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Elimination or Minimization of Soil Erosion Using Geosynthetics

by

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Abstract

The magnitude of worldwide soil erosion is enormous and geosynthetics, among many other materials and strategies, are doing their best to eliminate, or more realistically, minimize its impact. This paper is focused on describing the situation in the following series of interconnected sections;

- 1. An introduction,
- 2. Erosion control materials categories
- 3. Design of erosion control materials; specifically RECPs
- 4. Laboratory and field testing of erosion control materials
- 5. Generic specifications for TRMs

Inasmuch as the entire area of soil erosion and its control spans from degradable fibers broadcast into the ground surface to large rock rip-rap protecting coastal infrastructure, this paper focuses on rolled erosion control products, or RECPs, which are geosynthetically based. These products are capable of being manufactured in a controlled quality manner, have a bevy of appropriate standardized test methods, have a reasonable approach toward rotational design, and have generic specifications for both installation and manufacturing quality control. While the overall situation is reasonable at this point in time, more research and development can, and should, be expected in the future.

Elimination or Minimization of Soil Erosion Using Geosynthetics

1. Introduction

Natural soil erosion has always been an issue of worldwide concern, however, human activities have greatly exacerbated the situation. Each year, about 75 billion tons of soil is eroded from the land, a rate that is 13 to 40 times as fast as natural erosion (ref. Wikipedia). The primary reasons for such enormous amounts of soil loss are generally considered to be the following: agricultural practices, deforestation, roads and urbanization, and climate change.

The above said, the three basic mechanisms involved in soil erosion have been well established; i.e., detachment, transportation and deposition. See Figure 1a for the general behavior and Figures 1b, c and d for typical illustrations. Clearly, the geosynthetics industry (among others) is keenly interested in providing products and systems to eliminate or minimize soil erosion from occurring. This paper is focused on describing these materials and associated efforts.



(a) Erosion mechanisms, after Mitchell (1976)



(b) Magnified view of raindrop impact and subsequent soil detachment (after Wikipedia)



(c) Transportation rills/gullies in a landfill cover (GSI Photo)



(d) Soil deposition at toe of the landfill cover slope (GSI Photo)

Figure 1. Basic soil erosion mechanisms with accompanying illustrations of each.

2. Erosion Control Materials Categories

While there are several approaches toward categorizing the vast array of erosion control materials, Theisen (1992) provides a reasonable template, which can be used to embrace essentially all types of materials. The categories are as follows:

- Temporary biodegradable (natural materials)
- Geosynthetic related (polymeric materials)
- Hard armor systems (concrete, stone, etc.)

See Table 1 for specific materials in each category, each of which will be described.

Temporary	Perm	anent
Biodegradable	Geosynthetic Related	Hard Armor Systems
Straw, hay and hydraulic	UV stabilize fiber roving	Fabric formed revetments
mulches	systems (FRSs)	(FFRs)
Tackifiers and soil stabilizers	Erosion control revegetation	Geogrid stone mattresses
	mats (ECRMs)*	
Hydraulic mulch geofibers	Turf reinforcement mats	Non vegetated concrete
	(TRMs)*	block systems
Erosion control meshes and	Discrete length geofibers	Articulated concrete block
nets (ECMNs)		(ACB) systems
Erosion control blankets	Vegetated Geocellular	Stone rip-rap
(ECBs)	containment systems (GCSs)	
Fiber roving systems (FRSs)		Gabions

Table 1. Erosion Control Categories/Types (modified from Theisen, 1992)

*Also called "rolled erosion control products, or RECPs", which will be the focus herein.

2.1 <u>Temporary biodegradable materials</u> consist of materials that are wholly or partly degradable. They provide short-term erosion control and are either degradable after a given period, or only function long enough to facilitate vegetative growth. After the growth is established, the material becomes sacrificial. All natural products are completely biodegradable, while the polymer associated products are only partially so.

The first two products in the category are self-explanatory. They consist of traditional methods of soil erosion control using straw, hay, or mulch loosely bonded by asphalt or other adhesive. Their stability in remaining as-placed is often quite poor. Geofibers in the form of short pieces of polymer fibers or microgrids can be mixed with soil by machines or rototillers to aid in lay-down and continuity. The fiber or grid inclusions provide for greater stability over straw, hay, or mulch simply broadcast over the ground surface.

Erosion-control meshes and nets (ECMNs) are biaxially oriented nets manufactured from polypropylene or polyethylene. They do not absorb moisture, nor do they dimensionally change over time. They are lightweight and are stapled to previously seeded ground using hooked nails or U-shaped pins. Their erosion resistance is somewhat improved over the previously mentioned all natural materials.

