Large-Scale Performance and Design for Construction Activity Erosion Control Best Management Practices

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The National Pollutant Discharge Elimination System (NPDES) Phase II requires construction activities to have erosion and sediment control best management practices (BMPs) designed and installed for site storm water management. Although BMPs are specified on storm water pollution prevention plans (SWPPPs) as part of the construction general permit (GP), there is little evidence in the research literature as to how BMPs perform or should be designed. The objectives of this study were to: (i) comparatively evaluate the performance of common construction activity erosion control BMPs under a standardized test method, (ii) evaluate the performance of compost erosion control blanket thickness, (iii) evaluate the performance of compost erosion control blankets (CECBs) on a variety of slope angles, and (iv) determine Universal Soil Loss Equation (USLE) cover management factors (C factors) for these BMPs to assist site designers and engineers. Twenty-three erosion control BMPs were evaluated using American Society of Testing and Materials (ASTM) D-6459, standard test method for determination of ECB performance in protecting hill slopes from rainfall induced erosion, on 4:1 (H:V), 3:1, and 2:1 slopes. Soil loss reduction for treatments exposed to 5 cm of rainfall on a 2:1 slope ranged from-7 to 99%. For rainfall exposure of 10 cm, treatment soil loss reduction ranged from 8 to 99%. The 2.5 and 5 cm CECBs significantly reduced erosion on slopes up to 2:1, while CECBs < 2.5 cm are not recommended on slopes ≥ 4:1 when rainfall totals reach 5 cm. Based on the soil loss results, USLE C factors ranged from 0.01 to 0.9. These performance and design criteria should aid site planners and designers in decision-making processes.

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Soil erosion is considered the largest contributor to nonpoint-source pollution in the United States according to the federally mandated NPDES (USEPA, 1997). Due to the loss of soil, nutrients, water, and reduced plant yields, it has been estimated that the on-site cost of soil erosion in the United States is more than $27 billion per year, while the annual cost due to sedimentation of eroded soil is more than $17 billion per year, bringing the total cost of erosion and sedimentation to more than $44 billion per year (Brady and Weil, 1996).

In 1987, amendments to the federal Clean Water Act mandated that construction sites must control storm water, erosion, and sediment originating from their site (USEPA, 2000). In 2003 the U.S. Environmental Protection Agency (USEPA) began enforcement of NPDES Phase II. Under NPDES Phase II, construction activities ≥ 0.4 ha (1 acre) are required to have erosion and sediment control BMPs designed and installed for site storm water management. Although these BMPs are required by law, and are typically specified on SWPPPs as part of the construction GP, there is very little evidence in the research literature as to how these management practices perform or should be designed. Recently, standard test methods have been developed to evaluate the performance of erosion control blanket (ECB) materials on hill slopes; however, since the ASTM D-6459 Standard Test Method for Determination of Erosion Control Blanket Performance in Protecting Hillslopes from Rainfall Induced Erosion (ASTM, 2006) has been approved, no research publications have been put forth as to the performance of erosion control materials used under this standard test method. Although CECBs, hydromulch, straw mulch, wood mulch, and topsoil have been comparatively evaluated (Persyn et al., 2004; Faucette et al., 2005, 2006, 2007), these studies did not use the ASTM D-6459 standard test method, nor did they include widely used slope stabilization BMPs such as tackifiers, polyacrylamides, and rolled erosion control blankets (RECBs).

In 2005, the USEPA included CECBs on the list of NPDES Phase II BMPs for Construction Activities (USEPA, 2006). Al-

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Abbreviations: BMP, best management practice; CECBs, compost erosion control blankets; GP, general permit; NPDES, National Pollutant Discharge Elimination System; PAM, polyacrylamide; RECBs, rolled erosion control blankets; RO, reverse osmosis; SERL, Soil Erosion Research Laboratory; SWPPPs, storm water pollution prevention plans.

though this BMP is widely accepted and used, the specifications presented by the USEPA have not been widely evaluated. A study conducted by Faucette et al. (2007) evaluated the performance of various particle size distributions for CECBs under simulated rainfall of 10 cm/h for 60 min; however, the specified blanket thickness has never been effectively evaluated. The USEPA specifies, under the NPDES National Menu of BMPs for CECBs, application thickness should correspond with *annual* rainfall accumulation rates. Compost erosion control blanket thickness of 1.25 cm (0.5 in) is recommended for rainfall accumulations up to 62.5 cm (25 in); a thickness of 2.5 cm (1.0 in) is recommended for rainfall accumulations between 62.5 (25 in) and 125 cm (50 in); and a thickness of 5.0 cm (2.0 in) is recommended for annual rainfall accumulations above 125 cm (50 in).

