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Innovative Geosynthetic Revetment System to Prevent Erosion under High Flow Conditions

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Abstract

Controlling surface water runoff and erosion at mine sites is always a challenge, especially in applications where high flows exist. These applications include the dam spillways on mine tailings impoundments, steep downchutes off of tailings piles or in canyons, and large perimeter diversion channels. Protection of these areas, which have extreme concentrated flows, requires high-performing revetment technologies to prevent erosion. The traditional hardened revetment technologies (such as articulated concrete block, concrete paving, and rock riprap) are expensive and have various levels of performance. The Concrete-Enhanced Synthetic Turf (CEST) Revetment System was developed with this in mind.

CEST is an innovative geosynthetic technology developed to resist the high hydraulic stresses that are present in dam spillways, steep downchutes, and large perimeter channels. CEST is a unique, fiber-reinforced concrete revetment consisting of a high-friction, structured geomembrane overlain by an engineered synthetic turf which is infilled with a high-strength, 5,000 psi (34 MPa) cementitious material.

Extensive full-scale testing was conducted on CEST at Colorado State University's Engineering Research Center (CSU). Steady-state overtop testing up to 5 ft (1.52 m) overtop depths was completed on a 2H:1V sloped flume. Testing was performed for twenty hours up to a maximum velocity of 29.2 fps (8.9 m/sec). Assessments of the CEST in the steady-state flume included the performance of the intact system; the resilience to impact and abrasion under heavy debris loads (concrete rubble); and the function in a damaged state (intentionally punctured with a pickaxe driven into the underlying subgrade). Also, a sluice gate was placed in the flume to create hydraulic jumps. The CEST dissipated hydraulic jump loadings of as much as 30 horsepower per foot of width (22.4 kW). The CEST experienced no uplift, damage, instability, or subgrade erosion.

This paper defines the components of the CEST; describes the testing facility and procedures; provides an explanation of the preparation of the test trays; and reports the results. Also, a case study is presented in which CEST was used on a steep down chute application at the Grouse Creek Mine in Idaho.

Introduction

Concrete-Enhanced Synthetic Turf (CEST) Revetment Technology (a geosynthetic armoring system) was developed from the combination of synthetic turf, concrete, and geomembrane. This innovative system is used for preventing erosion in dam spillways, on levees and embankments, in channels, and on slopes. CEST is a fiber-reinforced concrete armoring solution that has the aesthetics of vegetation. A high-friction, structured geomembrane with an integrated drainage layer is overlain by an engineered synthetic turf, which is infilled with a high-strength, 5,000 psi (34 MPa) cementitious material. A schematic section of the CEST is shown in Figure 1.

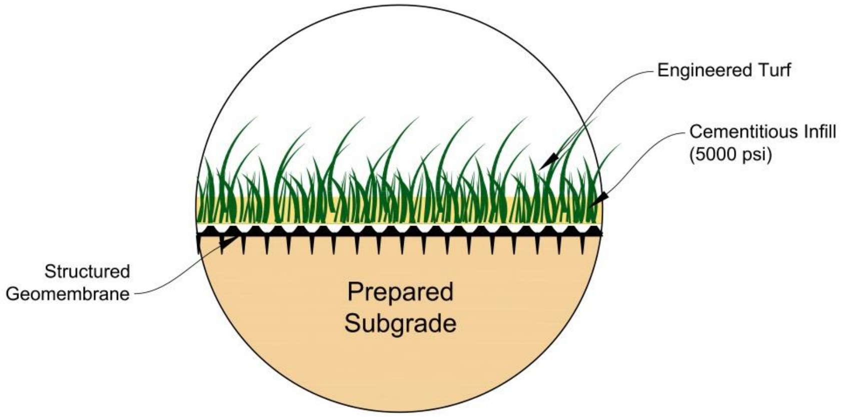

Figure 1: Concrete-Enhanced Synthetic Turf (CEST) Revetment System

Full-scale hydraulic performance thresholds for the CEST were evaluated by Colorado State University's Engineering Research Center (CSU). A thorough steady-state testing program was performed under four separate conditions as follows:

1. Steady-state Overtopping: Testing was performed in general accordance with ASTM D7277-08—Standard Test Method for Performance Testing of Articulated Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow. The results of the testing were analyzed in accordance with ASTM D 7276 - Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow.