Erosion-control blankets (ECBs) are also lightweight biaxially oriented nets manufactured from polypropylene or polyethylene, but these are now placed on one or both sides of a blanket of straw, excelsior, cotton, coconut, or polymer fibers. The fibers are held to the net by glue, lock stitching, or other threading methods. A special case of ECBs is *geojute*, which is a fibrous growth indigenous to Southeast Asia formed as a multifilament and woven into a thick mat. Its ability to achieve intimate contact to the soil being protected is excellent.

Fiber roving systems (FRSs) are continuous strands, or yarns, usually of polypropylene, that are fed continuously over the surface that is to be protected. They can be hand placed or dispersed using compressed air. After placement on the ground surface, an emulsified asphalt or other soil stabilizer is used for controlled positioning.

2.2 Within the <u>geosynthetic-related</u> category are a variety of wholly or partially related polymeric materials, as shown in Table 1. These polymer products furnish erosion control, aid in vegetative growth, and eventually become entangled with the vegetation to provide reinforcement to the root system. As long as the material is shielded from sunlight, via shading and soil cover, it will not degrade, at least within the limits of other polymeric materials. The seed is usually applied after the material is placed and is often carried directly in the materials backfilling soil.

The polymers in FRSs can be stabilized with carbon black and/ or chemical stabilizers, so they can are generally considered in the permanent category. They were described earlier. The next two types (ECRMs and TRMs) come from the manufacturing facility as rolled products and can be grouped as *"rolled erosion control products, or RECPs"*. Erosion-control revegetation mats (ECRMs) and turf reinforcement mats (TRMs) are closely related to one another. The basic difference is that ECRMs are placed on the ground surface with a soil infill, while TRMs are placed on the ground surface with soil filling in and above the material. Thus,

TRMs can be expected to provide better vegetative entanglement and longer performance. Other subtle differences are that ECRMs are usually of greater density and lower mat thickness. Seeding is generally done prior to installation with ECRMs, but is usually done while backfilling within the structure of TRMs. *These geosynthetic products are focused upon in the remaining paper*.

Discrete-length geofibers are short pieces of polymer yarns or filaments mixed with soil for the purpose of providing a tensile strength component against sudden forces for facilities such as athletic fields, trafficked slopes, and so on. Geocellular containment systems (GCSs) consist of three-dimensional cells of geomembranes or geotextiles that are filled with soil and, when used for erosion control, are vegetated. See Koerner (2012), among many others, for additional information regarding geocells.

2.3 <u>Hard armor systems</u> consist of infill material which is permanent, as with concrete or grout filled geocells; they are considered in the hard armor category. Also, fabric-formed revetments (FFRs) are hard armor materials. These are usually back-to-back geotextiles, stitchbonded at intervals, and filled with flowable concrete grout. In a similar manner geogrids can be made into a mattress and filled with coarse gravel.

Numerous concrete block systems are available for erosion control. Hand-placed interlocking masonry blocks are popular for low-traffic pavement areas such as carports, driveways, off-street parking, and so on. The voids in the blocks and between them are usually soil-filled and vegetated. From a sustainability perspective, these systems far outperform asphalt or concrete pavements. Alternatively, the system can be factory-fabricated as a unit, brought to the job site, and placed on prepared soil. For example, articulated concrete blocks (ACBs) are quite common due to low cost in comparison to other similar materials. The prefabricated blocks can be either laid on or bonded to a geotextile substrate or be interconnected with polymer or steel cables. The finished mat can bend and torque by virtue of the blocks being articulated with mechanical joints, weaving patterns, or cables. Such systems are generally not vegetated.

Stone rip-rap can be a very effective erosion control method whereby large rock is placed on a geotextile substrate to prevent against subsidence. The geotextile placed on the soil surface before rock placement serves as both a filter and separator. The stone can vary from small hand placed pieces to machine placed pieces of enormous size. Canals and waterfront property are often protected from erosion using stone rip-rap. The above said, when performing a sustainability calculation, stone rip-rap often comes up lacking with respect to other hard armor system, see Goodrum, 2011.

Closely related are gabions, which consist of discrete cells of wire netting filled with hand-placed stone. The wire is usually galvanized steel hexagonal wire mesh, but in some cases, it can be a plastic geogrid. Gabions require that a geotextile be placed beneath and behind them, acting as a filter and separator for the adjacent soil.