The same USEPA specifications recommend that CECBs can be used on slopes ≤ 2:1, although published research on CECB performance has only been conducted on modest slope angles, ranging from 10:1 (Faucette et al., 2005, 2007) to 3:1 (Persyn et al., 2004). It should be noted erosion control BMPs may provide varying levels of effectiveness on vegetation establishment and sustainability, which ultimately provides long-term soil stabilization and erosion control. Faucette et al. (2006) reported that CECBs provided 2.75 times more vegetative cover and significantly less weed biomass relative to hydromulch treatments in plots 1 by 4.8 m over a 1 yr growing period. Studies by Faucette et al. reported decreased soil loss, partly due to increases in vegetation, over 3 mo (2007) and 1 yr (2005) time periods.

Effective performance evaluation and reporting is critical to provide regulators, specifiers, planners, and designers the information needed to critically choose between soil erosion control BMP options based on prevailing site and climate conditions. However, once performance is understood, designers need to effectively apply it to site design. Best management practice determination of C Factors used in the USLE can help designers predict soil loss over a given soil disturbance area or construction site. This can be critical if there is a particular soil loss reduction goal within the project site watershed. Cover management factors used in the USLE have been widely reported for erosion control management practices (Georgia Soil and Water Conservation Commission, 2000, p.19–191; Demars and Long, 1998; ECTC, 2004; Faucette et al., 2007). ASTM D-6459 includes a standard methodology for determining and reporting cover management factors for the USLE.

The objectives of this study were to: (i) comparatively evaluate the performance of commonly used construction activity erosion control BMPs under a standardized test method, (ii) evaluate the performance of various CECB thicknesses, (iii) evaluate the performance of compost erosion control blankets on a variety of slope angles, and (iv) determine USLE cover management factors for these erosion control BMPs to assist site designers and engineers.

Materials and Methods

The experiment was conducted at the Soil Erosion Research Laboratory (SERL), in the Civil, Construction and Environmental Engineering Department at San Diego State University (SDSU). The SERL was established in 1998 by the California Department of Transportation (CalTrans) in response to the need for consistent and quantitative soil erosion and sediment control product research and development. The core component of the laboratory is a 3-m wide by 10-m long tilting soil bed with overhead rainfall simulators. The adjustable tilt of the soil bed is parallel to the long-axis and has a maximum slope of 2:1 (Fig. 1).

Experimental Set-up

Rainfall was applied to the soil bed using a Norton Ladder Rainfall Simulator, developed at the USDA-ARS National Soil Erosion Research Laboratory. Two six-head simulators installed above the bed applied uniform precipitation over the entire plot area. Each six-head simulator is a self-contained unit that includes six spray nozzles, each with a dedicated pressure gauge, drive motor, oscillating mechanism, and sweep rate controller. The Veejet 80100 spray nozzles are spaced evenly over the bed and located 2.5 m above the soil surface (Fig. 1a). To ensure uniform intensity across the plot, the centers of the spray patterns from two laterally adjacent nozzles meet at the plot surface. Each simulator has a system of valves that allow internal water pressure to be adjusted from a low of 28 kPa to a high of 55 kPa. As used here, the pressure was 41 kPa, which provides a flow rate of approximately 14.7 lpm from each nozzle, a 2.25 mm median drop diameter, a nozzle exit velocity of 6.8 m/s, and a spherical drop with a soil surface impact velocity similar to the impact velocities of drops from natural rainstorms.

The water used to simulate rainfall in this study was municipal water treated with reverse osmosis (RO). Before entering the RO unit, municipal water is passed through one activated carbon vessel, two softening vessels, and a prefilter to remove particulates larger than 5 microns. The system is capable of producing 1200 to 2400 L per day and uses a 3800 L polyethylene storage tank. The treated water is pumped to the rainfall simulators positioned above the soil test bed, and unused water from within the simulators is returned via gravity to the holding tank for reuse.

Sixty-nine simulated rainfall-runoff runs were performed at the SERL following the general guidelines outlined in ASTM D-6459. The runs consisted of 23 different erosion control treatments including the control conditions (i.e., bare soil, no treatment), each performed in triplicate (23 × 3 = 69). All runs were performed on SERL's tilting soil bed at slopes ranging from 4:1 to 2:1. Based on the USDA textural classification system, the test soil was a loamy sand (approximately 85% sand, 15% fines). This soil was chosen because it was the only textural class commercially available in large quantities near the SERL. The soil had a plastic limit of 22.0% and a liquid limit of 18.4%. The particle size distribution for the study soil is shown in Fig. 2. The experiments were performed on a test area 2 m wide by 8 m in length. Runoff from the test area was directed into a flume and collected at the outlet. Before each test, wetted soil on the bed was removed to expose untested soil and additional soil was added to maintain a consistent bed height of 45 cm. The added soil was moistened, tilled with the existing soil, and hand-compacted to uniform consistency with mean bulk density approximately 1.4 g/cm^3, ranging from 1.3 to 1.5 g/cm^3, and antecedent soil moisture content of 20%. In

