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16. Abstract

The objective of this research project was to develop a cost-performance index (CPI) for products in the Texas Department of Transportation's (TxDOT's) Approved Products List (APL). TxDOT's APL was created from performance testing conducted in the Hydraulics, Sedimentation, and Erosion Control Laboratory (HSECL) of the Texas Transportation Institute (TTI). The performance testing includes sediment loss and vegetation growth. Both slope protection and channel protection products are evaluated. The intention of developing the CPI was to further include cost data in the APL so that users of the APL can justify the use of a product based on the combined cost and performance information. Data used for the CPI development include surveyed cost from manufacturers, material composition and sediment loss performance data from TTI performance testing. The conceptual model of the CPI can be described as "the benefit of potential soil protection per unit cost of both product and potential topsoil replacement expense." The benefit of potential soil protection is a hypothetical cost savings from slope or channel failure over the entire product lifespan. The potential topsoil replacement expense reflects the fact that soil loss will occur no matter how well the surface is protected. When soil is lost, there is a potential of topsoil replacement, which in turn costs money. With this concept, a typical topsoil price of $25 per cubic yard was used. The result of the project includes a series of tables listing products with high/medium CPI. Five project durations were used: temp (0-3 months), short (3-12 months), mid (12-24 months), long (24-36 months), and permanent (36-54 months). For slope protection products, two slopes and two soil types were included: 2:1 clay, 3:1 clay, 2:1 sand and 3:1 sand. For channel protection products, six shear stresses were used to separate different products: 0-2, 0-4, 0-6, 0-8, 0-10 and 0-12 lb/ft^2. The improved APL will enable erosion control designers and specifiers to select products best suited for different project durations with great cost-savings potential.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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INTRODUCTION

BACKGROUND AND SIGNIFICANCE OF WORK

In order to maintain federal regulatory compliance and ensure that the most effective erosion control products are used on its construction and maintenance projects, the Texas Department of Transportation (TxDOT) bases material selection on an Approved Product List (APL). This APL is based on field performance of the products through a formal evaluation program at the TxDOT/Texas Transportation Institute (TTI) Hydraulics, Sedimentation, and Erosion Control Laboratory (HSECL) at the Texas A&M University Riverside Campus. The two critical performance factors identified are:

- how well the product protected the seedbed of an embankment and drainage channel from the loss of sediment during simulated rainfall or channel flow events, and
- how well the product promoted the establishment of warm-season, perennial vegetation.

While these two factors are critical to erosion control performance, there has been no consideration for material cost and longevity. Furthermore, there are potentially less expensive erosion control techniques which have not previously been included in the approval process. These techniques include crimped or tacked hay/straw, compost, slope tracking, wood mulch, and soil binders. This project examined available performance and cost data of these non-manufactured techniques in terms of cost, sediment loss prevention, and vegetation establishment. This project also looked at the cost of current products on the APL in terms of costs for the material, installation, maintenance, repair, and effectiveness, and developed a cost-performance index. The objective of the effort is to provide guidance for selecting the most cost effective erosion control materials and methods.

Study Problem Statement

In order to meet water quality mandates, TxDOT utilizes a number of products to control erosion on construction projects throughout the state. The overall cost for the use of soil retention blankets in construction projects in 2004 was 1.2 million dollars.

To ensure that products meet standard performance criteria TxDOT utilizes an APL, which is based on an established testing program initiated by TxDOT in 1990. Since its creation, the TxDOT APL has become a nationally recognized authority for the performance of temporary erosion control materials. Products on the APL have passed the standard performance tests and, if properly installed can be expected to perform the needed erosion control during construction. TxDOT design engineers, inspectors, contractors, and even other state DOTs have benefited from this program through the continuing FHWA pooled fund study sponsored by TxDOT.

In reviewing the 12 years of performance data developed by the HSECL, and comparing it to some very recent tests on natural materials, it appears that the less expensive natural materials have sediment reduction and vegetation establishment performance properties equivalent to the manufactured rolled erosion control products (RECPs). For example, it is estimated that on average, straw can be blown and crimped/tacked onto a slope at a cost of between $0.08 to $0.24 per square yard, as compared to RECPs that cost from $1.00 to $3.00 per square yard in place, and will yield a similar level of protection. Therefore, it seems prudent to look closer at these materials and begin to consider cost as a significant part of the process for recommending a material for use by TxDOT.

Despite the recognition of the APL by erosion control professionals and its significant contribution to date, there is room for improvement. First, cost information is not included in the APL. Cost of materials, installation, and removal (if necessary) will further guide designers in their selection of cost-effective products. Second, following the need for cost information is further consideration of older technologies such as crimped straw, slope tracking, and compost that may be just as effective and less expensive.

Current TxDOT Practice

Current TxDOT design references that address temporary soil erosion control are located in the Standard Specification for Highways Streets and Bridges (TxDOT, 2004) and the APL. Using this Standard Specification, designers can select the appropriate erosion control product based on site conditions (slope steepness and soil type). The data used to select a product considers a material's ability to reduce sediment loss and establish vegetation. Data for material cost and longevity are not used in the current APL evaluation procedure.

Underlying Principles

Researchers categorize temporary erosion control into two types: slope protection and channel protection. Slope protection represent highway embankments and planar rights-of-way where only overland or sheet flow will occur. Channel protection, where concentrated flow is the result, produces greater erosive forces on the channel bed and sides. When these conditions are encountered during construction, the appropriate type of erosion control material is essential.

There are three measures of performance considered for erosion control on slopes, they are: reduction of rain impact on soil surface, reduction of sediment laden runoff, and establishment of vegetation. While commercial RECPs listed on the APL can achieve such performance, non-proprietary techniques such as soil roughing, surface terracing, crimped straw, and others, may achieve the same results with lower costs and less maintenance. Figure 1 illustrates the basic schematic erosion control mechanisms for slopes.

For channels, protection from shear stress exerted on the channel bottom and vegetation establishment are the critical factors in determining a material's suitability. The shear stress (τ) on an open channel is expressed as $\tau = \gamma ds$ and is computed as the product of the slope of the channel (s), fluid specific gravity (γ), and the depth of the flow (d) (Chow 1959). Common techniques to control channel erosion include rock riprap, cabled blocks, and turf-reinforcing mats (TRMs) which can be described as a high-strength RECP. For temporary channel erosion control, a long-term TRM or temporary, bio-degradable channel liners are the most common methods of protection.

Approach to the Problem

The objective of this project is to synthesize all the available data to develop a Cost-Performance Index (CPI) for products currently on the APL, as well as several inexpensive alternative best management practices (BMPs), including compost, crimped and tacked hay/straw, and soil roughening. In addition, a standard procedure will be created so that future products or methods can be evaluated and their CPI can be determined.

IMPLEMENTATION

The results of this project will provide TxDOT specific information necessary to determine the cost effectiveness of various erosion control products and methods (both old and new), which could result in a significant cost savings to the Department while improving compliance with Federal storm water regulations.

Information generated by this study may form the basis for revising the current APL for erosion control to include cost effectiveness. This revision would be a guide to assist in selecting the most cost-effective practice or product. Once completed, the information will be included in the current erosion control training curriculum (ENV102) offered by TxDOT.

LITERATURE REVIEW

This literature review has two purposes:

- to introduce the performance of various erosion control measures including RECPs, soil roughening and organic measures (composts and mulches), and
- to determine the most effective method to standardize the test results from various erosion control studies using the Universal Soil Loss Equation (USLE) model.

This review can be summarized as follows.

- Erosion control performance without vegetation can be compared as:
  RECPs > Mulch > Soil roughening > Compost
- Soil roughening and compost may be combined with other measures such as vegetation and mulch, which improves their performance.
- Test conditions vary among studies making it difficult to standardize the test results used to compare performance of the different products evaluated.
- The USLE cannot provide an ideal method to standardize tests conducted on different conditions. The model was based on tests conducted on relatively flat areas and ignored the impact of slope change in the erosion mechanism.

PERFORMANCE OF EROSION CONTROL MEASURES

Performance of Rolled Erosion Control Products (RECPs)

Based on indoor rainfall simulation tests, the California Department of Transportation (CALTRANS) (2000) suggests that RECPs reduce more than 90 percent in soil loss on 2:1 clayey sand slopes (Table 1). The range of erosion control performance in CALTRANS' study is consistent with what has been observed in rainfall simulation testing for TxDOT APL at the HSECL. TxDOT approves soil erosion products that can reduce soil loss at a minimum of 83 percent on 2:1 sand slope and 98 percent on 2:1 clay slope (Table 2). The test results of both test facilities are comparable as they utilized similar facilities and test conditions except soil type and rainfall scheme. The difference in effectiveness among different soil type (i.e. 83 percent at clay, 90 percent at clayey sand, and 98 percent at sand) indicates that RECPs are less effective in erodible soils, that is, the effectiveness is higher at clay slope than sand slope.

Table 1: Soil Protection Effectiveness Of Selected BMPs.

Soil Stabilization Measure	Average Erosion Reduction on Bare Soil 2:1 Clayey Sand (%)
Bonded fiber matrix	100%
Straw blanket	98%
Wood fiber blanket	98%
Straw-coconut blanket	97%
Straw incorporated	96%
Coir blanket	94%
Curled wood fiber blanket	91%
Rainfall:	Part1 – 5 mm/hr, 30 min Part2 – 40 mm/hr, 40 min Part3 – 5 mm/hr. 30 min(1) One 3-part event (3 replicate plots)

(1) Corresponds to 10-yr storm in District 7 of California

Adapted from Caltrans (2000)

Table 2: TxDOT/TTI Sediment Loss Thresholds.

Slope Condition	Soil loss Bare Soil (lb/100 ft^2)	TxDOT APL Threshold (lb/100 ft^2)	Erosion Reduction Bare Soil (%)
2:1 Clay	350.0	7.9	98%
2:1 Sand	3885.3	631.8	84%
3:1 Clay	266.5	7.9	97%
3:1 Sand	1709.6	284.3	83%
Rainfall:	30.2 mm/hr, 10 min (twice) (1) 145.5 mm/hr, 10 min (twice) (1) 183.6 mm/hr, 10 min (twice) (1) Six events run two weeks apart (plots not replicate)		

(1) Corresponds to 1-yr, 2-yr, and 5-yr storms in Texas, respectively

Performance of Soil Roughening

CALTRANS (2000) tested the erosion control performance of soil roughening techniques including imprinting, sheepsfoot-rolling, trackwalking, and ripping. The tests show that soil roughening is less effective in erosion control than RECPs (Table 3). Soil roughening can be combined with other erosion control measures including compost and mulch, making them perform better. The imprinting technique demonstrated good performance at 2:1 clayey sand slope (76 percent decrease in soil loss), which implies imprinting could be a candidate for protecting 3:1 clay slopes.