3. Design of Erosion Control Materials; Specifically RECPs

Of the three categories of erosion control products shown in Table 1, this section on design does not pertain to the "permanent hard armor" category of materials. While some information is available on certain products in this category, the materials are so different that a unified procedure is simply not available. In a totally different manner, the temporary biodegradable materials are usually discrete natural fibers and are rarely designed as such. Converse to the above two categories, the "geosynthetics-related" have been the focus of what design is available and will be presented in this section. This is particularly the case for products that are in roll-form coming from the manufacturing facility and are often referred to as rolled erosion control products (RECPs). The various design approaches are generally bifrigated into long and wide "slopes" versus narrow-linear "channels or ditches", see Figure 2. Furthermore, the latter can be addressed on either a velocity or shear stress basis. These three approaches follow.



(a) Erosion control material on steep side slope (Compliments of Low & Bonar, Inc.)



(b) As installed erosion control material in water runoff channel (Compliments TenCate Geosynthetics, Inc.)



(c) In-situ performance of previous water runoff channel (Compliments TenCate Geosynthetics, Inc.)

Figure 2. Use of RECPs in the two major erosion control applications.

3.1 Universal Soil Loss Equation (USLE) for Slopes

The USLE was developed based on soil erosion data collected beginning in the 1930s by the U.S. Department of Agriculture (USDA) Soil Conservation Service (now the USDA's Natural Resource Conservation Service). The model has been used for decades for purposes of agricultural conservation planning both in the United States where it originated and around the world. It has also been used for soil loss prediction at large and small construction sites. In this latter regard, the methodology's use is required by some states, which also have maximum soil loss values embedded in their construction permitting regulations. The Revised Universal Soil Loss Equation (RUSLE) [USDA, 2014] and the Modified Universal Soil Loss Equation (MUSLE) are extensions and are used for similar purposes.

The two primary types of erosion control design models are process-based and empirically based models. Process-based (physically based) models mathematically describe the erosion processes of detachment, transportation, and deposition and through the solutions of the equations describing those processes provide estimates of soil loss and sediment yields from specified land surface areas. Empirical models relate management and environmental factors directly to soil loss and/or sedimentary yields through statistical relationships. Lane, et al. (1988) provide a detailed discussion regarding the nature of both process-based and empirical-based models. The above said, the standard model for most erosion assessment planning is the empirical-based USLE, which continues to be actively developed, NRCS (1996). The basic Universal Soil Loss Equation (USLE) will be described and used accordingly. The essential equation used to calculate soil loss at a given site is shown below.

$$E = RK (LS) PC \tag{1}$$

where:

- P = conservation practice factor (dimensionless) (e.g., terracing, contouring, etc... assumed to be 1.0 for standard slopes)
- **C** = **vegetative cover factor (dimensionless)...** see Figure 3d and Table 2

Note that these figures, charts and tables, and many more, are available free from USDA-ARS at... <u>http://fargo.nserl.purdue.edu/rusle2_dataweb/</u>.



(a) R-Factors for the eastern United States Isoerodent map of eastern United States (after Renard, et al., 1997)



(b) K-Factors (after Renard, et al., 1997)

Values for 7	Fopographic	Factor, LS,	for High	Ratio o	of Rill to	Interill	Erosion
		, , ,	L)				