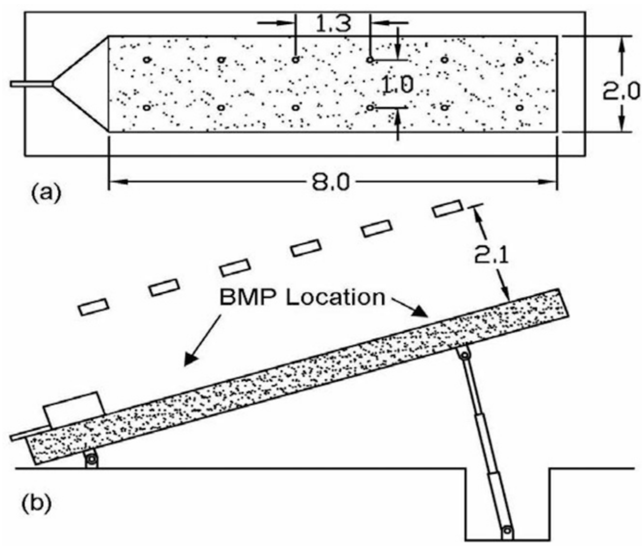

Fig. 1. Soil Erosion Research Laboratory's (SERL's) tilting soil bed with overhead rainfall simulators: (a) plan view showing bed dimensions (m) and rainfall simulator spray nozzle locations shown as circles; (b) sectional view showing vertical placement of simulator spray boxes and downstream collection flume shown in both (a) and (b).

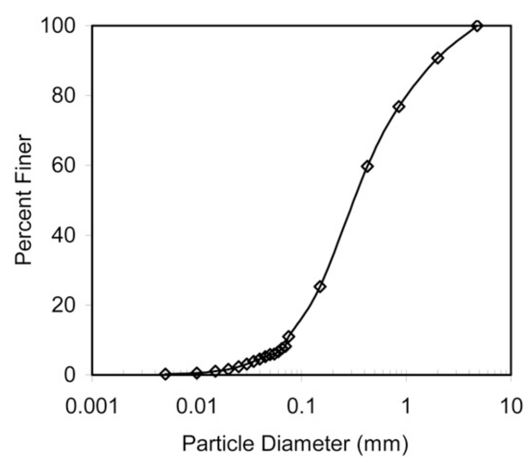

Fig. 2. Particle size distributions for laboratory soil used in erosion experiments.

accordance with ASTM D-6459, erosion control products were installed following manufacturer's specifications.

Treatment Description

Twenty-three erosion control treatments were evaluated for their potential to reduce soil loss (Table 1). A granular, anionic, medium charge density, 2.2% active polyacrylamide (PAM) with a molecular weight of 20,000,000 g/mol was evaluated on a bare, untreated soil surface using an application rate of 2270 kg/ha (2000 lb/acre). The PAM was applied by manually broadcasting the granules, wetting the surface using the rainfall simulators at 15 mm/h for 45 s, and allowing to dry by mechanical fans for 24 h. A proprietary soil tackifier, derived entirely from corn starch polymers, was evaluated using an application rate of 280 kg/ha (250 lb/acre [dry weight]) mixed in a 1% solution and applied to the soil with a high pressure, low volume (HPLV) power sprayer. The soil surface was allowed to dry under mechanical fans for 24 h before simulated rainfall began. Four different RECBs were evaluated: single- and double-net straw blankets; double-net coconut (*Cocos nucifera* L.) fiber blanket; and a single-net excelsior wood fiber blanket. All RECBs were installed per manufacturer specifications which included systematically stapling the blanket to the soil surface and trenching the blanket into the top of the slope.

Nine CECBs treatments were evaluated at three different thicknesses: 1.25 cm (1/2 in), 2.5 cm (1 in) or 5 cm (2 in); on three different slopes: 4:1, 3:1 and 2:1. The CECBs were derived from green waste and adhered to federal standard specifications for compost used for erosion control on construction sites (USEPA, 2006). The CECB's were installed manually to ensure uniform coverage, while not disturbing the soil surface during the installation process. For each installation, the CECB thickness was measured at 10 locations throughout the bed to verify the desired depth was achieved.