Table 3: Soil Protection Effectiveness of Soil Roughness.

Soil Roughening Technique	Average Erosion Reduction from Bare Soil at 2:1 Clayey Sand (%)
Imprinted	76%
Sheepsfoot	55%
Trackwalked	52%
Ripped	12%

Adapted from Caltrans (2000)

Performance of Organic Measures (Composts and Mulches)

Studies on the effectiveness of compost and mulches as erosion control measures are more readily available than the use of RECPs and soil roughening. This availability of data may be the result of the effectiveness and environmental sensitivity of these products over many other erosion control methods. Most experimental studies on the effectiveness of compost and mulches focus on two major areas – (1) sediment loss reduction and (2) vegetation establishment. In addition, they have been examined to determine if they cause any changes to soil characteristics which could affect erodibility (i.e., soil texture and structure, plasticity, sheer strength, water holding capacity, permeability, soil moisture, and bulk density). Most studies agree that both compost and mulch are effective in reducing soil loss by increasing vegetation yield (Table 4). However, it is unclear whether their performance level is enough to be applied to steep slopes. Moreover, the mechanism bringing about such results is not clearly addressed in the literature supporting the effectiveness of organic amendments on erosion control and vegetation yield. The lack of theory might limit the general application of those organic treatments.

Table 4: Performance test results obtained from various studies

	70% Soil + 30% Biosolids Compost (Puppala et al. 2004)	100% Manure Compost (Puppala et al. 2004)	Wood Mulch (Storey et al. 1996)	Compost (USCC 2001)	Potato+ manure+ sawdust Compost (Edwards et al. 2000)	Straw mulch (Edwards 2000)
Soil loss	↓	↓	↓	↓	-	↓
Vegetation yield	↑	↑	↑	n/a	-	-
Plasticity	↑	↓	n/a	n/a	n/a	n/a
Sheer strength	↑	↑	n/a	n/a	-	-
Water holding	↑	↑	n/a	↑	↑	↑
Permeability	↓	↑	n/a	↑	n/a	n/a

↓: decrease, ↑: increase, -: no change, n/a: not applicable

The performances of organic erosion control measures vary by study simply because of variances in the test materials, application, experimental condition, and test protocol. Such variances make it difficult to standardize test results. Physical characteristics of composts vary by source (biosolids, manure, sewage sludge, food waste, straw, sawdust, etc.) and composting technique (processing time and temperature). For this reason, the US Compost Council has developed and recommends standardized test parameters to examine the quality of compost including pH, soluble salts (conductivity), nutrient content, organic matter, moisture percent, particle size, maturity (bioassay), stability (respirometry), inters, trace metals, and weed seed and pathogens. Mulch also has various source materials (straw, wood chips, litter, etc.), and the unit size of the different materials affect product performance.

Different material properties (thickness, quantity, density) may also create a variance. For example, Edwards et al. (2000) applied 4 t/ha of straw mulch while Doring et al. (2005) applied 1.25 to 5 t/ha of straw mulch. Persyn et al. (2005) applied 100 mm thickness of compost, whereas, Storey et al. (1996) applied 76 to 101 mm thickness.

Different experimental conditions (rainfall, slope, antecedent soil characteristics) also contributed to the difficulty of comparing test results. Many studies provide a detailed description of rainfall, slope conditions, and soil characteristics, but it is difficult to standardize such varying conditions. This difficulty was especially evident on organic soil amendment studies, which are typically conducted on relatively flat areas used for agricultural purposes rather than on steep slopes, which may alter the mechanism of erosion. It was determined that results from studies conducted on slopes were to be used for this study since slope steepness and length play a major role in the erosion process.

Table 5 shows the erosion control effectiveness of several organic materials on a 2:1 slope. The Texas Transportation Institute (TTI) determined the effectiveness of crimped straw, applied at three tons per acre, demonstrated comparable performance to RECPs (over 90 percent). Compost is less effective when it is solely utilized (39 percent), but the performance might be greatly improved with vegetation seeding as compost facilitates vegetation establishment. A 76 to 101 mm layer of compost produced 92 percent vegetation cover on the 3:1 sand slope and 99 percent cover on the 3:1 clay slope within nine weeks in May 1995 at the HSECL (Storey et al. 1996).

Table 5: Soil Protection Effectiveness of Organic Measures.

Erosion Control Measure	Average Sediment Loss Reduction on Bare Soil (%)	Test Condition
Compost	39%	Tested at SDSU **2:1 clayey sand** Rainfall: Part1 – 5 mm/hr, 30 min Part2 – 40 mm/hr, 40 min Part3 – 5 mm/hr. 30 min One 3-part event (3 replicate plots)
Paper Mulch with Polymer	75%	
Paper Mulch with Psyllium	61%	
Wood Mulch with Polymer	50%	
Wood Mulch with Psyllium	87%	
Crimped Straw 1 ton/acre	85% (26%)	Tested at TTI/HSECL **2:1 clay (2:1 sand)** Rainfall: 30.2 mm/hr, 10 min (twice) 145.5 mm/hr, 10 min (twice) 183.6 mm/hr, 10 min (twice) Six events run two weeks apart (plots not replicate)
Crimped Straw 2 tons/acre	90% (71%)	
Crimped Straw 3 tons/acre	96% (92%)	
Crimped Straw 4 tons/acre	99% (97%)	

Adapted from Caltrans (2000) and TTI (2006)

SOIL EROSION FACTORS

The Universal Soil Loss Equation model developed by Wischmeier and Smith (1978) is a prominent soil erosion prediction model. It is based on a series of extensive studies analyzing over 10,000 annual erosion records collected from 20 years of erosion trials on plots and small catchments at 46 stations on the Great Plains in at least 10 states in the U.S. (Roose 1996). The original USLE model has been recently updated and there are two additional versions; the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE). These revisions tend to focus on the change of rainfall index or the creation of additional cover (C) or practice (P) indices. The researchers intended to use the RUSLE for this study to determine a procedure to standardize the various test conditions among previous studies but there were problems that needed to be solved before doing so.

The following equation illustrates the RUSLE:

$$\mathbf{A = R \cdot K \cdot LS \cdot C \cdot P}$$

where, A: Soil loss (tons/acre/year)

R: Rainfall erosivity index

K: Soil erodibility index

LS: Slope length to slope steepness ratio

C: Cover index

P: Support practices index

The five factors identified in the USLE series are described below:

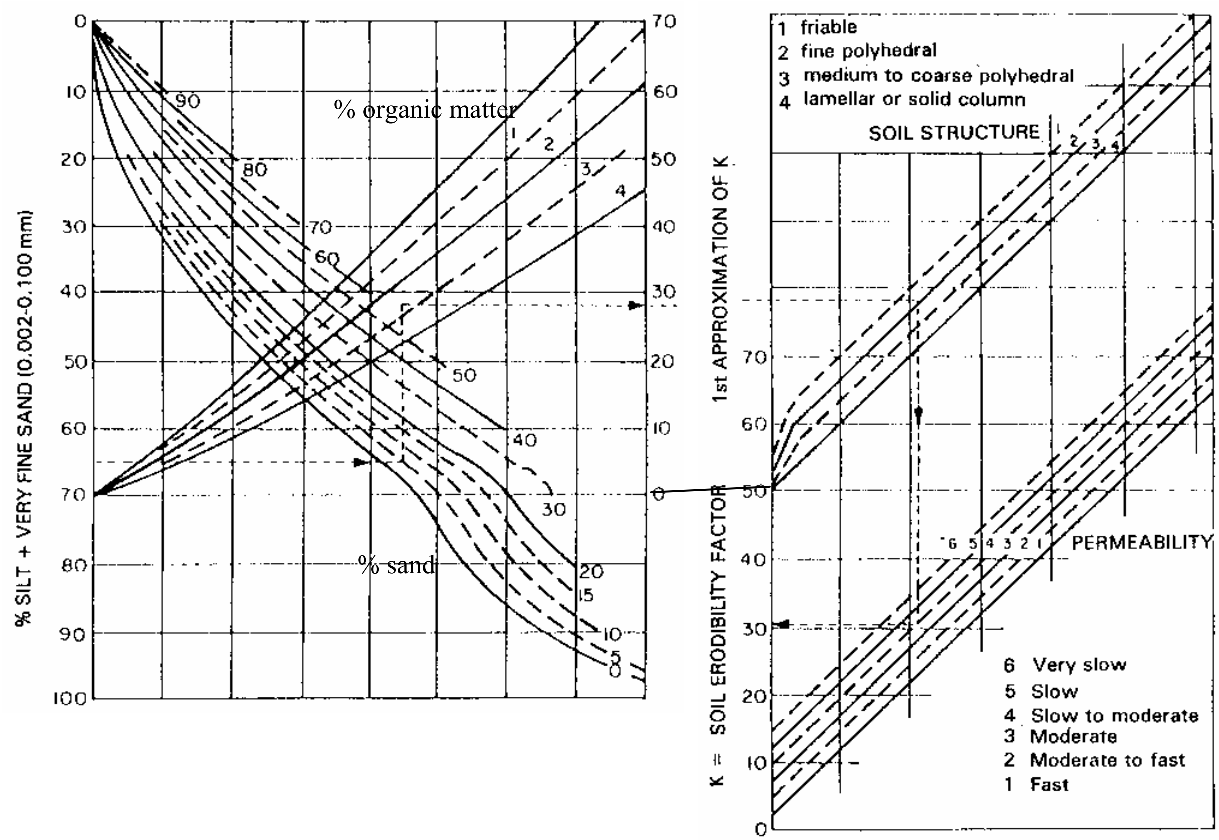
Rainfall Erosivity (R)

The rainfall erosivity index is a measure of the erosive force of a specific rainfall. It indicates the two most important characteristics affecting rainfall erosivity – rainfall amount and the peak intensity of rainfall (IWR 2005). The USLE and the RUSLE model can calculate the annual level of rainfall erosivity index (R) by using the kinetic energy of rainfall multiplied by a maximum 30-minute rainfall intensity, whereas, the MUSLE model can calculate the index for a single rainfall event using total runoff and peak discharge of a rainfall event.

Soil Erodibility (K)

Soil erodibility represents the rate of runoff and the vulnerability of soil to erosion (IWR 2002). The resistance to erosion typically depends upon the weight and coherence of soil particles. The structure of the soil determines the amount of infiltration and runoff.