Slope	<3	6	9	12	15	25	50	75	100
0.2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.5	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09
1.0	0.09	0.09	0.09	0.09	0.09	0.10	0.13	0.14	0.15
2.0	0.13	0.13	0.13	0.13	0.13	0.16	0.21	0.25	0.28
3.0	0.17	0.17	0.17	0.17	0.17	0.21	0.30	0.36	0.4
\$.0	0.20	0.20	0.20	0.20	0.20	0.26	0.38	0.47	0.5
5.0	0.23	0.23	0.23	0.23	0.23	0.31	0.46	0.58	0.6
5.0	0.26	0.26	0.26	0.26	0.26	0.36	0.54	0.69	0.8
3.0	0.32	0.32	0.32	0.32	0.32	0.45	0.70	0.91	1.1
0.0	0.35	0.37	0.38	0.39	0.40	0.57	0.91	1.20	1.4
2.0	0.36	0.41	0.45	0.47	0.49	0.71	1.15	1.54	1.8
\$.0	0.38	0.45	0.51	0.55	0.58	0.85	1.40	1.87	2.3
3.0	0.39	0.49	0.56	0.62	0.67	0.98	1.64	2.21	2.7
0.0	0.41	0.56	0.67	0.76	0.84	1.24	2.10	2.86	3.5
5.0	0.45	0.64	0.80	0.93	1.04	1.56	2.67	3.67	4.5
0.0	0.48	0.72	0.91	1.08	1.24	1.86	3.22	4.44	5.5
0.0	0.53	0.85	1.13	1.37	1.59	2.41	4.24	5.89	7.4
0.0	0.58	0.97	1.31	1.62	1.91	2.91	5.16	7.20	9.1
0.0	0.63	1.07	1.47	1.84	2.19	3.36	5.97	8.37	10.6
()	9			-					
<u>6</u> .2	. 0	06	0.08	0.08	0,08	0.5 0	5,00	0.00	0.0
0.8	0	.09	0.10	0.18	0.10	0.11	8 N	8,12	\$.1
1.0	1 8	.17	0,16	0.75	0.25	0.22	0.54	0.55	\$,2
2.0	1.0	38	0.37	0.40	0.43	0.42	0.08	0.63	92
3,5	i .	.50	0.57	0.64	0.69	0.60	0.96	1.19	12
4.1	i a	.66	0.78	0.69	0.66	1.14	1.42	1.86	1.
5.5	. 0	.88	1.08	1.15	1.28	1.81	1.95	2.25	2.8
6.6	1 1	.045	1.26	1.43	1.00	1.60	Z.43	2.89	3.2
8.5	1	£3	1.72	1.99	2.24	2.70	3,42	4.24	4,6
10.0	۶ s	1	2.34	2.71	1.09	3.76	4.95	6.93	74
124	> 2	.61	3.97	3.30	4.69	8.01	8.97	. 8.17	· 9,6
14,0	5 1		3.91	4.49	5.11	4.20	8,43	10,40	12.2
19.0) j 1	.ee.	4.50	8.37	6.12	7.50	10.24	12.80	\$4.5
30.0	•	89.	\$,04	7.18	6.23	18.24	18.64	17.38	20,1
26.0) a	.30	7.68	9,38	10.81	13.83	18.67	22.34	27.4
30.0	\$ j 7	.70	9,87	11.55	12.85	16.77	. 23.14	28.07	34.7
40.0	10	144 U	12.07	15.87	18.17	21.88	¥1.89	41,22	46.2
60.) 12	.78	18.18	18,48	22.57	26.60	33.94	. 10.61	60.

(c) LS Factors (after Renard, et al., 1997) -8-

Treatment	Dry M	Iulch Rate	C-Factors for Growing Period**			
	kg/m ²	Slope, %	< 6 wks	1.5-6 mos.	6-12 mos.	annualized*
No mulching or seeding	all	all	1.00	1.00	1.00	1.00
Seeded grasses	none	all	.70	.10	.05	.15
Seeded grasses	0.22	< 10	.20	.07	.03	.07
Seeded grasses	0.34	< 10	.12	.05	.02	.05
Seeded grasses	0.45	< 10	.06	.05	.02.	.04
Seeded grasses	0.45	11-15	.07	.05	.02	.04
Seeded grasses	0.45	16-20	.11	.05	.02	.04
Seeded grasses	0.45	21-25	.14	.05	.02	.05
Seeded grasses	0.45	26-33	.17	.05	.02	.05
Seeded grasses	0.45	34-50	.20	.05	.02	.05
Second Year Grass	-	all	.01	.01	.01	.01
Organic & Synthetic	-	all	.07	.01	.005	.02
Blankets						
Composite Mats	-	all	.07	.01	.005	.02
Synthetic Mats	-	all	.14	.02	.005	.03
Fully Vegetated Mats	-	all	.005	.005	.005	.005

*annualized C-Factor = (<6 wks value x 6/52) + (1.5-6 mos. values x 20/52) + (6-12 mos. value x 26/52)

**approximate time periods for humid climates; <u>Conversion</u>: $kg/m^2 \times 4.46 = ton acre$

(d) C-Factors for various slope treatments (after Renard, 1997 & IECA, 1996)

Figure 3. Figures, charts and tables for use in calculating soil loss per Equation 1.

Table 2. C-Factors for	Various RECPs by	y Erosion Control	Technical Council	(ECTC), 2001
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Category	Composition	Time	H-to-V	"C"-Factor
(all RECMs)	_	(mos.)	(max.)	(for USLE)
Biodegradable	MCN	≤ 3	5:1	0.10
	ECS	≤ 3	4:1	0.10
	ECB/OWT	≤ 3	3:1	0.15
	ECB double	≤ 3	2:1	0.20
Biodegradable	MCN	≤ 12	5:1	0.10
	ELC	≤ 12	4:1	0.10
	ECB/OWT	≤ 12	3:1	0.15
	ECB double	≤ 12	2:1	0.20
GS-Related	MCN	≤ 24	5:1	0.10
	ECB/OWT	≤ 24	1.5:1	0.25
GS-Related	ECB double	≤ 36	1:1	0.25
GS-Related	TRM	n/a	1:1	n/a
	TRM	n/a	0.5:1	n/a

The critical variable for use of erosion control materials in the design process is the value of "C". This is the variable in Eq. 1 which is basically different between bare soil and soil protected by a vegetated erosion control materials. While Figure 3d shows some data in this regard, Table 2 goes into much more specificity regarding different RECPs. A numeric example follows. In this regard, the Erosion Control Technology Council has recommended C-values for many of the erosion control materials listed in Table 1.