Building on the benefits of CECBs, five additional CECBs treatments were evaluated using combinations of other products at a slope angle of 2:1 (Table 1). Three CECBs thicknesses (1.25, 2.5, 5.0 cm) were combined with a polypropylene netting to help maintain the placement and stabilization of the CECB during simulated rainfall and runoff. The netting was installed on the soil surface before the CECB. A 1.25 cm CECB was evaluated in conjunction with PAM, where PAM in granular form was applied to the surface of the CECB at a rate of 2270 kg/ha (2000 lb/acre) as described previously. A 2.5 cm CECB was evaluated in conjunction with a single-net excelsior wood fiber blanket, with the CECB applied on top of the excelsior blanket.

Rainfall and Runoff Sampling

In accordance with ASTM D-6459, simulated rainfall consisted of a 60 min storm separated into three periods of constant rainfall intensities. The initial intensity was 50 mm/h (2.0 in/h) for 20 min, followed by 100 mm/h (4.0 in/h) for 20 min, followed by a peak intensity of 150 mm/h (6.0 in/h) for 20 min (Fig. 3). The total rainfall applied over the 60-min period was 10 cm: 1.65 cm at 20 min, 5 cm at 40 min and 10 cm at 60 min. Results are presented and discussed for each 20-min period.

Once a simulation began, all runoff was collected at the downstream (toe) end of the flume in a container with a known stage-volume relationship. Although rainfall was simulated for 60 min, runoff did not occur until the rainfall intensity exceeded the rate of absorption by the product and/or the rate of infiltration into the soil. Once runoff occurred, runoff samples were collected (300 mL) and runoff volumes were recorded every 3 min. The runoff volume during each 3 min interval plus the volume of the collected water sample was used to determine the average volumetric flow rate for each 3-min interval. Each sample was measured (volume) and dried in an oven to determine the weight of dry sediment in the sample. The initial volume of the runoff sample was then used to determine the average sediment concentration (mg/L) for each 3-min interval during the runoff period. The measured volumetric flow rates and calculated sediment concentrations were then used to determine the runoff (volume) and dry sediment (weight) exported in each 3-min period; and summed to determine total runoff and sediment export.

Analysis of Results

To assess product performance for soil erosion control, sediment export results from erosion control treatments were compared to the control/no treatment. Two measures were used: (1) sediment reduction and (2) USLE C factor.

Sediment-retention throughout an experiment (E_k) was determined by:

$$E_k = \left[\sum_{i=1}^{k} (S_{NT,i} - S_{T,i}) / \sum_{i=1}^{k} (S_{NT,i}) \right] \times 100\% \quad [1]$$

where i is the time interval for measured sediment export; k is the number of time intervals; $S_{NT,i}$ and $S_{T,i}$ are the masses of dry sediment exported in time interval i for the no treatment (NT) and treatment (T) experiments, respectively. E_k greater than zero indicates a sediment reduction; conversely, E_k less than zero indicates an increase in sediment export relative to the control conditions.

A two step process was used to determine the effective C factor in the USLE:

$$A = R \times K \times LS \times C \times P \quad [2]$$

where A is sediment yield, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, LS is the slope steepness-length factor, C is the cover management factor, and P is the support practice factor (Wischmeier and Smith, 1960). First, K was determined from the bare soil/control experiments where C and P are equal to 1.0. The above equation can then be re-written as:

$$K = A\ (LS \times R)^{-1} \quad [3]$$

where A is the sediment yield (tons/acre/simulation period) from the bare soil/no treatment conditions, LS is equal to 2.79, 2.12 or 1.62 for SERL's tilting soil bed at a respective 2H:1V, 3H:1V or 4H:1V slope and R is equal to $\Sigma EI_{30}(10^{-2})$, where E is the total storm kinetic energy and I_{30} is the maximum 30 min rainfall intensity. For the rainfall intensities used in this project, the R factor is approximately 8, 60, and 230 [MJ mm (ha h yr)$^{-1}$] at times 20, 40, and 60 min, respectively. Therefore, the calculated K factor (soil erodibility) is dependent on the determined sediment yield, and slope steepness and length, and rainfall-runoff erosovity factors used in this experiment. See Table 2 for experimental K factors.

Each treatment/no treatment condition was evaluated in triplicate to determine experimental treatment means. SAS version 8.2 (SAS Institute, 2001) was used for statistical analysis. Separation of means for sediment loss was determined by PROC GLM using Duncan's Multiple Range test to determine any significant differences between treatments ($P \leq 0.05$). Before means separation using Duncan's Multiple Range test, type 1 error was controlled for at the ≤0.05 level and any resultant $P > F$ values > 0.05 were not deemed to be significant.

Table 1. Experimental erosion control treatments and control.