The soil erodibility index (K) used in USLE models varies from 0.7 for the most erodible soil to 0.01 for the most stable soil. The calculation for K factor is measured on bare soil plots 22.2 m long on 9 percent slopes, tilled in the direction of the slope and having received no organic matter for three years (Roose 1996). Wischmeier et al. (1978) conducted multiple regressions between soil erodibility and 23 different soil parameters.



Procedure: in examining the analysis of appropriate surface samples, enter on the left of the graph and plot the percentage of silt (0.002 to 0.1 mm), then of sand (0.10 to 2 mm), then of organic matter, structure and permeability in the direction indicated by the arrows. Interpolate between the drawn curves if necessary. The broken arrowed line indicates the procedure for a sample having 65 percent silt + very fine sans, 5 percent sand, 2.8 percent organic matter, 1st approximation of K = 0.28, 2 of structure and 4 of permeability. Erodibility factor K = 0.31.

Figure 1: Nomograph Allowing a Quick Assessment of the "K" Factor Of Soil Erodibility.

(Roose 1996 and reference therein; Wischmeier et. al. 1971)

Figure 1 demonstrates the process of the calculation of the erodibility index using major soil characteristics including percentage of silt and very fine sand, percentage of sand, percentage of organic matter, soil structure, and permeability. This graph indicates that lower erodibility results from:

- lower percentage of silt and very fine sand,
- higher percentage of organic matter,
- more solid soil structure, and
- higher soil permeability.

According to the USLE, coarse textured soils like sand seem to show low erodibility due to their weight and high infiltration/low runoff level despite their low coherence. Whereas, dense textured soils like clay may show higher erodibility because of their lightness and high runoff possibility despite strong coherence. As mentioned earlier, these USLE results are from tests conducted on relatively flat 9 percent slopes. This 9 percent slope allowed infiltration rates much higher than typical highway environments. Godfrey and Long (1994) pointed out that sand produces high sediment yield despite its low erodibility value on slopes typically used in highway construction (Table 6).

Table 6: Soil Erodibility Guide

Soil texture	Erodibility index	Sediment yield
Sand	**0.02 - 0.05**	**High**
Loamy sand	0.08 - 0.12	Low
Clay	0.13 - 0.20	Low to Medium
Very fine sand	0.28 - 0.42	Medium to High
Loam	0.29 - 0.38	Medium
Silt	0.42 - 0.60	High

Adapted from Godfrey et al. (1994)

Slope Steepness and Length (LS)

Increased slope steepness and length increases the potential for erosion as it increase runoff velocity and mass. Wischmeier and Smith' equation (1957) established such relationship (see Figure 2). However, many studies pointed out that the equation missed the interaction between slope and surface condition (cover type, roughness, the shape of surface line, and prior moisture)

(Roose 1996 and references therein; Roose 1973; Roose 1980a; Wischmeier 1966; and Lal 1975).

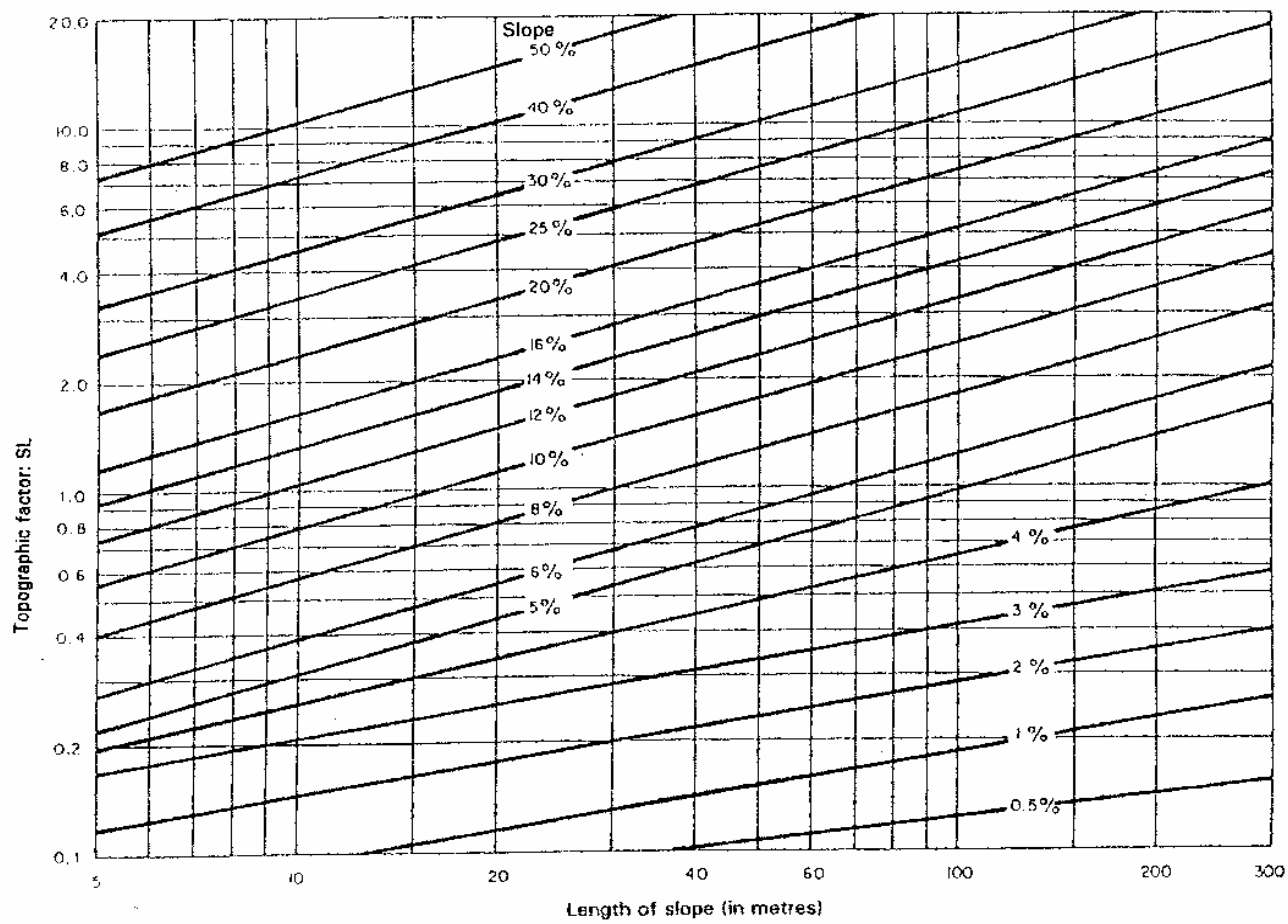


Figure 2: Relationship Among Erosion Level, And Slope Length And Steepness
(Roose 1996)

Cover (C)

Cover factor represents the effect of plants, soil cover, soil biomass, and soil disturbing activities on erosion (IWR 2002). The cover index is the ratio of soil loss observed under a specific cover condition to soil loss under the bare soil condition. The USLE considers only plant cover, its production level, and the associated cropping techniques (Roose 1996). RUSLE deals with additional cover material including various types of mulch. The index is computed with several soil characteristics including canopy, surface cover, surface roughness, prior land use, and antecedent soil moisture (IWR 2002). The total percent of covered area and the density of cover material are main considerations in calculating the C factor. Cover index in the USLE varies from 1 on bare soil to 0.001 under forest conditions.

Erosion Control Practice (P)

Various human practices to control soil surface including contour tilling, mounding, and contour ridging can change the level of soil erosion. The support practice index provided by the USLE varies from 1 on bare soil with no erosion control to about 0.1 with contour ridging on a gentle slope. However, numerous experiments carried out by Asseline, Collinet, Lafforgue, Roose and Valentin under simulated rainfall confirmed the null or negative effects of tillage on soil erosion. In summary, Roose (1996) concluded:

- The very temporary improvement in infiltration as a result of tillage: after 120 mm of rain, there is practically no trace of this improvement on any of the soils tested at Adiopodoumé Centre and in Burkina Faso;
- The increase in the fine suspended load in runoff after tillage;
- The extremely beneficial and lasting effect for soil and water conservation of plant cover and of leaving crop residues on the surface; and
- The very marked but temporary effect of tied ridging and other methods aimed at increasing the roughness of the soil (Lafforgue and Naah 1976; Roose and Asseline 1978; Collinet and Lafforgue 1979; Collinet and Valentin 1979).

Limitations of the USLE Model

Despite the rationale based on numerous test trials in various controlled conditions, the USLE model has intrinsic limitations as Roose (1996) concluded:

- The model applies only to sheet erosion since the source of energy is rain; so it never applies to linear or mass erosion.
- The type of countryside: the model has been tested and verified in moderately hilly country with 1-20 percent slopes, and excludes mountains, especially slopes steeper than 40 percent, where runoff is a greater source of energy than rain and where there are significant mass movements of earth.
- The relations between kinetic energy and rainfall intensity generally used in this model apply only to the American Great Plains and not to mountainous regions although different sub-models can be developed for the index of rainfall erosivity.

- A major limitation of the model is that it neglects certain interactions between factors in order to distinguish more easily the individual effect of each. For example, it does not take into account the effect on erosion of slope combined with plant cover, nor the effect of soil type on the effect of slope.

Another limitation of the model is that it is based on gentle slopes, which do not represent the typical steep slopes occurring along our roadsides designed and maintained by TxDOT. The test slopes at the HSECL are 33 percent and 50 percent, which more accurately reflect ‘real-world’ conditions.

METHODOLOGY

DATA COLLECTION AND TREATMENT

Cost of Products on the Approved Product List

A telephone survey was used to collect product cost data. The information includes product price per 10,000 square yards, installation cost, product size, and discount availability (if any). During the survey, the researchers also identified discontinued products and products manufactured under multiple trade names on the TxDOT APL (Appendix C). The APL includes 60 slope protection products and 47 channel protection products after excluding discontinued or duplicated products. Among all of these products, 16 products have been approved for use on both slope and channel protection.

During the telephone survey, many manufacturers were reluctant to provide price information as they recognized the survey was part of a comparison study. The price survey obtained about 80 percent and 65 percent of response rate for slope products and channel products, respectively (Table 7). Installation costs were difficult to obtain since labor costs vary by region. It was expected that end-users (such as municipalities and governmental bodies) could provide the approximate installation cost by product type (i.e., mulch, composite, synthetic, etc.) but such detailed information was not available. TxDOT provides bid price information; however, this information is not based on product type but by specific project condition including soil type and slope steepness or channel shear stress. Hence, the researcher's utilized only material price collected from the telephone survey for the cost-performance analysis.