2. Hydraulic Jump—Hydraulic jump testing was performed to quantify the performance of the CEST under the high energy and power dissipation loading caused by a hydraulic jump.
3. Heavy Debris Loads—This qualitative test was used to assess the resilience of the CEST to impact and abrasion from large, angular concrete rubble/debris being dropped into the flume.
4. Assessment of Performance in an Intentionally Damaged State—This qualitative test was used to evaluate the integrity and resilience of the CEST to a hole created from driving a pickaxe through both layers of the CEST and into the underlying embankment soil subgrade.

The testing facility, sample installation and preparation, procedures, analyses and results are described in the following sections of this paper.

Testing Facility and Sample Preparation

An existing outdoor flume at the Hydraulics Laboratory at CSU was utilized. This flume measures 4 ft (1.22 m) wide by 100 ft (30.5 m) long with a 2H:1V slope. The Horsetooth Reservoir provides a gravity–fed water supply for this flume. The head-box configuration and hydraulic supply limitations in this flume allowed for a maximum of 5 feet (1.52 m) of overtopping depth. This correlates to a maximum deliverable discharge of 120 cfs (204 m^3/min). Flume geometry incorporated a horizontal, 10 ft (3 m) long crest section, and a specified slope length of 30 ft (9.1 m). Figure 2 presents a profile drawing of the steep overtopping facility utilized for the testing program.

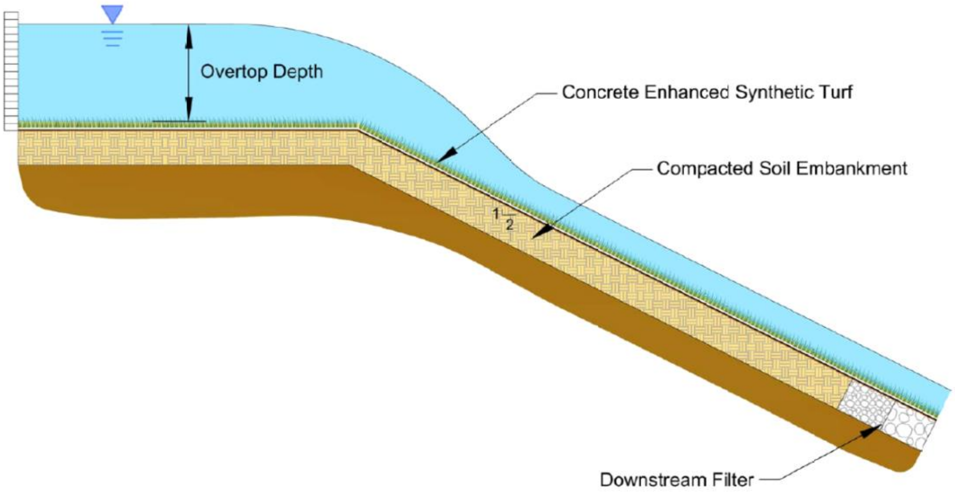

Figure 2: Profile of the Overtopping Facility at CSU

Installation and preparation of the CEST test sample was completed in general accordance with ASTM D7277-08. Subgrade soil material (sandy loam) was placed in the flume in order to simulate an earthen embankment. It was compacted in two equal 6 in (15.2 cm) lifts. Target compaction was achieved and verified between 87 percent and 93 percent of Standard Proctor (ASTM D698) density. Figure 3 presents a photograph of the embankment following soil compaction.