Erosion control practice	Slope(s)
None, bare soil	2H:1V, 3H:1V, 4H:1V
CECB† 5.0 cm	2H:1V, 3H:1V, 4H:1V
CECB 2.5 cm	2H:1V, 3H:1V, 4H:1V
CECB 1.25 cm	2H:1V, 3H:1V, 4H:1V
Single-net straw	2H:1V
Single-net excelsior fiber	2H:1V
Double-net straw	2H:1V
Double-net coconut fiber	2H:1V
Tackifier	2H:1V
PAM	2H:1V
CECB 5.0 cm + netting	2H:1V
CECB 2.5 cm + netting	2H:1V
CECB 1.25 cm + netting	2H:1V
CECB 1.25 cm + PAM	2H:1V
CECB 2.5 cm + Single-net excelsior fiber	2H:1V

† CECB, compost erosion control blanket; PAM, polyacrylamide.

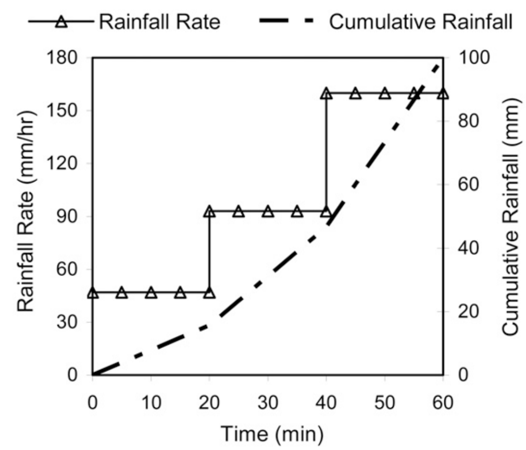

Fig. 3. Simulated rainfall rates and accumulated rainfall over three 20-min periods of constant rainfall intensity.

Table 2. Experimental soil erodibility factors (*K*) for rainfall time increment 20, 40, and 60 min at three slope angles.

Time (min)	4H:1V	3H:1V	2H:1V
20	1.00	0.58	0.49
40	0.58	0.54	0.43
60	0.33	0.33	0.30

Results and Discussion

Soil Loss for Erosion Control Practices

Results for all erosion control practices evaluated at a 2:1 slope are presented in Table 3. Results for soil loss and soil loss reduction are cumulative for each incremental rainfall intensity. For the first 20 min rainfall duration (20 min at 5 cm/h, 20 min and 1.65 cm total), 11 of the 14 erosion control treatments had significantly less soil loss relative to the control. Treatments that did not significantly reduce soil loss (PAM, single-net straw, 1.25 cm CECB) were likely due to lack of sufficient soil cover (observed not quantified) to prevent splash erosion, sheet transport and minor rilling (observed); and likely absorbed a smaller fraction of the rainfall, thereby increasing runoff. To support this, thicker CECBs and straw blankets generated less soil loss at this rainfall

Table 3. Mean cumulative soil loss and reduction (%) relative to bare soil for each erosion control practice at 2:1 slope after each 20 min rainfall intensity increment (total rainfall accumulation).

Erosion control practice	Runoff	Soil loss at 5 cm/h 20 min (1.65 cm)			Runoff	Soil loss at 10 cm/h 40 min (5.0 cm)			Runoff	Soil loss at 15 cm/h 60 min (10.0 cm)		
	L	kg	t/ha/cm	% red	L	kg	t/ha/cm	% red	L	kg	t/ha/cm	% red
Bare soil	133	38a ± 31	15.2	na†	628.6	256ab ± 14	34.3	na	1524.8	685a ± 81	42.8	na
CECB‡ 5.0 cm	7.7	0.08c ± 0	0	99.8	421.6	85.06defg ± 71	11.4	66.8	1083.4	193e ± 98	12.0	71.9
CECB 2.5 cm	16.8	0.33c ± 0.5	0.1	99.1	450.6	99.52def ± 41	13.3	61.1	1119.6	213de ± 70	13.3	68.9
CECB 1.25 cm	55.9	18abc ± 21	7.3	52.1	560.4	179.0bcd ± 43	24.0	30.1	1253.6	290cde ± 67	18.1	57.7
Single-net straw	96.3	20abc ± 11	7.8	48.8	561.9	158.0cde ± 10	21.1	38.3	1359.7	406bc ± 72	25.3	40.8
Single-net excelsior fiber	104.9	11bc ± 8	4.5	70.2	546.7	102.0def ± 27	13.7	60.1	1313	266cde ± 77	16.6	61.1
Double-net straw	83.2	14bc ± 9	5.7	62.7	505.2	116.0def ± 13	15.5	54.7	1230.2	302cde ± 39	18.9	56.0
Double-net coconut fiber	38.1	0.20c ± 0.9	0.1	99.5	454.4	67.79efg ± 19	9.1	73.5	1302.8	282cde ± 49	17.7	58.8
Tackifier	108.7	7.7bc ± 5	3.1	79.9	489.3	112.1def ± 63	15.0	56.2	1333	403bcd ± 122	25.2	41.2
PAM	116.6	27ab ± 13	10.7	29.9	653.4	274.0a ± 112	36.6	−6.8	1531.4	632a ± 234	39.5	7.7
CECB 5.0 cm + Netting	6.9	0.02c ± 0	0	99.9	262.5	54.84fg ± 33	7.3	78.6	945.5	211cde ± 99	13.2	69.1
CECB 2.5 cm + Netting	11.4	0.06c ± 0	0	99.8	351.7	82.69efg ± 47	11.1	67.7	1008.5	201de ± 93	12.6	70.6
CECB 1.25 cm + Netting	53.5	0.72c ± 0.4	0.3	98.1	472.3	119.16def ± 66	15.9	53.5	1288.5	379cde ± 180	23.7	44.7
CECB 1.25 cm + PAM	76.2	1.3c ± 1	0.5	96.7	588.7	219.9abc ± 66	29.4	14.1	1464.7	570ab ± 47	35.6	16.8
CECB 2.5 cm + Single-net excelsior fiber	31.3	0.17c ± 0.1	0.1	99.6	295.9	3.32g ± 2	0.4	98.7	815.5	6f ± 4	0.4	99.1