Table 7: Survey Response Rate.

	Total products	Surveyed products	Response rate
APL Product for Slope Protection	58	46	79.3%
APL Product for Channel Protection	45	29	64.4%

Surveyed product price was then used for the calculation of price index (PI) which is a single cost variable in the cost-performance analysis. The PI is defined as "product price per 100 square feet. The researchers converted the surveyed 10,000-square-yard price to 100-square-feet price for two reasons. First, it might reflect fluctuating real market price by reducing variances among price data (i.e., '$ 3200' to '$ 4000' has same index value '4'). Second, the unit area of 100 square feet matches the criteria TxDOT uses in quantifying the soil loss performance, that is, pounds per 100 square feet. Unit matching is important when calculating the cost-benefit ratio. The price index is expressed by:

$$\textbf{Price Index (PI) = Price per 100 ft}^2 \textbf{ = Price per 10,000 yd}^2 \textbf{ / 900}$$

Soil Loss Data

Soil loss performance data of the TxDOT APL originates from experiments conducted at the TTI HSECL. The HSECL evaluates slope protection products in four soil-slope conditions including clay and sand in 1V:2H slope, and clay and sand in 1V:3H slope, and channel protection products in six shear stress conditions (i.e., 0 to 2, 0 to 4, 0 to 6, 0 to 8, 0 to 10, and 0 to 12 lb/ft^2). This testing program began in 1991 and changed its protocol from outdoor field testing to large-scale indoor testing in 2000. TxDOT (2000) and TxDOT (2005) detail the outdoor and indoor experimental protocols, respectively. To investigate the influence by difference of test protocol on the indoor vs. outdoor data, Li et al. (2003) conducted a comparison study on data collected from the two different test protocols. They found that the ratio between field and indoor data in HSECL slope erosion experiments is relatively constant regardless of soil type and test slope (Table 8). Therefore, the researchers use the average value '0.088' to standardize the APL slope soil loss data.

Table 8: Ratio of Field Soil Loss Data to Indoor Soil Loss Data of The HSECL.
(adapted from Li et al. 2003)

Product Type	Field Soil Loss (kg/10m^2)	Indoor Soil Loss (kg/10m^2)	*Soil Loss Ratio*
1:2 Clay			
Product A	0.18	2.05	0.088
Product B	0.24	3.75	0.064
Product C	0.19	3.06	0.062
Product D	0.31	2.22	0.140
		Average	*0.089*
1:2 Sand			
Product A	23.42	306.60	0.076
Product B	18.81	279.86	0.067
Product C	21.85	181.79	0.120
Product D	26.47	312.57	0.085
		Average	*0.087*

Table 8: Ratio of Field Soil Loss Data to Indoor Soil Loss Data of the HSECL. **(cont)_**

Product Type	Field Soil Loss ($kg/10m^2$)	Indoor Soil Loss ($kg/10m^2$)	*Soil Loss Ratio*
1:3 Clay			
Product C	0.15	1.62	0.093
Product D	0.27	2.11	0.127
Product E	0.15	2.82	0.053
Product F	0.31	4.02	0.078
		Average	*0.088*
1:3 Sand			
Product C	8.00	82.94	0.096
Product D	8.12	72.61	0.112
Product E	4.42	57.60	0.077
Product F	11.95	170.29	0.070
		Average	*0.089*

- Product A – turf reinforcement mat (TRM) made of polypropylene fibers bound together by two biaxially oriented nets and stitched with polypropylene thread, manufactured by Synthetic Industries.
- Product B – open weave textile (OWT) made of polypropylene fibers woven together, manufactured by Synthetic Industries.
- Product C – erosion control blanket (ECB) made of wheat straw bound together by top and bottom jute netting and stitched with twisted jute thread, manufactured by Synthetic Industries.
- Product D – ECB made of straw fibers bound together by top polypropylene netting sewn together by degradable thread, manufactured by North American Green.
- Product E – ECB made of aspen curled wood excelsior bound together by top degradable netting, manufactured by American Excelsior Company.
- Product F – bonded fiber matrix (BFM) consisting of long strand, residual, softwood fibers joined together by adhesive, manufactured by Canfor.

Such a comparison study described above is not necessary for channel test data since the tests were all conducted on a vegetated surface in both old and new protocols. The soil loss value for channel products indicates the change of surface elevation after a series of flume tests with different shear stresses. Both field and flume test protocols recorded soil loss depth in inches.

To develop the soil loss index (SLI) that could represent a products' soil loss level, researchers classified the soil loss test data of the HSECL. To classify soil loss data in both channel and slope protection products, the researchers use the APL maximum allowable sediment loss thresholds. The researchers defined that if the soil loss of a product is within 0 to 10 percent of the threshold, the SLI value is '5' which indicates the best product. Likewise, 10.1 to 20 percent of the threshold has a value of '15', and 90.1 to 100 percent has a value of '95' which represents the lowest performing group among products in the APL. A product that failed on the APL test has a value of over 100 (%).

Tables 9 and 10 show the performance thresholds for the slope and channel tests, respectively. The thresholds have been determined from a series of statistical tests on over 100 products for 6 years (Northcutt and McFalls 1997).

Table 9: Threshold Of TxDOT APL Slope Test.

Slope & Soil	Soil Loss (lb/100 ft^2)
1:3 Clay	7.89
1:2 Clay	7.89
1:3 Sand	284.30
1:2 Sand	631.80

Table 10: Threshold Of TxDOT APL Channel Test

Shear Stress Range (lb/ft^2)	Soil Loss	
	(lb/100 ft^2)	(in)
0 - 2	350	0.43
0 - 4	500	0.48
0 - 6	620	0.60
0 - 8	800	0.77
0 - 10	1180	1.13
0 - 12	1200	1.15

The purposes of using the SLI rather than the actual soil loss value are as follows:

- The problem associated with data variance could be alleviated due to the variance that might result from minor experiment errors. For example, the value of 5 is assigned to cover soil loss ranges from 0 to 63.18 lb/100 ft^2 in 1:2 sand slopes (Table 11).
- The test protocol assumes that a product can protect conditions that are less severe than the level for which it is approved. For example, a product approved for 1:2 slopes on clay also qualifies for 1:3 slopes on clay. In this case, the researchers assume the product has the same soil protection performance in both 1:2 and 1:3 slopes on clay.

Tables 11 and 12 show the assumed soil loss index that corresponds to soil loss ranges in pounds per 100 square feet. The researchers used the soil loss index, along with the longevity of a product, as the performance variable of a product.

Table 11: Soil Loss Index and Corresponding Soil Loss Range for Slope Protection Products.

Criteria	Soil Loss Index (% to APL threshold)	Soil Loss (lb/100 ft^2)			
		1:3 Clay	1:2 Clay	1:3 Sand	1:2 Sand
0~10% of threshold	5	0.00~0.79	0.00~0.79	0.00~28.43	0.00~63.18
10~20% of threshold	15	0.80~1.58	0.80~1.58	28.44~56.86	63.19~126.36
20~30% of threshold	25	1.59~2.37	1.59~2.37	56.87~85.29	126.37~189.54
30~40% of threshold	35	2.38~3.16	2.38~3.16	85.30~113.72	189.55~252.72
40~50% of threshold	45	3.17~3.95	3.17~3.95	113.73~142.15	252.73~315.90
50~60% of threshold	55	3.96~4.73	3.96~4.73	142.16~170.58	315.91~379.08
60~70% of threshold	65	4.74~5.52	4.74~5.52	170.59~199.01	379.09~442.26
70~80% of threshold	75	5.53~6.31	5.53~6.31	199.02~227.44	442.27~505.44
80~90% of threshold	85	6.32~7.10	6.32~7.10	227.45~255.87	505.45~568.62
90~100% of threshold	95	7.11~7.89	7.11~7.89	255.88~284.30	568.63~631.80

Table 12: Soil Loss Index and Corresponding Soil Loss Range for Channel Protection Products

Criteria	Soil loss Index (% to APL threshold)	Soil Loss (in)					
		0 - 2	0 - 4	0 - 6	0 - 8	0 - 10	0 - 12
0~10% of threshold	5	0.00~0.04	0.00~0.05	0.00~0.06	0.00~0.08	0.00~0.11	0.00~0.12
10~20% of threshold	15	0.05~0.09	0.06~0.10	0.07~0.12	0.09~0.15	0.12~0.23	0.13~0.23
20~30% of threshold	25	0.10~0.13	0.11~0.14	0.13~0.18	0.16~0.23	0.23~0.34	0.24~0.35
30~40% of threshold	35	0.14~0.17	0.15~0.19	0.19~0.24	0.24~0.31	0.35~0.45	0.36~0.46
40~50% of threshold	45	0.18~0.22	0.20~0.24	0.25~0.30	0.32~0.38	0.46~0.57	0.47~0.58

50~60% of threshold	55	0.23~0.26	0.25~0.29	0.31~0.36	0.39~0.46	0.58~0.68	0.59~0.69
60~70% of threshold	65	0.27~0.30	0.30~0.34	0.37~0.42	0.47~0.54	0.69~0.79	0.70~0.81
70~80% of threshold	75	0.31~0.34	0.35~0.38	0.43~0.48	0.55~0.61	0.80~0.91	0.82~0.92
80~90% of threshold	85	0.35~0.39	0.39~0.43	0.49~0.54	0.62~0.69	0.92~1.02	0.93~1.04
90~100% of threshold	95	0.40~0.43	0.44~0.48	0.55~0.60	0.70~0.77	1.03~1.13	1.05~1.15

Product Type (Classified by Material Composition and Longevity)

This study classifies material composition into four types – 1) mulch, 2) natural, 3) composite, and 4) synthetic. The mulch category represents spray-on products while the other three categories represent RECPs. The natural type specifies products composed of natural fill materials including jute, coconut fibers and excelsior with a bio-degradable netting. Composite products are generally composed of natural materials and non-biodegradable synthetic netting. The material composition is an important factor determining the longevity and environmental friendliness of an erosion control product. For example, synthetic products tend to perform better and have a longer lifetime than natural products, while natural ones are more environmentally compatible than synthetic products. Most composite products tend to be fill in the gap between the pure-natural or pure-synthetic products.

Longevity is an important factor affecting soil protection performance because longer lifetime provides longer protection. The researchers define five categories of longevity as follows.