Example Problem Using USLE Equation

Given a sandy loam soil slope at 3H-to-1V slope, i.e., 18.4° with the horizontal distance that is 100 ft. long and located in Asheville, NC. Determine the soil loss for bare soil (C = 1.0) and then two RECPs with C values of 0.03 and 0.05.

Variables are R = 250; K = 0.33; LS = 6.20; P = 1.00 and

C = 1.0, 0.03, and 0.005 for three situations (from Figure 3d)

(a) $E_{unprotected} = 250 \times 0.33 \times 6.2 \times 1.0 \times 1.0 = 512$ tons/acre/year

(b) $E_{\text{protected, 1 yr}} = 250 \times 0.33 \times 6.2 \times 1.0 \times 0.03 = 15 \text{ tons/acre/year}$

(c) $E_{\text{protected, 2 yrs}} = 250 \times 0.33 \times 6.2 \times 1.0 \times 0.005 = 3 \text{ tons/acre/year}$

Note: Readily seen is that the soil loss using the RECPs is greatly minimized over the unprotected soil... by 34 and 170 times!

3.2 Velocity Design for Channels and Ditches

One approach for RECP design against excessive soil loss in channels and ditches is based on simply limiting the maximum velocity of flow. Alternatively, one could calculate a velocity FS-value by comparing the allowable flow of a given RECP to the site-specific required flow, i.e., $FS = V_{allow}/V_{reqd}$. This latter approach is used herein. Equation 2 presents the requisite formula for " V_{reqd} " with Figure 4b giving the V_{allow} value.

$$V_{reqd} = \frac{\kappa}{n} R^{2/3} S_f^{1/2}$$
(2)

where

V_{reqd} = required flow velocity

K = 1.00 (SI) and 1.49 (English)

n = Manning's coefficient (see Figure 4a)

- R = hydraulic radius (= A/wetted perimeter)
- A = cross sectional area
- S_f = slope factor

Lining Category	Lining Type	Depth Ranges		
		0.0.5 ft	0.5-2.0 ft	>2.0 ft
		(0-15 cm)	(15-60 cm)	(> 60 cm)
Rigid	Concrete	0.015	0.013	0.013
	Grouted Riprap	0.040	0.030	0.028
	Stone Masonry	0.042	0.032	0.030
	Soil Cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.023	0.020	0.020
	Rock Cut	0.045	0.035	0.025
Biodegradable	Woven Paper Net	0.016	0.015	0.015
	Jute Net	0.028	0.022	0.019
	Fiberglass Roving	0.028	0.021	0.019
	Straw with Net	0.065	0.033	0.025
	Curled Wood Mat	0.066	0.035	0.028
RECPs	RECMs & TRMs	0.036	0.025	0.021
Gravel Riprap	1-inch (2.5-cm) D ₅₀	0.044	0.033	0.030
	2-inch (5-cm) D ₅₀	0.066	0.041	0.034
Rock Riprap	6-inch (15-cm) D ₅₀	0.104	0.069	0.035
	12-inch (30-cm) D ₅₀		0.078	0.040

(a) Manning's Roughness Coefficients, i.e., n-values (ref. HEC-15)



(b) Recommended allowable design, i.e., V_{allow}, for various classes of erosion control materials (after Theisen, 1992)



Using Equation 2 for the required (or design) velocity and Figure 4b for the allowable velocity with different types of soil subgrade using either ECRMs or TRMs, the following example illustrates the method.

 $K = 1.00; n = 0.025; A = 2.75 m^2; P = 7.16 m; S_f = 0.03$ Given: Find: V_{reqd} and compare to V_{allow} for FS-values Solution using Equation 2: $R = \frac{2.75}{7.16} = 0.384$ $R^{2/3} = 0.528$ $S^{1/2} = 0.173$ $V_{reqd} = \frac{1}{0.025} (0.528) (0.173)$ = 3.65 m/secCompare to V_{allow} (Figure 4b) (i) try using an ECRM: $FS_{max} = \frac{4.2}{3.65} = 1.15$ or $FS_{min} = \frac{2.5}{3.65} = 0.68$ (ii) try using a TRM $FS_{max} = \frac{6.0}{3.65} = 1.64$ or $FS_{min} = \frac{4.3}{3.65} = 1.18$ Answer; use a "TRM"!