† na = not applicable. Treatments with same letter are not significantly different at α = 0.05 using Duncan's multiple range test.

‡ CECB, compost erosion control blanket; PAM, polyacrylamide.

intensity and duration. Additionally, the PAM would have likely benefited from a supplemental technology that could prevent the intense action of rain drop impact and soil particle dislodgment. Three erosion control treatments did not significantly reduce soil loss relative to the three previously mentioned erosion control treatments: tackifier, double-net straw, and single-net excelsior. The netting addition to the 1.25 cm CECB appeared to provide enough stability of the CECB to significantly reduce soil loss compared to bare soil and PAM at this rainfall intensity.

For the next 20 min rainfall duration (20 min at 10 cm/h, 40 min and 5 cm total), 11 of the 14 treatments had significantly less soil loss than the control. Of the three that did not significantly reduce soil loss relative to the control, the reason appeared to be the same as the treatments that were not significantly different for the previous rainfall intensity (CECB 1.25 cm+PAM did not appear to cover 100% of the soil surface). The CECB+single-net excelsior fiber significantly reduced soil loss relative to most of the treatments, followed by the 5 cm CECB+netting, double-net coconut fiber, and 2.5 cm CECB+netting. Each of these erosion control treatments provided full cover of the soil surface, prevented observable rilling underneath the blanket, and absorbed a larger fraction of the rainfall relative to the other treatments. Adding compost to a rolled erosion control product or netting appears to reduce soil loss under these experimental conditions.

For the final 20 min rainfall duration (20 min at 15 cm/h, 60 min and10 cm total) 11 of the 14 treatments generated significantly less soil loss relative to the control. Of these treatments, the CECB+single-net excelsior fiber treatment had significantly less soil loss than all other erosion controls, with a reduction of 99% relative to the control. The 5 and 2.5 cm CECBs with and without netting also significantly reduced soil loss relative to other erosion controls and had an average soil loss reduction near 70% relative to the control. For the 60-min event it does not appear that netting provides an added benefit to the CECB. Erosion control practices that provided the best erosion control were those that appeared to have greater soil coverage and a thicker blanket, likely preventing splash erosion caused by intense rainfall impact and by reducing transport from sheet runoff and erosion, and ultimately delaying the onset of rilling.

Effect of Slope Angle and Thickness on CECB Performance

Three compost erosion control blanket thicknesses were evaluated, 5.0 cm (2.0 in), 2.5 cm (1.0 in), and 1.25 cm (0.5 in) at three slope angles (2:1, 3:1, and 4:1). Table 4 shows the soil loss and soil loss reduction, relative to the control, for each thickness at each slope angle after each 20-min rainfall intensity increment. The values represented are cumulative.