- temporary term (0 - 3 months);
- short term (3 -12 months);
- mid term (12 - 24 months);
- long term (24 - 36 months); and
- permanent term (over 36 months and up to 54 months).

The researchers classify all products in the APL into ten categories based on material composition and longevity in the following list.

- <u>Temporary Mulch (TM):</u> These products are hydraulically applied using spray-on procedures. Temporary mulches can be mixed with seed to establish both temporary erosion control and seeding in the same application. The types of temporary mulches vary greatly from simple low slope products to complex BFMs and mulches that are designed for severe slope applications. Temporary mulches are design for ease of application and to aid in rapid vegetative establishment in a variety of settings.

- Temporary Natural (TN): Products in this category are temporary all-natural blankets. The netting, stitching, and fill material of these blankets is made up entirely of natural materials. These blankets are ultra-short term in use and are designed to degrade quickly and last only until vegetation can be established.
- Temporary Composite (TC): Products in this category are temporary blankets that contain natural filler material and synthetic netting and/or stitching. These blankets can be either single or double net products with a netting that photodegrades or biodegrades very quickly. These blankets are designed for temporary erosion control until vegetation can be established.
- Short-term Natural (SN): Products in this category are short-term all-natural blankets. The netting, stitching, and fill material of these blankets is made up entirely of natural materials. These blankets are short term in use and are designed to degrade rapidly. These blankets last longer than temporary products and can assist in protecting the soil until more dense vegetation is established.
- Short-term Composite (SC): Products in this category are short-term blankets that contain natural filler material and synthetic netting and/or stitching. These blankets can be either single or double net products with a netting that photodegrades or biodegrades quickly. These blankets are designed for short term erosion control and last long enough to provide that adequate vegetation can be successfully established.
- Mid-term Natural (MN): Products in this category are mid-term all-natural blankets. The netting, stitching, and fill material of these blankets is made up entirely of natural materials. These blankets provide erosion control until vegetation can be established and remain for some time after vegetation is growing to help continue to provide erosion control in conjunction with the vegetation. These products are usually double net products.
- Mid-term composite (MC): Products in this category are mid-term blankets that contain natural filler material and synthetic netting and/or stitching. These blankets are usually always double net products with a medium strength synthetic netting that photodegrades

or biodegrades slowly. These blankets are designed to last until vegetation is fully established and can protect the soil.

- Long-term Natural (LN): Products in this category are long-term all-natural blankets. The netting, stitching and fill material of these blankets is made up entirely of long-lasting natural materials. These blankets provide erosion control until vegetation can be established and remain long after vegetation is growing to help continue to provide erosion control and establish a good root system and dense coverage in the vegetation. These products are designed to last until total revegetation and permanent vegetative establishment has been achieved.
- Long-term Composite (LC): Products in this category are long-term blankets that contain natural filler material and synthetic netting and/or stitching. These blankets are usually always double net products with a strong synthetic netting that photodegrades or biodegrades very slowly. These blankets are designed for long-term erosion control and to provide total vegetative establishment and strong root system establishment. These blankets also remain long after vegetation is growing to help continue to provide erosion control.
- Permanent Synthetic (PS): These products are totally synthetic blankets, which usually contain a stable polypropylene or similar synthetic fiber and netting. These blankets are designed for permanent erosion control protection and are designed to be used in situations where vegetation alone is not adequate and permanent continuing erosion control is needed. These blankets are designed to work with vegetation permanently to provide protection for severe erosion control applications.

Table 13 shows the classification of product type based on material type and longevity.

Table 13: Classification of Product Type.

		Material composition	Mulch	Natural	Composite	Synthetic
		Environmental Friendliness	Good	Good	Fair	Poor
Longevity	Temporary	3 mo	TM	TN	TC	.
	Short	12 mo	.	SN	SC	.
	Mid	24 mo	.	MN	MC	.
	Long	36 mo	.	LN	LC	.
	Permanent	54 mo	.	.	.	PS

LIFETIME SOIL PROTECTION PERFORMANCE

APL soil loss test data and corresponding soil loss index (SLI) indicate *initial* performance rather than lifetime performance. This section introduces the concept of lifetime soil protection performance that reflects the change of the performance over a product's lifetime.

Lifetime Soil Protection by Product

Assumptions for estimating soil amount protected by products include:

- Soil protection performance of a product decreases with time. Specific details include:
    - Performance of a product decreases linearly over time;
    - Soil loss data obtained from HSECL's testing represents the *initial* soil loss level of products.
    - The soil loss of a product at the end of its lifespan is set as 150 percent of the APL threshold (i.e., 150 percent of the soil loss index) when the product no longer protects the soil.
    - The condition is considered failed, when the soil loss level exceeds 150 percent of the threshold.

Figure 3 shows an example of soil protection ability of various products over time. In this example, a product with temporary longevity (3 months) loses the highest amount of soil during the initial period, while a product with permanent longevity (54 months) loses the least amount of soil. Also for comparison purposes, the soil loss produced by all products at the end of their lifespan is set the same as 150 percent of the APL threshold.

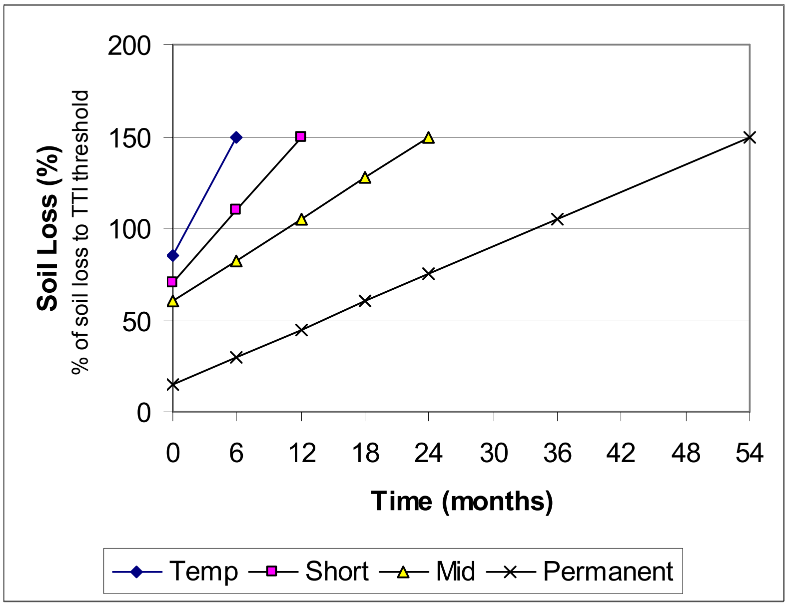


Figure 3: An Example of Life-Performance Of Erosion Control Products.

The life-long performance line of a product can be expressed as:

$$\textbf{Soil Loss}_{\textbf{product, time}} = \frac{\textbf{Final Soil Loss}_{\textbf{product}} - \textbf{Initial Soil Loss}_{\textbf{product}}}{\textbf{Product Longevity}} \cdot \textbf{Time} + \textbf{Initial Soil Loss}_{\textbf{product}}$$

where,

Soil Loss $_{\text{product, time}}$ = Soil loss level of a product at a specific time (% of soil loss to APL threshold)

Final Soil Loss $_{\text{product}}$ = Soil loss level when the product no longer protects the soil.
It is set as '150' (% of soil loss to APL threshold)

Initial Soil Loss $_{\text{product}}$ = Soil loss level immediately after the product is installed.
It is extracted from HSECL's soil loss data (% of soil loss to APL threshold)

Product Longevity = Longevity of the product (months)

Time = A specific time (months)

Lifetime Soil Protection by Vegetation

Assumptions for estimating soil amount protected by vegetation include:

- Vegetation's ability to protect soil increases over time. Specific details include:

- Vegetation's ability to protect increases linearly with time.
- The initial soil loss level of vegetation starts at 150 percent of the APL threshold when no vegetation has established.
- The final soil loss of well-established, mature vegetation is set at 4 percent of the APL threshold. The 4 percent value is considered for the natural erosion condition. The 4 percent value also avoids infinite value in calculating the CPI when a product starts at 5 percent with a longevity rate the same as the vegetation establishment time.

Vegetation's initial soil loss level is set at 150 percent of the APL threshold because no vegetation is assumed at the initial stage of seeding. The soil protection performance of vegetation increases with time assuming vegetation steadily grows. Hence, the soil loss level decreases with time and is finally set at 4 percent of the APL threshold when the vegetation is fully established. The time required for complete vegetation establishment depends on the conditions of a project such as slope steepness, climate, and soil type. Figure 4 shows an example of the soil protection ability of vegetation with different establishment times (temporary, short, etc.).

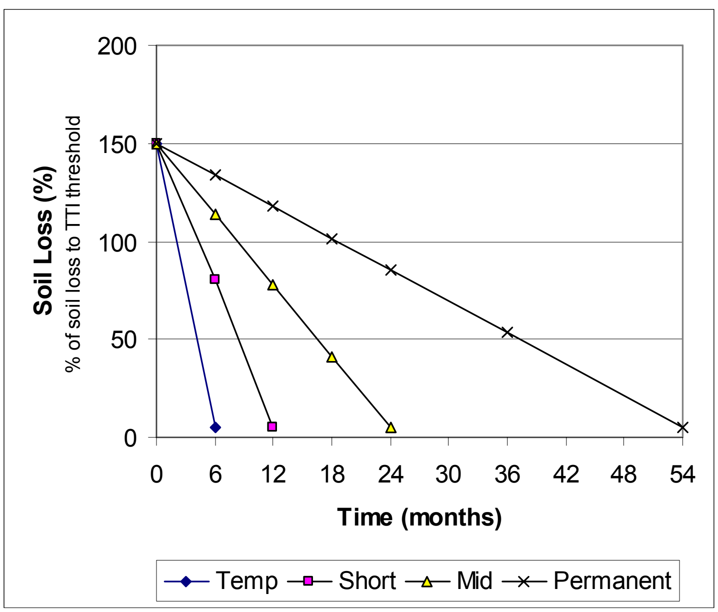


Figure 4: An Example of Vegetation Performance with Different Establishing Times.