Figure 3 – Compacted Subgrade in Bottom of Flume

Figure 4 – Completed Installation of the CEST Prior to Testing

The structured geomembrane was placed in the flume as one continuous piece on top of the compacted soil subgrade. Next, the engineered synthetic turf was placed on the geomembrane. A horizontal seam was installed in the synthetic turf layer near the bottom of the flume in order to test its strength under high flow conditions. Two pieces of synthetic turf were heat-bonded together using equipment similar to that used for field installations (see Figure 6). Angle steel with a silicon bead was used to hold down the geomembrane and turf at the flume edge. Finally, the three-quarters inch (19 mm) thick layer of dry cementitous infill was applied into the fibers of the synthetic turf. It was hydrated by applying a light spray of water until saturation. Figure 4 shows the completed installation of the CEST test sample.

After the steady-state overtopping tests on the intact CEST, a vertical sluice gate was placed in the flume approximately three quarters down the slope from the top of the embankment. This gate was used to facilitate the creation of a hydraulic jump. The opening in the gate was 36 in (0.9 m) wide, and had a 3 in (7.62 cm) sill plate. Figure 5 shows a section of the flume for the hydraulic jump testing with the approximate location of the gate. Figure 6 shows a picture of the gate installed in the steep overtopping flume.

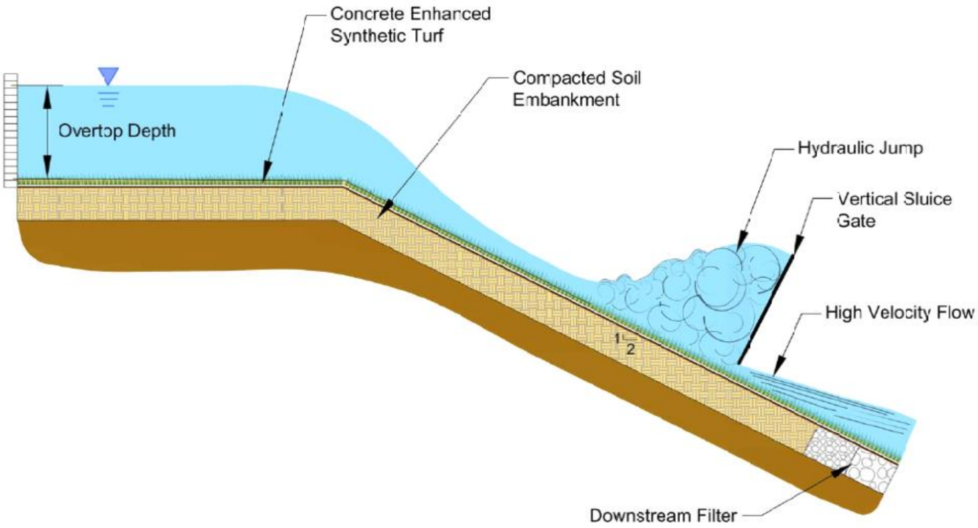

Figure 5: Cross Section of the Overtopping Flume with the Vertical Sluice Gate to Create a Hydraulic Jump

Figure 6: Vertical Sluice Gate Installed in the Overtopping Flume

Testing Procedures

Steady-state Overtopping

Steady-state overtop testing was performed in general accordance with ASTM D7277-08. Three overtop depth intervals of 1.5, 3, and 5 ft (0.46, 0.91 and 1.52 m) were tested. Each interval of the testing following the procedures is listed below:

- The flow was increased to the target discharge corresponding to the predetermined overtopping depth interval.
- The flow was continuously maintained for four hours over the CEST for each specific overtopping depth interval.
- At pre-established locations, water surface elevation measurements were collected using a point gage (accurate to the nearest 0.01 ft [3 mm]). They were collected at the start of each interval and every hour over the four-hour test period.
- After four hours the flow was stopped for each target discharge interval. Post-test elevations of the CEST were measured, and visual observations were performed. Failure of the CEST was defined as the loss of intimate contact with the subgrade embankment, instability, deformation and/or damage. If it was determined that there was no loss of intimate contact, no instability, no deformation, or no damage; then the discharge was increased and the next interval was started.
- This procedure was repeated until failure or until the maximum flow capacity of the testing facility was reached.