After the first 20 min duration (1.65 cm total), all CECB thicknesses at all slope angles significantly reduced soil loss relative to the bare soil, with the exception of the 1.25 cm CECB at a 2:1 slope. It is interesting to note that there was slightly more soil loss at the 4:1 slope, relative to the steeper slopes at this rainfall increment. This may be due to natural variability in slope rill and interrill formation, particularly at lower intensity/duration rainfall events where soil erosion is not extreme. After the second rainfall duration and intensity (40 min total, 10 cm/h, 5 cm total), all CECB treatments significantly reduced soil loss, with the exception of the 1.25 cm CECB at a 3:1 slope. For the 2:1 and 3:1 slope angles, the 5.0 and 2.5 cm CECB generated significantly less soil loss relative to the 1.25 cm CECB; however the 5.0 and 2.5 cm CECB were not significantly different from each other. This provides evidence that at this rainfall intensity and duration a 2.5 cm CECB is sufficient for slopes up to 2:1. After the final 20-min event (60 min total, 15 cm/h, 10 cm total), all CECBs significantly reduced erosion at a 3:1 and 2:1 slope; however, only the 5.0 cm CECB significantly reduced erosion, relative to the control, at a 4:1 slope. Furthermore, the 5.0 cm CECB significantly reduced soil loss relative to the 1.25 cm at

Table 4. Mean cumulative soil loss reduction (%) for each CECB thickness by slope angle after each 20 min rainfall intensity increment (total rainfall accumulation).

CECB† Thickness	Slope angle (H:V)	Runoff	Soil loss at 5 cm/h 20 min (1.65 cm)			Runoff	Soil loss at 10 cm/h 40 min (5.0 cm)			Runoff	Soil loss at 15 cm/h 60 min (10.0 cm)		
cm		L	kg	t/ha/cm	% red	L	kg	t/ha/cm	% red	L	kg	t/ha/cm	% red
Bare soil	2:1	133	38a ± 31	15.2	na‡	628.6	256ab ± 14	34.3	na	1524.8	685a ± 81	42.8	na
5.0	2:1	7.7	0.08c ± 0	0	99.8	421.6	85.06defg ± 71	11.4	66.8	1083.4	193e ± 98	12.0	71.9
2.5	2:1	16.8	0.33c ± 0.5	0.1	99.1	450.6	99.52def ± 41	13.3	61.1	1119.6	213de ± 70	13.3	68.9
1.25	2:1	55.9	18abc ± 21	7.3	52.1	560.4	179.0bcd ± 43	24.0	30.1	1253.6	290cde ± 67	18.1	57.7
Bare soil	3:1	117.3	34.0a ± 14	13.7	na	626.9	246ab ± 20	3.3	na	1545.7	576ab ± 92	36.0	na
5.0	3:1	10.2	0.34b ± 0.5	0.1	99.0	288.3	49.2cd ± 18	6.6	80.1	889.9	140de ± 53	8.8	75.7
2.5	3:1	41.1	0.90b ± 0.8	0.4	97.4	342.8	33.4cd ± 8	4.5	86.4	1168.7	286cd ± 143	17.9	50.4
1.25	3:1	54.5	3.4b ± 5	1.4	90.0	560	174.6b ± 72	23.4	29.1	1467	401c ± 249	25.0	30.5
Bare soil	4:1	183.7	46.0a ± 33	18.1	na	686.1	203ab ± 102	27.1	na	1434.8	442bc ± 131	27.6	na
5.0	4:1	4	0.02b ± 0	0	100.0	238.2	17.4d ± 13	2.3	91.4	886.8	77e ± 32	4.8	82.6
2.5	4:1	39.7	1.4b ± 2	0.6	96.8	427.7	78.2cd ± 49	10.5	61.4	1184.8	239cd ± 141	15.0	45.9
1.25	4:1	641	0.82b ± 0.4	0.3	98.2	525	104.4c ± 12	14.0	48.4	1292.3	274cd ± 100	17.1	38.0

† CECB, compost erosion control blanket.

‡ NA = not applicable. Treatments with same letter are not significantly different at α = 0.05 using Duncan's multiple range test.

Table 5. Cover management factors for erosion control best management practices (BMPs) using ASTM D-6459 after 60 min cumulative rainfall.

Erosion control practice	Thickness	Slope angle (H:V)	USLE C Factor
	cm		
CECB†	5.0	2:1	0.28
CECB	2.5	2:1	0.31
CECB	1.25	2:1	0.42
Single-net straw	na‡	2:1	0.59
Single-net excelsior fiber	na	2:1	0.39
Double-net straw	na	2:1	0.44
Double-net coconut fiber	na	2:1	0.41
Tackifier	na	2:1	0.59
PAM	na	2:1	0.92
CECB + Netting	5.0	2:1	0.31
CECB + Netting	2.5	2:1	0.29
CECB + Netting	1.25	2:1	0.55
CECB + PAM	1.25	2:1	0.83
CECB + Single-net excelsior fiber	2.5	2:1	0.01
CECB	5.0	3:1	0.24
CECB	2.5	3:1	0.50
CECB	1.25	3:1	0.70
CECB	5.0	4:1	0.17
CECB	2.5	4:1	0.54
CECB	1.25	4:1	0.62

† CECB, compost control erosion blanket; PAM, polyacrylamide.