The formula of the vegetation performance lines is:

$$\textbf{Soil Loss}_{\textbf{veg., time}} = \frac{\textbf{Final Soil Loss}_{\textbf{veg.}} - \textbf{Initial Soil Loss}_{\textbf{veg.}}}{\textbf{Vegetation Establishing Time}} \cdot \textbf{Time} + \textbf{Initial Soil Loss}_{\textbf{veg.}}$$

where Soil Loss $_{\text{veg., time}}$= Soil loss level of vegetation at a specific time (% of soil loss to APL threshold)

Final Soil Loss $_{\text{veg.}}$ = Soil loss level when vegetation is fully established. It is set at '4' (% of soil loss to APL threshold)

Initial Soil Loss $_{\text{veg.}}$ = Soil loss level when no vegetation is established. It is set at '150' (% of soil loss to APL threshold)

Vegetation Establishing Time= Time required for complete vegetation establishment (months)

Time= A specific time (months)

COST-PERFORMANCE INDEX

Basic Concept

The Cost-Performance Index (CPI) was developed to quantify the cost effectiveness of erosion control products during a designated period. The CPI considers 1) cost, 2) initial soil protection performance, and 3) longevity. As mentioned earlier, this study uses product prices surveyed from manufacturers as cost, and test results of the HSECL as initial performance. The product longevity was determined based on material composition.

The CPI is defined as the potential soil protection benefit per the cost of both product and potential topsoil replacement expense. The CPI can be expressed as:

$$\textbf{CPI} = \frac{\textbf{Benefit of Potential Soil Protection}}{\textbf{Product Expense + Cost of Potential Topsoil Loss}}$$

Thus, a higher CPI means better cost-effectiveness of a product. An important step of the CPI development is to estimate potential protected soil amount and potential soil loss amount. For the slope protection, the estimation of the soil amounts includes the amount protected by products and the amount protected by vegetation. For channel protection, only the amount protected by products is considered because HSECL's channel APL tests are conducted on vegetated conditions.

Cost-Performance Index for Slope Products

The estimate of slope product performance considers both product and vegetation performance. Figure 5 shows the example that combines mid-product (24 months) and 12-month maturing time for vegetation. The resulting trend line in this example is shown as the bold line in Figure 5. This trend line indicates the combined performance of products and vegetation over time.

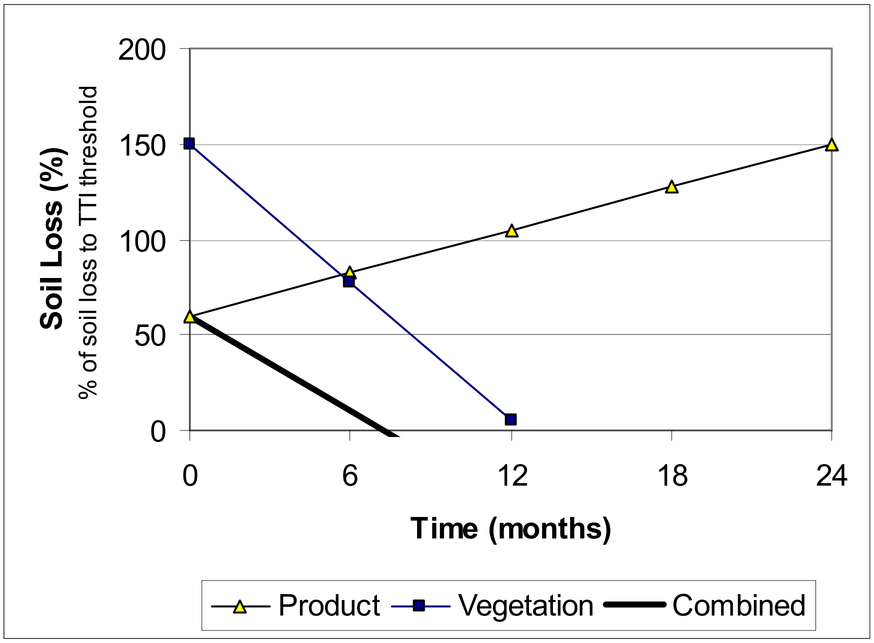


Figure 5: Combination of Product and Vegetation Performance Lines in Slope

By expressing both product and vegetation performance lines as follows,

$$\textbf{Soil Loss}_{\text{product, time}} = \mathbf{a \cdot time + b}$$

$$\textbf{Soil Loss}_{\text{vegetation, time}} = \mathbf{p \cdot time + q}$$

The equation of combined net soil loss can be expressed as:

$$\textbf{Soil Loss}_{\text{(product + vegetation), time}} = \mathbf{(a + p) \cdot time + b}$$

where a = (Final Soil Loss $_{\text{product}}$ – Initial Soil Loss $_{\text{product}}$) / Product Longevity

b = Initial Soil Loss $_{\text{product}}$

p = (Final Soil Loss $_{\text{vegetation}}$ – Initial Soil Loss $_{\text{vegetation}}$) / Vegetation Establishing Time

q = Initial Soil Loss $_{\text{vegetation}}$

time = A specific time in month

Figure 6 further illustrates soil protection/loss amount for the example shown in Figure 5. Protection by vegetation increases during a 12-month-period. After 12 months, vegetation becomes the major role of soil protection. On the other hand, the erosion control product provides the most protection in the beginning and gradually loses its protective ability over the product's longevity (24 months). By applying a product to a seeded slope, the product provides additional protection to the protection offered by the vegetation. Another benefit of using a protection product is that it prevents surface failure. The failure risk may continuously exist unless vegetation is fully established. Despite the increasing protection by vegetation and erosion control products, soil loss still occurs. Three important components shown in Figure 6 are used to determine a product's performance: soil protected by a product (P), failure protection by a product (F), and net soil loss (L).

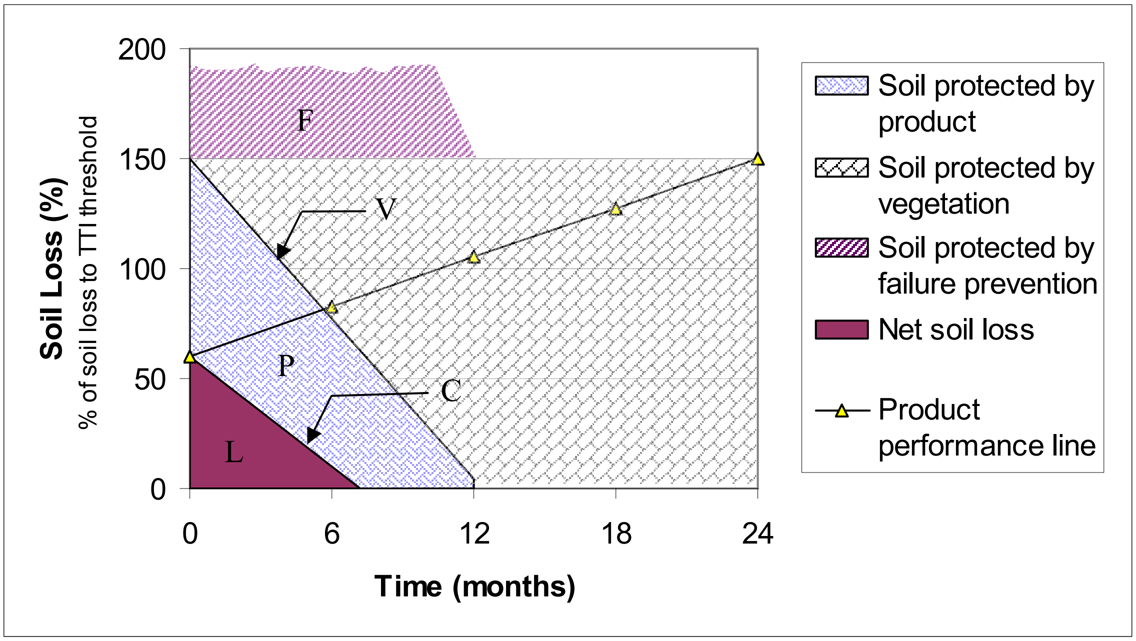


Figure 6: The Soil Loss Model of Product and Vegetation Combined for Slope Condition

The area of P, F, and L in Figure 6 has the unit of '% · month' which is not an intuitive unit. To help understand the concept of protected soil by products, the researchers use the term 'unit soil amount' as the unit to describe the areas of P, F, and L. The unit soil amounts can be calculated using intercepts at the x- and y-axis of vegetation performance line (V) and combined performance line (C).

Again, vegetation performance line can be expressed as:

$$\textbf{Soil Loss}_{\textbf{vegetation, time}}\ \textbf{(V)} = \textbf{p} \cdot \textbf{time} + \textbf{q}$$

The intercept at y-axis = q, and

The intercept at x-axis = - q / p

Similarly, combined soil loss equation is:

$$\textbf{Soil Loss}_{\textbf{(product + vegetation), time}}\ \textbf{(C)} = \textbf{(a + p)} \cdot \textbf{time + b}$$

The intercept at y-axis = b, and

The intercept at x-axis = - b / (a + p)

Using the intercepts from vegetation and combined performance lines (V and C), the area of unit net soil loss (L) and unit soil protected by product (P) can be calculated as follows:

$$\textbf{Unit Net Soil Loss (L)} = b \cdot (-b / (a + p)) / 2$$

$$\textbf{Unit Soil Protected}_{\textbf{product}} \textbf{(P)} = q \cdot (q / p) / 2 - \textbf{Unit Net Soil Loss (L)}$$

where a = (Final Soil Loss $_{product}$ – Initial Soil Loss $_{product}$) / Product Longevity

b = Initial Soil Loss $_{product}$

p = (Final Soil Loss $_{vegetation}$ – Initial Soil Loss $_{vegetation}$) / Vegetation Establishing Time

q = Initial Soil Loss $_{vegetation}$

time = A specific time in month

To estimate the potential benefit of using an erosion control product, researchers also included a failure scenario in their consideration. HSECL's tests show that a bare soil surface is very susceptible to failure, in which a soil failure may lose about 7 to 40 times the APL threshold depending on the test slope and soil type (Table 14).

Table 14: The Ratio of Soil Loss to APL Threshold on Bare Soil Surface Condition.

Test Condition	(A) Soil loss at bare soil slope (lb/100 ft^2)	(B) APL threshold (lb/100 ft^2)	Ratio of A to B
1:2 Clay	350.0	7.9	45.0
1:2 Sand	3885.3	631.8	7.0
1:3 Clay	266.5	7.9	34.0
1:3 Sand	1709.6	284.3	7.0

Erosion control products in TxDOT APL are expected to prevent soil failure. Assuming the risk of failure decreases linearly as vegetation grows, the failure prevention by erosion control products can be illustrated in Figure 7. The area of F, denoted as 'Unit Soil Protected $_{failure}$', is a benefit from using any APL products.

