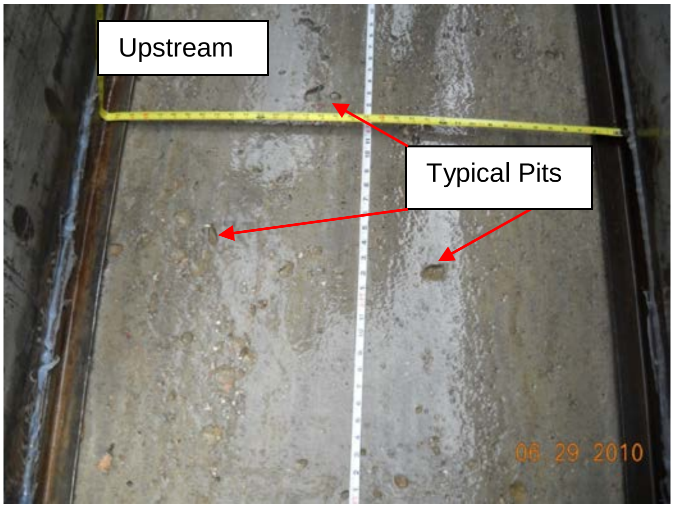
Examples of the surface of the soil-cement for each test are shown below.



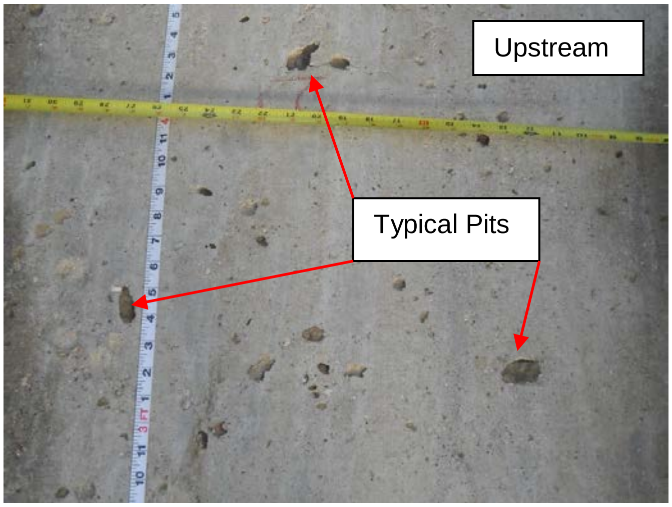
Photograph 18. Test 1 – 12 percent at 20 cfs



Photograph 19. Test 2 – 12 percent at 40 cfs



Photograph 20. Test 3 – 12 percent at 100 cfs



Photograph 21. Close Up – Erosion area after Test 3 – 12 Percent at 100 cfs.

2.4.4. Hydraulic Performance Test Findings

Although each test specimen experienced marginal loss of material in localized areas (i.e., pits), none of the three test specimens were observed to have deformed to significant extents indicative of channel scour, and no obvious system failure or instabilities were identified. It appears that the pits were a result of dislodged clay balls, poorly mixed soil-cement, or poorly bonded aggregate at the surface of the test specimens. Visual observation of the surfaces prior to testing confirmed the presence of unknown material “clumps” at the surface that were usually darker than the surrounding soil-cement. The unmixed material within these pits was typically lost during the first performance test on each specimen with little subsequent loss of material during the final two tests; this was confirmed by measurement of pit depths and visual observation following each test.

Based on the defined performance threshold, the soil-cement test specimens were determined to be stable for the conditions shown in Table 6.

Table 6. Summary of Test Results

Mix Design (by cement content)	**Maximum Velocity (ft/s)**	**Maximum Shear Stress (psf)**
8 percent	32.5 (9.9 m/s)	6.6 (32.2 kg/m²)
10 percent	32.6 (9.9 m/s)	6.6 (32.2 kg/m²)
12 percent	32.8 (10.0 m/s)	6.7 (32.7 kg/m²)

3. CONCLUSIONS

Based on the results of this evaluation, we offer the following conclusions and opinions:

- Soil-cement lining as defined in the "Test Program" with a minimum of 8-percent cement content can be effectively and economically designed to withstand velocities for durations of at least 32 fps (9.8 m/s) for at least 6 hours and likely longer without significant erosion of the surface for the base soils used in this evaluation. The base soil is a well graded, fine to coarse sand with about 8 percent fine gravel and 15 percent fines. The cement content ranges from 8 to 12 percent by dry weight.
- It is probable that soil-cement with a minimum of 8-percent cement content can be used for channel lining applications where the applied velocity exceeds 32 fps (9.8 m/s) for durations greater than 6 hours; however, the performance will depend on the base soil and site specific properties of the soil-cement mix.
- The cement content required to produce a product that met the design criteria for wet/dry durability (maximum 6 percent loss) and freeze-thaw durability (maximum 8 percent loss) also met the criteria for high velocity flows.
- The erosion and surface deterioration from high velocity flows was not significantly impacted in the test specimen by additional cement contents greater than 8 percent.
- The effect of base soil gradation on the behavior of soil-cement subject to high velocity flows was not evaluated. The results and conclusions from this evaluation may not be appropriate for soil-cement materials with a significantly different grain size distribution and cement contents.
- The long-term performance of soil-cement used for high velocity flow will vary and it is probable that the effects of freeze-thaw cycles at the locations of the pits will be more severe than at other locations.
- The testing represents the performance of high velocity flows over a rigid surface and the long-term performance could be impacted by environmental factors.

4. ACKNOWLEDGEMENTS

This work was conducted in collaboration with the Hydraulics Laboratory at the Engineering Research Center of Colorado State University (CSU) and with contribution from Ken Hansen.

Information in this paper was presented at Dam Safety 2011 and reprinted courtesy of ASDSO.

5. REFERENCES

Bass, R., Flood Proofing Channel Stabilization Utilizing Soil-Cement, ASCE WRPMD, 1999.

Casias and Howard, Performance of Soil-Cement Dam Facings – 20-Year Report, National Technical Information Service (NTIS), 1984.

Holtz and Walker, Utilization of Soil-Cement as Slope Protection for Earth Dams, Bureau of Reclamation, 1962.

Huzjak, R.J. and Kadrmas, K.J, Soil-Cement for High-Velocity Spillway Flow Applications. ASDSO, Dam Safety 2011, August. http://www.damsafety.org/

Litton, L.L and Lohnes, R.A., Soil-Cement for Use in Stream Channel Grade—Stabilization Structures, Transportation Research Record 839, 1982.

Kenneth D. Hansen, Erosion and Abrasion Resistance of Soil-Cement and Roller-Compacted Concrete, RD126, Portland Cement Association, Skokie, Illinois, 2002.

Soil-Cement for Flume Lining Gets a Tryout, Soil-Cement News, Portland Cement Association, 1943.

Simons, Li & Associates. Minimizing Embankment Damage During Overtopping Flow, Federal Highway Administration, Report 88-181 and video, November 1988.