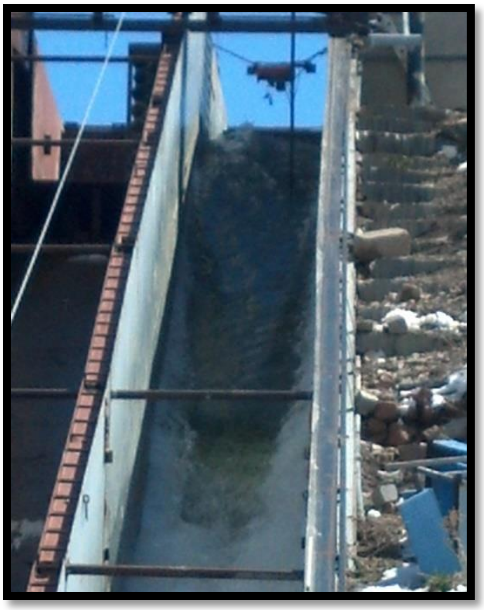

Figure 7: CEST Testing of 5 Foot Overtopping Depth in Process

A photograph of the steady-state testing at the 5 ft (1.52 m) overtop depth interval is presented in Figure 7.

Hydraulic Jump

CSU developed a standard testing program to adequately quantify the performance of the CEST subjected to hydraulic jump conditions. Testing was performed at the three overtopping depth intervals of 1.5, 3, and 5 ft (0.46, 0.91 and 1.52 m). Each interval of the testing followed the procedures listed below:

- The flow was increased to the target discharge corresponding to the predetermined overtopping depth.
- Each test interval consisted of at least 1.5 hours of continuous flow at the target discharge for the specified overtopping depth.
- A hydraulic jump was created on the CEST by adjusting the vertical sluice gate.
- When the hydraulic jump was determined to be stable, laboratory personnel measured the water surface at the gate, at the beginning of the jump and at approximate 2 ft (0.61 m) intervals upstream along the centerline of the slope.
- This hydraulic jump was held for at least thirty minutes of flow. Then, the sluice gate was adjusted to move the hydraulic jump upstream. For this new hydraulic jump, measurements of water surface were taken at the gate, at the beginning of the jump and at approximate 2 ft (0.61 m) intervals upstream along the centerline of the slope.
- The procedure was repeated to collect data for three hydraulic jumps at each of the three discharge intervals.
- If it was determined that the CEST did not exhibit instability, deformation, damage, uplift and/or loss of intimate contact; the flow was increased to the next target discharge. This procedure was repeated until failure of the CEST or until the maximum flow capacity of the testing facility was reached.

A photograph of the hydraulic jump testing is presented in Figure 8.

Figure 8: Hydraulic Jump Testing of the CEST

Heavy Debris Loads

Following the hydraulic jump testing and the inspection of CEST material in the flume, the CEST was evaluated for performance under conditions of heavy debris loads. The headbox was flooded to an overtopping depth of 5 feet (1.52 m).

Broken, angular-concrete blocks, ranging in size from approximately 3 to 15 inches (7.6 to 38.1 cm) in diameter (see Figure 9), were dumped into the flume from a height of approximately 12 feet (3.7 m). Two bucket loads of concrete rubble were dumped into the flume. The flow was shutoff and the embankment was inspected. Figures 10 and 11 show the concrete debris dropping into the flume.