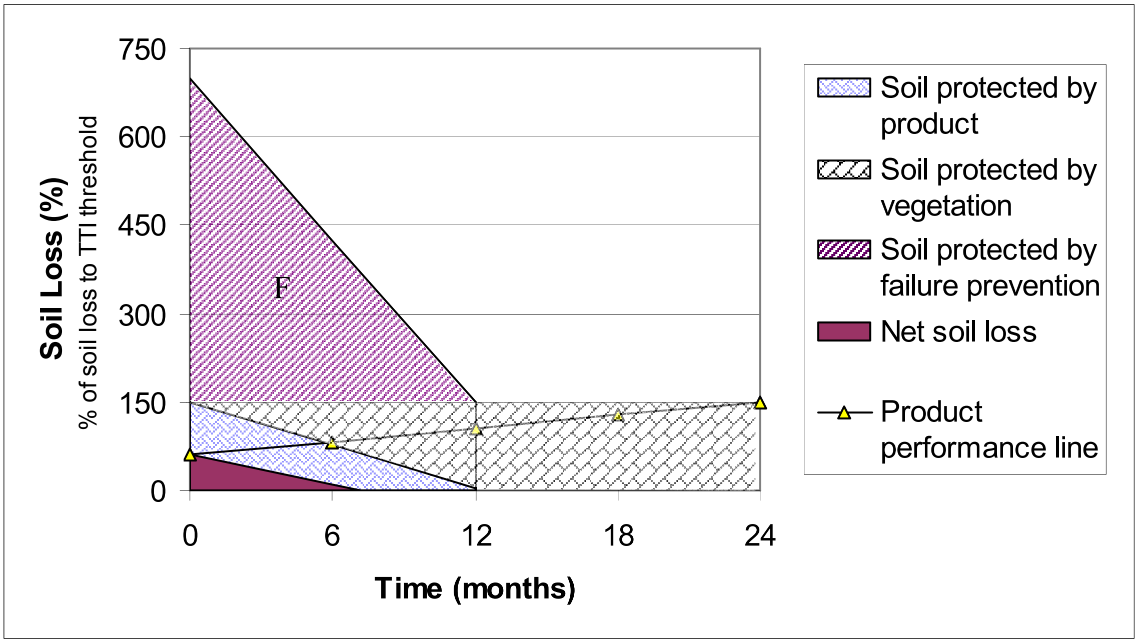


Figure 7: Failure Prevention by Erosion Control Product (F).

The unit amount of soil protected by failure prevention can be calculated by:

Unit Soil Protected $_{failure}$ (F) = (Soil Loss $_{bare}$ – Final Soil Loss $_{product}$) * time / 2

where Unit Soil Protected $_{failure}$ = Unit soil amount protected by failure prevention

Soil Loss $_{bare}$ = Soil loss level of bare soil condition (% of soil loss to APL threshold).

Final Soil Loss $_{product}$ = Soil loss level when the product no longer protects the soil. It is set as '150' (% of soil loss to APL threshold)

To compare benefits and costs, this study translates the unit soil amount to dollar value per 100 square feet of slope surface. Such adjustment was conducted in two steps: (1) estimate soil amount from 'unit soil amount'; and (2) translate the soil amount to monetary value. The unit of 'unit soil amount' is 'percent of soil loss to the APL threshold' times month (% · month). With the assumption that rainfall occurs once a month with the same intensity as HSECL's test condition, the unit soil amount multiplied by the APL threshold yields the amount of soil in lb/100 ft^2. This study makes the assumption that the actual rainfall frequency and intensity varies by location and season. Nevertheless, the HSECL's rainfall standard is considered severe enough to determine better performing products because the rainfall intensity used by the HSECL (3.5 in/hr) is much higher than most rainfall events in the state of Texas. According to TxDOT's latest hydrology research, the 99th percentile rainfall intensity in Brazos County, where HSECL is located, is 2.08 in/hr. The soil amount is calculated by:

$$\textbf{Soil amount (lb/100 ft}^2\cdot\textbf{ month)} = \textbf{Unit soil amount (\% }\cdot\textbf{ month)} \cdot \textbf{APL threshold (lb/100 ft}^2\textbf{) / 100 (\%)}$$

The value of soil in dollars per square feet is obtained by multiplying the soil amount by topsoil price per pound expressed as:

$$\textbf{Value of soil (\$/100 ft}^2\cdot\textbf{ month)} = \textbf{Soil Amount (lb/100 ft}^2\cdot\textbf{ month)} \cdot \textbf{Topsoil Price (\$/lb)}$$

Topsoil price varies by location. Given the limitation of information, the researchers used a topsoil price, $25/yd^3, equivalent to 0.01 $/lb considering the soil density of 1.4 g/cm^3. The calculation is as follows:

$$\textbf{Topsoil Price = 25 (\$/yd}^3\textbf{) / 1.4 (g/cm}^3\textbf{) = 0.92 (\$/ft}^3\textbf{) / 88 (lb/ft}^3\textbf{) = 0.01 (\$/lb)}$$

Using this soil value, the researchers can identify potential benefit and cost when using any erosion control product. The CPI is defined as the potential soil protection benefit per the cost of both product and potential topsoil loss. The benefit is the value of soil amount protected by using an erosion control product, which includes basic failure protection and additional soil protection. The cost includes the cost of the product as the well as the value of soil loss that needs repair using topsoil.

$$\textbf{CPI} = \frac{\textbf{Benefit of Potential Soil Protection}}{\textbf{Product Expense + Cost of Potential Topsoil Loss}}$$

$$= \frac{\textbf{Value of Soil Protected (\$/100 ft}^2\textbf{)}}{\textbf{Product Cost (\$/100 ft}^2\textbf{) + Value of Net Soil Loss (\$/100 ft}^2\textbf{)}}$$

where, Value of Soil Protected =

$$\frac{(\text{Unit Soil Protected}_{\text{failure}}\text{ (F) + Unit Soil Protected}_{\text{product}}\text{ (P))}}{100} \cdot \text{APL threshold} \cdot \text{Topsoil price}$$

Product Cost = Product price from telephone survey

Value of soil loss = Unit Net Soil Loss (L) / 100 · APL threshold · Topsoil price

Cost-Performance Index for Channel Product

Unlike slope conditions, the estimate of channel product performance does not have to consider the change of vegetation performance because the HSECL conducts channel product tests in a vegetated condition. The channel tests start after vegetation grows on the test trays for 90 days. Figure 8 illustrates the soil protection/loss of a channel product with mid-level longevity (24 months) for a short-term construction project (12 month).

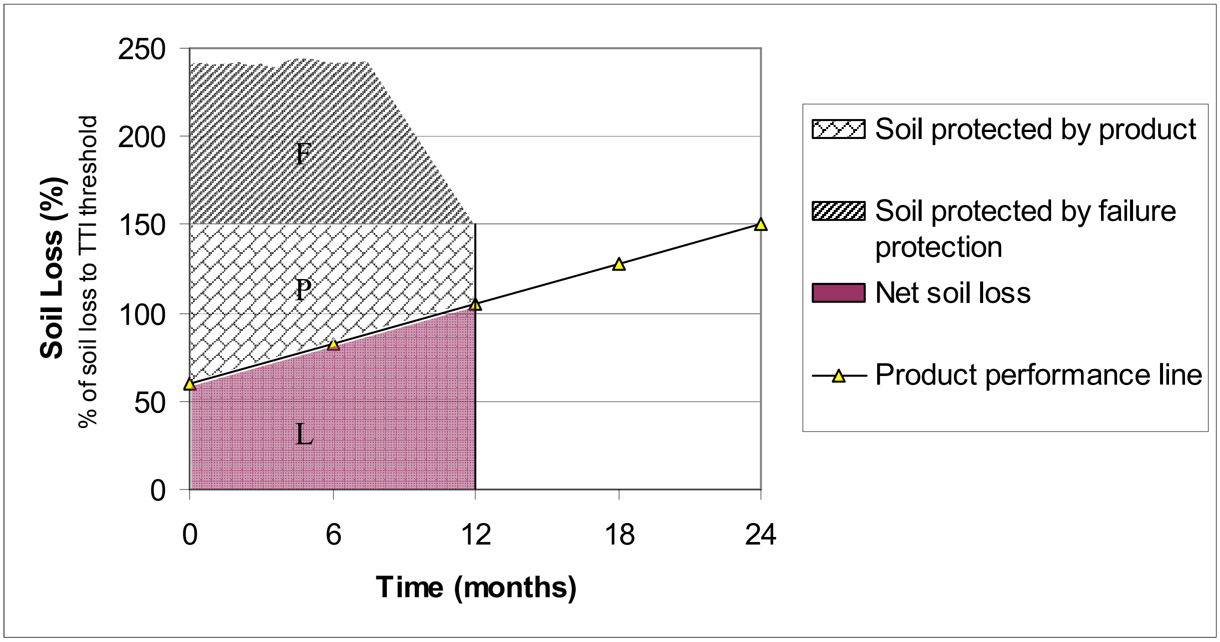


Figure 8: The Soil Loss Model of Products and Vegetation Combined In Channel

The product performance trend line can be simply expressed as:

'Soil Loss $_{product, time}$ = a · time + b', then:

Unit Net Soil Loss (L) = (b + a · time + b) / 2 = (a · time + 2b) / 2

Unit Product Protected $_{product}$ (P) = 150 · time – Unit Net Soil Loss (L)

where a = (Final Soil Loss $_{product}$ – Initial Soil Loss $_{product}$) / Product Longevity

b = Initial Soil Loss $_{product}$

time= Time designated to use the channel protection product (month)

In addition, the unit amount of soil protected by failure prevention can be calculated by:

Unit Soil Protected $_{failure}$ (F) = (Soil Loss $_{bare}$ – Final Soil Loss $_{product}$) * time / 2

where, Unit Soil Protected $_{failure}$ (F) = Unit soil amount protected by failure prevention

Soil Loss $_{bare}$ = Soil loss level of bare soil condition (% of soil loss to APL threshold)

Final Soil Loss $_{product}$ = Soil loss level when the product no longer protects the soil It is set as '150' (% of soil loss to APL threshold).