3.3 Shear Stress Design for Channels and Ditches

A related, but different, approach toward an erosion control design for channels and ditches is based on limiting the maximum shear stress on the subgrade soil that is imposed by the flowing water. One could calculate either a maximum shear stress or formulate a FS-value by comparing the allowable shear stress to a required value for site-specific conditions where $FS = \tau_{allow}/\tau_{reqd}$.

$$\tau_{reqd} = \gamma_w d S_f \tag{3}$$

where

 $\begin{array}{ll} \tau_{reqd} &= required \ shear \ strength \\ \gamma_w &= unit \ weight \ of \ water \\ d &= depth \ of \ flow \ (see \ Figure \ 5) \\ S_f &= slope \ of \ channel \end{array}$



Figure 5. Determination of "d" in Equation 3.

The allowable shear stresses for a variety of soil subgrade conditions and different erosion control materials are given in Figure 6 for various situations followed by an example problem.



(a) Allowable shear stress for non-cohesive soils (b) Allowable shear stress for cohesive soils

Lining Category	Lining Type	Allowable	Unit Shear Stress
		(lb/ft ²)	(Kg/m ²)
Temporary	Woven Paper Net	0.15	0.73
	Jute Net	0.45	2.20
	Fiberglass Roving:		
	Single	0.60	2.93
	Double	0.85	4.15
	Straw with Net	1.45	7.08
	Curled Wood Mat	1.55	7.57
	Synthetic Mat (RECM)	2.00	9.76
Vegetative	Class A	3.70	18.06
	Class B	2.10	10.25
	Class C	1.00	4.88
	Class D	0.60	2.93
	Class E	0.35	1.71
Gravel Riprap	1-inch	0.33	1.61
	2-inch	0.67	3.22
Rock Riprap	6-inch	2.00	9.76
	12-inch	4.00	19.52
Bare Soil	Non-cohesive	See Cha	rt 1 following
	Cohesive	See Cha	rt 2 following

Category (all RECMs)	Composition	Time (mos.)	H-to-V (max.)	Allow. S	hear Stress
Degradable	MCN	≤3	5:1	12	0.25
	ECS	≤ 3	4:1	24	0.5
	ECB/OWT	≤ 3	3:1	72	1.5
	ECB double	≤ 3	2:1	84	1.75
Degradable	MCN	≤12	5:1	12	0.25
	ELC	≤ 12	4:1	24	0.5
	ECB/OWT	≤ 12	3:1	72	1.5
	ECB double	≤ 12	2:1	84	1.75
GS-Related	MCN	≤24	5:1	12	0.25
	ECB/OWT	≤ 24	1.5:1	96	2.0
GS-Related	ECB double	≤ 36	1:1	108	2.25
GS-Related	TRM	n/a	1:1	288	6.0
	TRM	n/a	0.5:1	480	10.0

(d) Allowable shear stresses for RECPs by Erosion Control Technical Council (ECTC), 2001

(c) Allowable shear stress for non-cohesive soils

Figure 6. Calculation information for shear stress design in channels and ditches using various erosion control materials.

Example:	Determining the FS-value based on shear stress of a channel using Eq. 3 for an ECB from Figure 6d of 2.0 lb/ft^2 under the following condition.
	$\gamma_w = 62.4 \text{ lb/ft}^3; d = 0.56 \text{ ft}; S_f = 0.04$
Find:	τ_{reqd} and compare to τ_{allow} for a FS-value
Solution:	$\begin{split} \tau_{reqd} &= \gamma_w \ dS_f \\ \tau_{reqd} &= (62.4)(0.56)(0.04) \\ \tau_{reqd} &= 1.40 \ lb/ft^2 \end{split}$
now:	τ_{allow} (RECM) = 2.00 lb/ft ² (Fig. 6d)
	FS = 2.00/1.40 = 1.4, OK use an ECB

4. Laboratory and Field Testing of Erosion Control Materials

Inasmuch as the previous section on design was both somewhat empirical and based on broad classes of products, the selection and approval of a specific erosion control material within each class is often based on actual testing. This section presents three approaches; bench scale, laboratory scale and field scale testing. 4.1 *Bench scale testing* of erosion control materials has focused on slope erosion and shear stress of channels and ditch simulations. Figure 7 shows a mosaic of these testing devices. In general, bare soil loss is measured first and then compared to the use of a specific type of erosion control product. The comparison obviously favors the use of an erosion control product but how much and the differences between different products can be assessed accordingly. These various devices were developed by TRI Environmental, Inc. under the contract to the ECTC.