Figure 9: Concrete Debris

Figure 10: Concrete Debris Being Dropped into the Flume

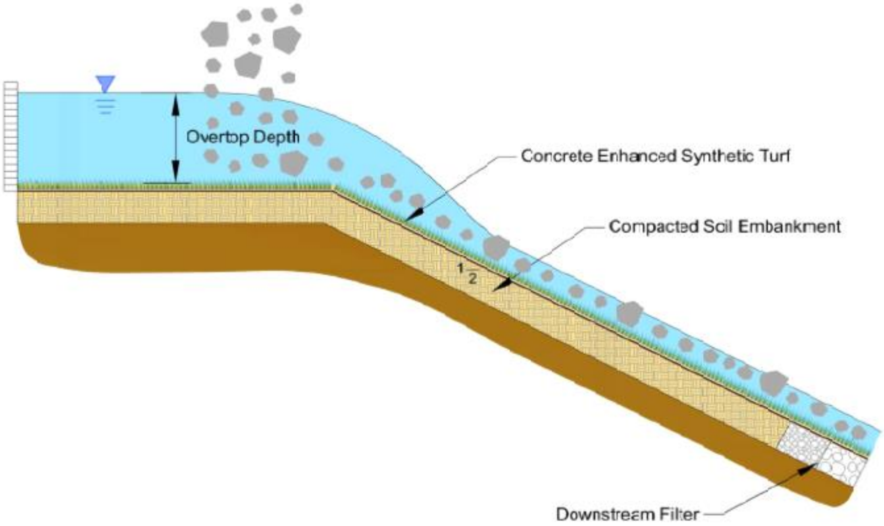

Figure 11: Concrete Debris Being Dropped into the Flume

Intentional Damage

After inspection of the CEST from the large debris testing, a hole was driven through the CEST and approximately 6 in (15.2 cm) into the underlying subgrade, using a pickaxe. The system was tested at an overtop depth of 3 feet (0.91 m) for one hour. Then the flow was increased to an overtopping depth of 5 feet (1.52 m) for another one hour period. A photograph of the hole being created is shown in Figure 12, and a photograph of the hole prior to testing is shown in Figure 13.

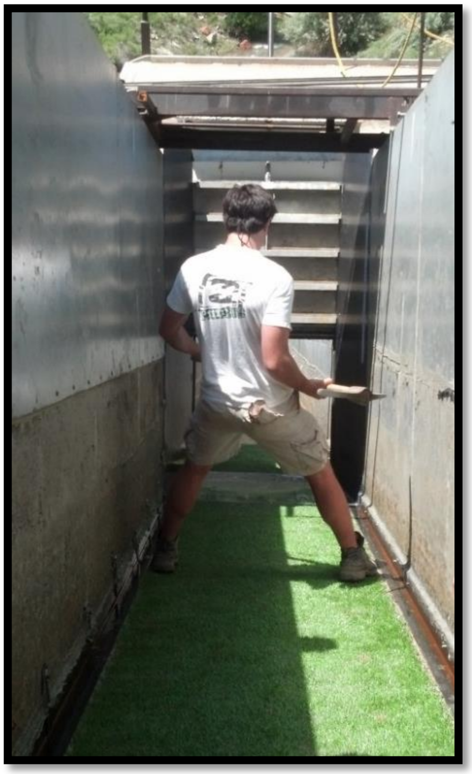

Figure 12: Pickaxe Being Used to Create an Intentional Hole

Figure 13: Intentional Hole in the CEST Prior to Testing

Analyses and Results

Steady-state Overtopping

ASTM D7276-08 is the appropriate methodology that is used to analyze the steady-state overtop testing. Based on this methodology, a standard step fore-water hydraulic model was used to create the water-surface profiles for each test interval of the CEST. This model computed the best-fit Manning's roughness based on the collected data. Theoretical water-surface profiles with varying Manning's roughness values were developed to evaluate the best-fit Manning's roughness for each profile. The best-fit Manning's roughness was defined as the value with the maximum coefficient of determination, R2.

After the best-fit water surface profiles were created, the continuity equation was used to calculate flow velocities. The velocity results are summarized as follows:

- Maximum stable flow velocity of the CEST was 29.2 fps (8.9 m/sec) with a Manning's n value of 0.020.
- Maximum velocity at the location of the horizontal seam was 28.5 fps (8.7 m/sec).
- Maximum velocity at the intentional pickaxe hole was 24.4 fps (7.4 m/sec).