‡ na = not applicable.

slope angles 3:1 and 4:1, but was not significantly different from the 2.5 CECB at 3:1 and 2:1 slopes. This provides evidence that at these rainfall intensities and durations, a 2.5 cm CECB may provide similar erosion control as a 5.0 cm CECB, although the percent reduction in soil loss at the 3:1 slope was much higher with the 5.0 cm CECB.

It is interesting to note at the 10-cm event that 2.5 cm CECB produced a higher percent soil loss on 4:1 slopes than 3:1 slopes. This is likely due to the propensity of the compost to become buoyant when exposed to high rainfall intensities without the benefit of the steeper slope to force runoff from the slope or into rill formations. This likely did not happen with the 5.0 CECB as the compost volume was sufficient to prevent buoyancy long enough to cover the soil for a longer period of time at this rainfall accumulation and these slope angles. Further research may investigate threshold buoyancy levels for various CECB thicknesses used on modest slope angles or develop materials that may prevent the CECB from becoming buoyant, such as netting.

Table 6. Recommended compost erosion control blanket (CECB) thickness (cm) based on slope angle (H:V) and rainfall accumulation (cm in 24 h period).

Slope angle	Rainfall = 1.65 cm	Rainfall = 5.0 cm	Rainfall = 10.0 cm
≤4:1	1.25 to 5.0	2.5 to 5.0 (5.0 preferred)	5.0
4:1 to 3:1	1.25 to 5.0	2.5 to 5.0	5.0
3:1 to 2:1	2.5 to 5.0	2.5 to 5.0	2.5 to 5.0

Design for Erosion Control Best Management Practices

Development of USLE (and RUSLE) C factors for erosion control management practices can assist site planners and designers in predicting soil loss, which can affect the size and design of other site BMPs such as sediment barriers, sediment traps, and ponds or basins. Cover management factors can also assist designers in choosing the optimum BMP for their site plan. Cover management factors for all BMP treatments evaluated are listed in Table 5. The cover management factor for the control (bare soil) is 1.0. Because the USLE is a linear equation, each C factor can be directly applied to a predetermined A (total soil loss) to determine the erosion control BMP effect on site soil erosion, where A was originally determined using a C factor of 1.0.

Site planners and designers should consult historical rainfall records for their region to determine which CECB thickness is appropriate for their site (slope angle) and prevailing rainfall accumulation and duration periods. Table 6 is a recommended specification for CECB thickness based on site slope angle and 24 h rainfall accumulation potential.

Summary and Conclusions

This study evaluated 23 erosion control treatments based on experimental conditions specified in ASTM D-6459. For rainfall events ≤1.65 cm, all erosion control practices evaluated provided significant erosion control with the exception of PAM, 1.25 cm CECB, and single-net straw. For rainfall events between 1.65 and 5 cm, all erosion control practices significantly reduced soil loss except: PAM, 1.25 cm CECB+PAM, and 1.25 cm CECB. For rainfall events between 5 and 10 cm, all erosion control practices significantly reduced soil erosion except: PAM and 1.25 cm CECB+PAM. The CECBs were also evaluated at three different slope angles and thickness levels. All three CECB thicknesses significantly reduced erosion for slopes ≤3:1 for rainfall events up to 1.65 cm, while 2.5 and 5.0 cm CECBs significantly reduced erosion on slopes up to 2:1. When rainfall increased to 5.0 and 10.0 cm, 2.5 and 5.0 cm CECBs provided similar erosion control at 3:1 and 2:1 slopes, while CECBs <2.5 cm are not recommended on slopes ≥4:1 when rainfall totals reach 5.0 cm. Erosion control practices that provided the best erosion control were those that had the greatest observed soil coverage and a thicker blanket, thereby preventing splash erosion caused by intense rainfall impact and by reducing transport from sheet runoff and erosion, ultimately delaying the onset of observable rilling. Based on the soil loss results presented here, USLE C factors ranged from 0.01 to 0.92, where bare soil is 1.0. These design criteria should aid site planners and designers in decision making processes through site soil loss prediction and appropriate application of CECBs for their site and climate conditions.

Future research should determine the performance of these erosion control practices on slopes steeper than 2:1, with and without vegetation established, and should include new and different erosion control practices and technologies, particularly those that are thicker, low cost, and made of natural materials. Additional research should also explore variations in plot scale to determine quantifiable relationships between plot sizes; and soil texture classes to evaluate how different soils may affect treatment performance. Soils with greater silt and clay content may have lower infiltration rates which can increase erosion, although some clay soils can be more resistant to erosion, thereby reducing soil loss. Developing results that can be readily used in existing prediction models or to aid decision making and design criteria for site planners, engineers, landscape architects, or regulators should be given precedence.

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