(a) Pots for test specimen preparation



(b) Bench-scale slope erosion test





- (c) Bench-scale slope erosion test
- (d) Original hydraulic bench-scale shear test apparatus



(e) Hydraulic shear applied



(f) Test plot being removed



(g) Larger hydraulic shear test apparatus

Figure 7. Bench scale laboratory testing of RECPs (compl. TRI Env. Inc.)

4.2 *Laboratory scale* erosion control studies, with bare soil vis-à-vis specific erosion control products has seen considerable investigation in many civil and hydraulics university laboratories. Figure 8 shows a mosaic of Drexel University's efforts produced by Professor Weggel and his graduate students, e.g., see Rustom and Weggel (1993).



(c) Channel test per GRI-GC6

(d) GRI-GC6 results

Figure 8. Laboratory-scale testing of RECPs in slope and channel simulations at Drexel University. (compl. of Professor Weggel)

4.3 *Field testing* at near, or full, scale of erosion control products have been developed at several state universities, e.g., Wisconsin, Colorado, Texas, Minnesota and Utah Universities. They often serve the purpose of approving (or rejecting) a specific product for a specific set of conditions. In turn, the associated state agency (usually the respective State Department of

Transportation) often provides an "approved bidders list" for their ongoing construction projects. In this regard, these state university sites are entering and competing with private enterprise in a manner, considered by the authors, to be a disadvantage in a free-market context. That said, one such non-university affiliated test site is that of TRI Environmental Inc. in its South Carolina facility. Figure 9 presents a mosaic of individual tests (all associated with ASTM standards) at their facility.



(a) Rainfall induced hillside erosion setup (per ASTM D6459)





(c) Temporary ditch performance channel (per ASTM D7208) (b) Stormwater flow in separate channels (per ASTM D6460)



(d) Sediment retention in sheet flow application (per ASTM D7351)

Figure 9. Field testing of RECMs in slope and channel situations at TRI Environmental's Anderson, SC facility. (compl. J. Sprague; see www.erosiontest.com)

5. Generic Specifications for TRMs

Clearly seen throughout this paper is that the erosion control industry is incredibly broad and extremely varied, e.g., from hand-spreading fibers on a slope to massive rock rip-rap protection of channels. Indeed private industry is a willing participant to solve or mitigate this situation as exemplified by the annual Erosion Control Technology Council's conferences, which are very informative and well-attended, providing a bevy of new and varied products. There also exists an installation guide which is very detailed and very well formulated (ECTC, 2017). On the other hand, design engineers, owners and regulators have a challenge in specifying a particular product for site specific conditions. Toward this end a recent generic specification for a specific class of products within the geosynthetic related category; i.e., turf reinforcement mats (TRMs). It should be noted that it only applies to this class of products as shown in Table 1!

The specification has categories for sheet-flow on soil slopes and soil erosion in channels and ditches. Its sets forth various physical, mechanical and endurance test properties, all of which are existing ASTM standard test methods. There are three qualitative classes; most severe, moderate and least severe. That said, it has taken approximately 15-years to develop and was finalized on December 11, 2015. The current specification is given as Table 3 following. The most recent version is always available at geosynthetic-institute.org/specs.htm. The eight properties required in this GRI-GC14 specification are as follows. Each test method is illustrated by a photograph and a brief description of relevant testing details.

- Mass per unit are, see § 5.1
- Thickness, see § 5.2
- Stiffness, see § 5.3
- Specific gravity, see § 5.4
- Resiliency, § 5.5
- Tensile strength and elongation, see § 5.6
- Light penetration, see § 5.7
- Ultraviolet light resistance, see § 5.8

Property	Units	Test Method	Class "1" or "A"	Class "2" or "B"	Class "3" or "C"
Mass per unit area	oz/yd ²	D6566	12	10	8
Thickness	mil	D6525	130	130	130
Stiffness	g-cm	D7748	300	300	300
Specific gravity	g/cc	D792	0.9	0.9	0.9
Resiliency	%	D6524	70	70	70
Tensile strength	lb/ft	D6818	150	125	100
Tensile elongation	%	D6818	10	10	10
Light penetration	%	D6567	60	60	60
UV resistance	% ret @ 3,000 hr	D7238	80	80	80

Table 3a - Turf Reinforcement Mat Specification per GRI-GC14; American (English) Units

Table 3b. Turf Reinforcement Mat Specification per GRI-GC14; S.I. (Metric) Units

Property	Units	Test Method	Class "1" or "A"	Class "2" or "B"	Class "3" or "C"
Mass per unit area	g/m ²	D6566	400	330	270
Thickness	mm	D6525	3.3	3.3	3.3
Stiffness	g-cm	D7748	300	300	300
Specific gravity	g/cc	D792	0.9	0.9	0.9
Resiliency	%	D6524	70	70	70
Tensile strength	kN/m	D6818	2.2	1.8	1.5
Tensile elongation	%	D6818	10	10	10
Light penetration	%	D6567	60	60	60
UV resistance	% ret @ 3000 hr	D7238	80	80	80

Notes: Classes 1, 2 and 3 (most severe to least severe) are for soil slope erosion control TRM's.