Since the CEST did not exhibit instability, deformation, damage, uplift and/or loss of intimate contact with the subgrade; a performance threshold was not reached during the steady-state overtopping tests. The maximum capacity of the flume facility was reached prior to a performance threshold for the CEST.

Hydraulic Jump

The hydraulic loading caused by a hydraulic jump can be quite significant at the toe of a dam spillway or steep channel chute. Therefore, the CEST was tested for performance against this type of loading. For the nine different hydraulic jump intervals, the CEST did not exhibit instability, deformation, damage, uplift and/or loss of intimate contact with the subgrade. A performance threshold was not reached prior to the maximum capacity of the flume facility.

Hydraulic jump performance is typically evaluated with two relationships. These are as follows:

- The energy ratio versus the ratio of the upstream and downstream Froude numbers. The energy ratio is the energy lost in the hydraulic jump compared to the energy that would be lost in the same channel without a hydraulic jump.
- Hydraulic power versus the specific upstream energy for the hydraulic jump. Hydraulic power is the energy lost in the hydraulic jump, and the specific upstream energy is the entrance energy for the jump.

Even though a hydraulic jump performance threshold was not reached for the CEST, curves were still created for the Energy and Froude Ratios (See Figure 14) and Power Dissipation as a Function of the Energy at the Entrance to the Jump (See Figure 15). These curves represent a known performance level for the CEST but do not represent a performance threshold. Note that the CEST withstood hydraulic loads caused by hydraulic jumps dissipating 30 horsepower per foot of width (22.4 kW).

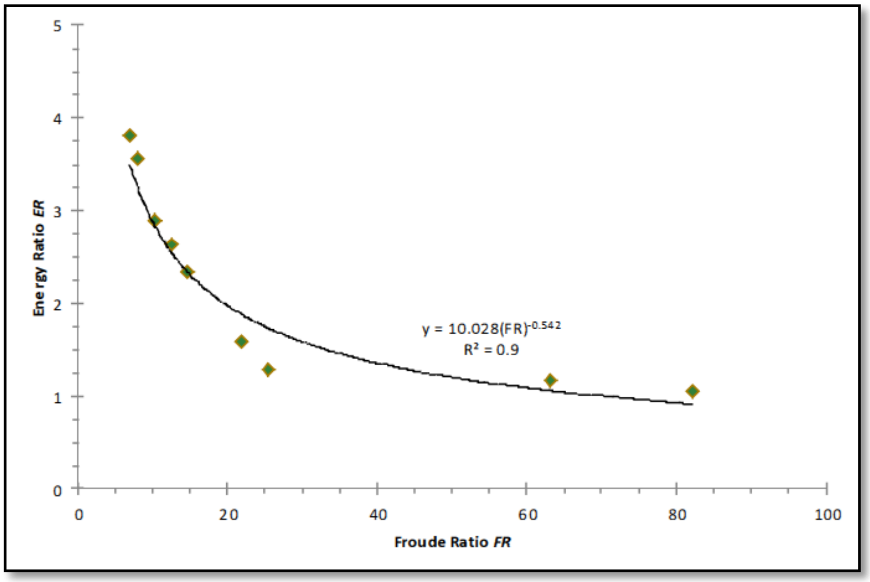

Figure 14: Energy Ratio as a Function of Froude Ratio for CEST

The vertical sluice gate used for the hydraulic jump testing had a small opening at the base. A pressurized “jet” of flow surged from under this gate out onto the CEST. A photograph of the “jet” flow is shown in Figure 16. Even though the extreme turbulence of the flow made it difficult to calculate the velocity precisely, a conservative estimate of the velocity was able to be made. It was estimated to be 35 fps (10.7 m/sec). There was no instability, deformation, loss of intimate contact, or damage of the CEST, and there was no erosion of the underlying highly-erodible subgrade caused by the “jet” of flow.