Classes A, B and C (most severe to least severe) are for channel and ditch erosion control TRM's.

Values are Minimum Average Roll Values (MARV) except for specific gravity, resiliency and UV resistance. In these cases they are minimum average values. Stiffness is a maximum average value and is listed as gram-centimeters.

5.1 Mass Per Unit Area

- follows ASTM D6566
- also called simply "weight"
- specimen size is relatively large
- 15.2 cm (6.0 in.) diameter
- minimum of five specimens



5.2 Thickness

- follows ASTM D6525
- dead weight micrometer with flat tip
- presser foot of 150 mm (6.0 in.) diameter
- applied pressure is $0.2 \text{ kPa} (4.2 \text{ lb/ft}^2)$
- 5 sec dwell time
- minimum of ten specimens



5.3 Stiffness

- needed to assure intimate contact with subsoil
- follows ASTM D7748
- properly called flexural rigidity (see calculation following)
- measurements averaged for MD and XMD
- value listed is maximum-average



Calculation for Flexural Rigidity

Measure the bending length for each specimen to the nearest 1 mm,

$$c = 0/2$$

where:

c = bending length, cm, and

0 = length of overhang (total specimen length minus the remaining horizontal length of specimen at the conclusion of the test, cm.

Calculate the flexural rigidity for each testing direction

$$G = W \times c^3$$

where:

G = flexural rigidity, g-cm,

W = geosynthetic mass per unit area, g/cm², and

c = bending length, cm.

Overall Flexural Rigidity =
$$(G_{MD} + G_{XMD})/$$

5.4 Specific Gravity

- generally follows ASTM D792 also called "density" •
- •
- this is the displacement method •
- two tests across roll width •
- also available in D1505 as the gradient column method ٠



5.5 Resiliency

- follows ASTM D6524 •
- 150 mm diameter (6.0 in.) presser foot •
- measures recovery after 3-cycles of load at 690 kPa (100 lb/in.²) for 1 min./cycle •
- dead weight may be used •
- minimum of ten specimens •



5.6 Tensile Strength and Elongation

- follows ASTM D6818
- CRE device at 300 mm/min. (12 in./min)
- specimens are $100 \times 150 \text{ mm} (4.0 \times 6.0 \text{ in.})$
- jaw (clamp) breaks are to be discarded
- tested in MD only



5.7 Light Penetration

- follows ASTM D6567
- light meter measures in foot-candles
- specimen is $200 \times 250 \text{ mm} (8 \times 10 \text{ in.})$
- a static light source shines through specimen
- percentage of light transmitted is measured on the substrate beneath the TRM
- a minimum of 60% penetration is required for all three classes





(vertical setup)

5.8 Ultraviolet Light Resistance

- follows ASTM D7238
- UV fluorescent tube method
- cycles between 20 hr. UV at 70°C and 4 hr. condensation at 60°C per day
- requires retained strength and elongation ≥ 80% of original after 3000 lt. hrs. (125 days)
- better to use individual TRM filaments for accuracy rather than the entire product itself



Typical ultraviolet weathering device and closeup of fluorescent bulbs

6. Summary

To the writers of this paper, three items are necessary in order to firmly entrench any technology. They are (i) having a requisite <u>theory</u>, (ii) having properly simulated <u>experiments</u> and (iii) eventually having successful economic and/or long-term <u>applications</u>. Illustrative of this is Terzaghi's consolidation work in the early 20th century. Known to all geotechnical engineers, all three aspects (theory, experiments and applications) have made this specific work everlasting and essentially unchanged over time. It is felt that the products listed in Table 1, including the geosynthetic RECPs, need such benchmarks in order to progress further in the context of full confidence in using the specific products being manufactured.

Unfortunately, the available design theory (USLE, velocity and shear stress design models) is felt to be insufficient for site and product specifity. In this regard the theory is still somewhat empirical; the experiments are more index oriented rather than performance oriented; and the applications are far from universally successful. Yet, there is certainly ongoing work to be done. Theoretical developments should be embraced by faculty in a research mode, performance experiments should be standardized for use by many testing laboratories, and critical and objective applications by public and private agencies should be written up as case histories for lessons learned going forward. All have, and are, progressing but without the intensity needed for the technology to reach its full potential. Soil erosion is certainly a worthwhile issue from financial, environmental and sustainable vantage points. Let's all try harder!

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