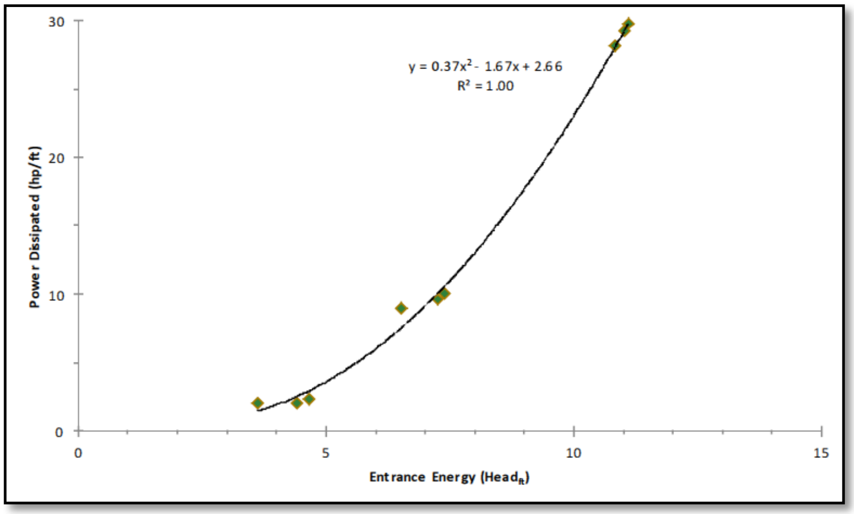

Figure 15: Power Dissipation per Foot of Width as a Function of Specific Energy at the Entrance to the Hydraulic Jump for the CEST

Figure 16: Pressurized “Jet” from Under the Sluice Gate Surging onto the CEST

Heavy Debris Loads

Dam spillways, large channels and steep channel chutes at mine sites have the potential to carry large debris. In order to assess the resilience of the CEST to impact and abrasion from debris loads, a qualitative test was performed. Large, angular-concrete rubble was dropped from a height of 12 ft (3.7 m) into the flume during an overtopping flow. After the two loads of concrete rubble were dropped and traveled down the flume, the flow was turned off and the CEST was inspected. The inspection revealed that the debris caused a few minor surface impressions (crack 1/16 in wide 3 to 4 in long) in the cementitious infill at the location of the 12 ft (3.7 m) drop (top of the flume). The integrity of the CEST was not compromised at the location of the drop, and there was no observed damage to the system downstream of this location. No instability, loss of intimate contact, or erosion was observed. The CEST performed well against the heavy debris loads.

Intentional Damage

A qualitative test was used to assess the performance and resilience of the CEST to a puncture hole. A pickaxe was intentionally driven through the CEST and approximately 6 in (15.2 cm) into the underlying sandy-loam subgrade. Flow discharges were run at the 3 ft (0.91 m) and 5 ft (1.52 m) overtop depths for a duration of one hour at each depth interval. During the testing, it was observed that there was no instability, loss of intimate contact, or discernible erosion. After the testing, the CEST was inspected. It was noted that the hole was still intact and did not further unravel. The condition of the hole is shown in the photograph in Figure 17.

Figure 17: Intentional Hole after Testing

Figure 18: Soil Subgrade at Location of Intentional Hole after Testing

After the completion of the twenty hours of testing in the steady-state overtop facility, the CEST was removed, and the subgrade was inspected. There was no erosion of the subgrade at the location of the intentional hole. The hole closed in (ee Figure 18). The velocity was calculated at the location of the hole in the flume to be 24.4 fps (7.4 m/sec). The CEST performed well after being subjected to puncture damage.

Also, the subgrade along the entire embankment showed no signs of erosion (see Figure 19).

Figure 19: Soil Subgrade of Embankment after Testing of the CEST

Case Study at Mine Site

Not only has the CEST been extensively tested in full-scale laboratory conditions, it has also been successfully utilized in real world applications. The Grouse Creek Unit is in the Salmon River Mountains of central Idaho 27 miles southwest of the town of Challis in the Yankee Fork Mining District. Gold mining at Grouse Creek began in late 1994 and ended in April 1997, due to higher-than-expected operating costs and less-than-expected operating margins, primarily because the ore occurred in thinner, less continuous structures than had been originally expected."[1] Closure of the mine site is currently underway.

High-volume discharges from the undisturbed western drainage areas flow through Washout Creek (aptly named) into the tailings impoundment reclamation area. Historically, Washout Creek had been built and rebuilt using rip-rap energy dissipation structures and other rock reinforced drainage conveyance structures. Summer-time thunderstorms can be quite intense in this area of the Rocky Mountain Range and would undermine the rock reinforcement and cause severe damage to rock-based drainage conveyance structures along the creek alignment. Storm water run-off in Washout Creek begins at an elevation of approximately 9,320 ft (2,840 m), flowing 5,905 ft (1,800 m) to the collection structure depicted above at an elevation of 7,315 ft (2,230 m) for an overall hydraulic grade line slope of 34 percent. The northern drainage basin area is approximately 128 acres (52 ha) in size. The southern basin

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[1] Idle Property Report, Form 10-K, Fiscal Year 2007, Hecla Mining Company

is approximately 39.5 acres (16 ha) in area. Using a 500 year return period, the design peak discharges were 671 and 385 ft^3/sec (19 and 10.9 m^3/sec) for the northern and southern basins, respectively.

In 2011, a CEST System was selected for use as a channel-lining material for the last phase of restoration of Washout Creek. This trapezoidal channel design utilized a low-flow channel section lined with CEST. The low flow section was 8 ft (2.4 m) wide base with 2:1 sideslopes to a flow depth of 2 ft (0.6 m). The edges of the CEST lining were to be anchored under a 4 ft (1.2 m) high rock wall that would extend 7 ft (2.1 m) on either side of the low-flow channel. A photograph of the CEST channel used on the steep tailings pile is shown in Figure 20.

Figure 20: CEST Channel at the Grouse Creek Mine

Hydraulic calculations using Manning's Equation indicate all flows, other than the 500 yr peak flow in the North Channel and Washout Creek Channel, would be contained within the CEST lined low-flow section with all flows contained between the design rock walls on either side of the low-flow section. Calculated design flow depths in the channel sections ranged from 1.78 ft (0.54 meters) in the South Channel with a slope of 15 percent to 3 ft (0.90 m) in Washout Creek with a channel slope of 25 percent. Corresponding flow velocities were 18.7 ft/sec (5.7 m/sec) and 34.8 ft/sec (10.6 m/sec), respectively. These calculated flow velocities within the 500 yr peak design flows would not exceed the values for the CEST as measured in the full-scale during the testing program conducted at CSU. Froude numbers for all flows were greater than 1 indicating supercritical flow in all three channel sections.

The CEST System channel lining is exceeding expectations and providing reliable storm water conveyance for the Grouse Creek Unit Closure.

Summary

CEST technology is a high-performing revetment solution for use at mine sites for dam spillways, steep down chutes, and large channels. Extensive testing of the CEST was conducted at the Hydraulics Laboratory at CSU. Instability or failure of the CEST did not occur in the twenty hours of full-scale testing up to the maximum discharge capacity of the flume facility (5.0 ft (1.52 m) overtop depth). The results of the steady-state overtop test demonstrate that the CEST has a Manning's n value of 0.020 under the tested conditions, and that it is able to withstand hydraulic loads resulting in a velocity exceeding 29.2 fps (8.9 m/sec). The hydraulic jump testing program established that the CEST has the ability to dissipate hydraulic loads greater than 30 horsepower per foot of width (22.4 kW) and to resist a velocity exceeding 35 fps (10.7 m/sec) from under the sluice gate. Qualitative testing showed that the CEST has the ability to endure impact and abrasion caused by falling debris loads and to resist erosion and instability when intentionally punctured. As instability or failure of the system did not occur, these test results should not be taken as performance thresholds. As a result of the hydraulic performance of CEST, it has been successfully implemented on numerous sites, including the Grouse Creek Mine.

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