After translating the unit soil amounts explained above to monetary values, the cost-performance index for a channel product can be calculated by:

$$\textbf{CPI} = \frac{\textbf{Value of Soil Protected (\$/100 ft}^2\textbf{)}}{\textbf{Product cost (\$/100 ft}^2\textbf{) + Value of Soil Loss (\$/100 ft}^2\textbf{)}}$$

where Value of Soil Protected =

$$\frac{(\text{Unit Soil Protected}_{\text{failure}}\ (F) + \text{Unit Soil Protected}_{\text{product}}\ (P))}{100} \cdot \text{APL threshold} \cdot \text{Topsoil price}$$

Product Cost = Product price from telephone survey

Value of soil loss = Unit Net Soil Loss (L) / 100 · APL threshold · Topsoil price

RESULTS

DESCRIPTIVE ANALYSIS OF EROSION CONTROL PRODUCTS IN THE APL

This section analyzes price and existing soil loss data of the TxDOT APL. The price index and soil loss index represent price and soil loss, respectively. The soil loss index does not represent the soil loss amount over time. It only represents the *initial* soil loss immediately following product installation. The lifetime performance of erosion control products in the cost-performance analysis is presented in a later section of this report. Suggested APL after cost-performance analysis is included in Appendix A.

Slope Protection Products

Longevity plays a role in product price. Typically, the products that offer the longest protection cost more than those offering short or temporary protection. Synthetic products are the most expensive yet they offer long-term or permanent protection. In addition, products with biodegradable netting tend to sell for a higher price among products with the same longevity. This increase in price could be due to their environmental compatibility. Mulch products (TM) compose the lowest price group. Figure 9 demonstrates the averages and variances of price index by product type.

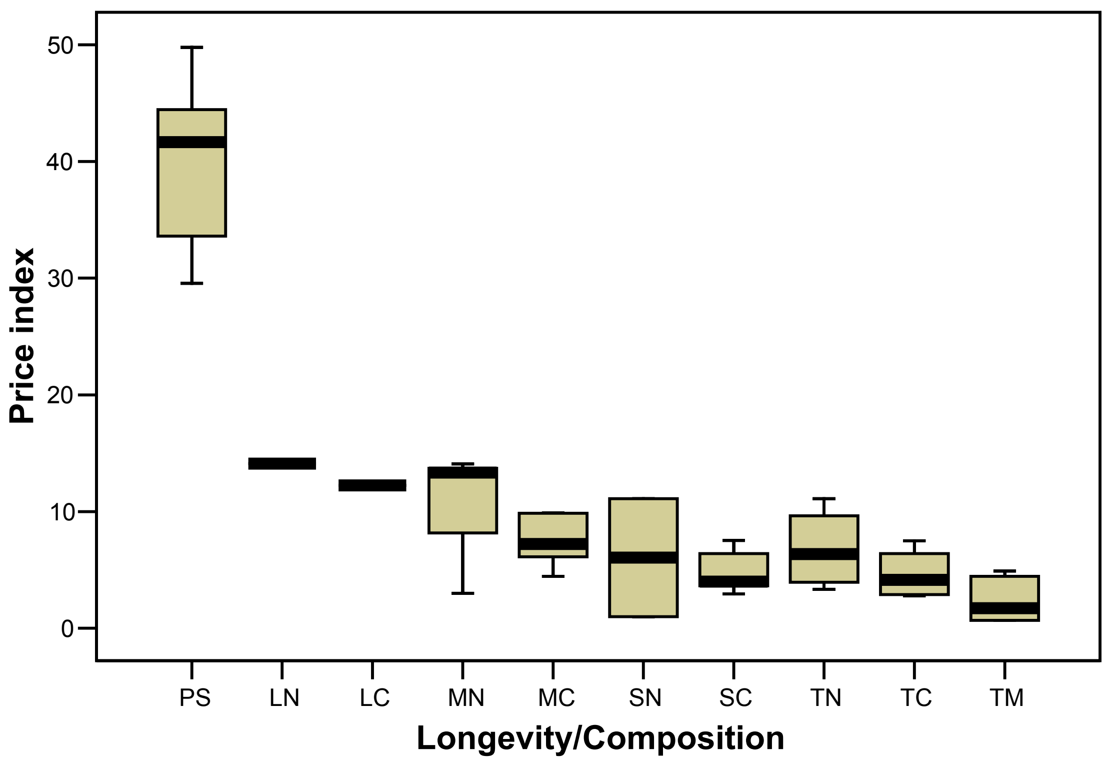


Figure 9: Price Index of Slope Protection Products (by product type).

Results also show that price does not always correlate to initial soil protection performance in slope erosion control. Figures 10 and 11 show that no obvious trend can be observed For example, blankets composed of natural products (i.e., MN and TN) do not perform on clay soils as well as composite products despite their higher price (higher soil loss index means lower performance). Environmental compatibility and soil protection performance are contradictive values in this case. Additionally, permanent synthetic products may not justify their higher price on clay soils because some permanent synthetic products did not pass the clay slope test at the HSECL. This failure may be caused by the fact that clay soils produce much less soil sediment than sandy soil surfaces or that some permanent synthetic products fail to protect clay soil which would indicate that end-users may not have to use the most expensive products for slope protection on clay soil. However, permanent synthetic products show very good performance on sandy soil slopes. Mulch products also perform well on sandy soil.

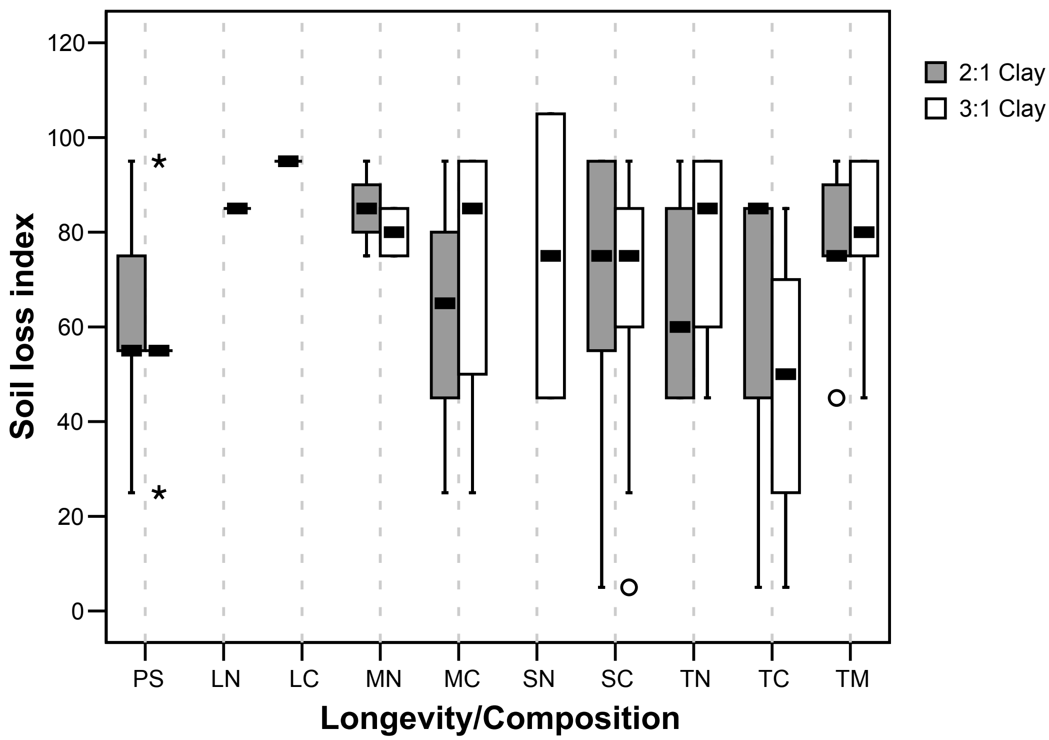


Figure 10: Soil Loss Index By Product Type In Clay Slope.

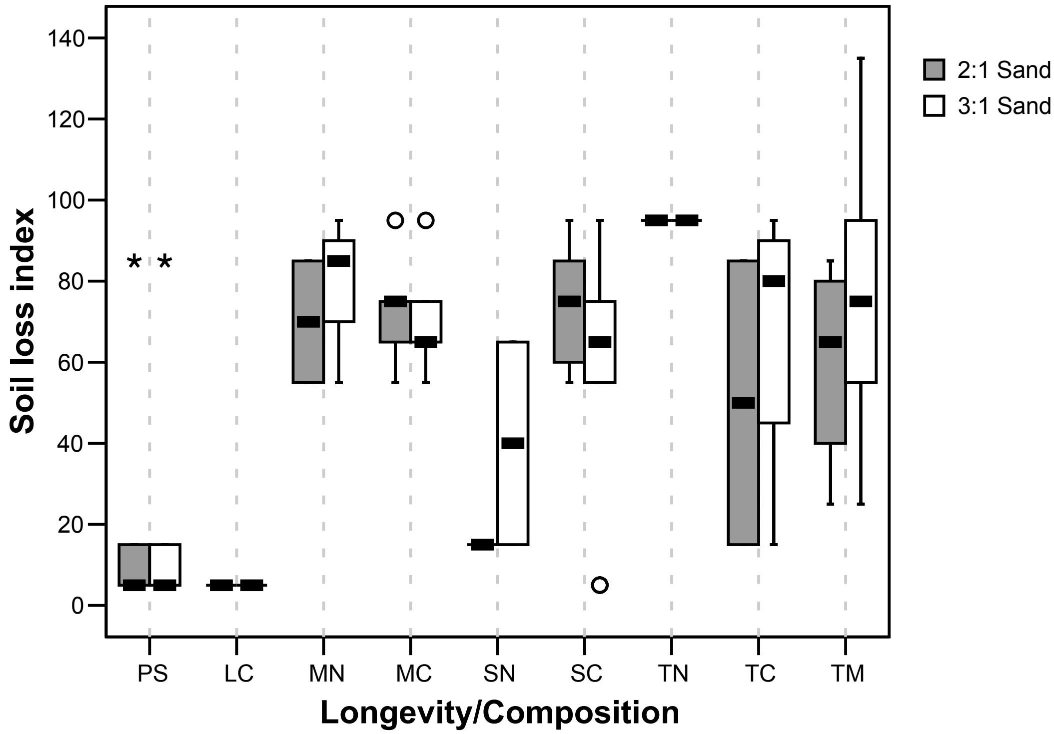


Figure 11: Soil Loss Index By Product Type In Sand Slope

Channel Protection Products

Channel protection products are required to be more durable and last longer than slope products since they must protect vegetation from concentrated channel flow rather than sheet flow. As mentioned earlier, prices are affected by longevity but research indicates there is a small difference in price especially between permanent products (i.e., PS: over 3 years) and long-term products (i.e., LN and LC: 2 to 3 years). The use of natural materials does not affect the price of channel protection products which indicates that performance is the primary factor (over environmental compatibility) for channel protection. Figure 12 shows the price trend by product type.

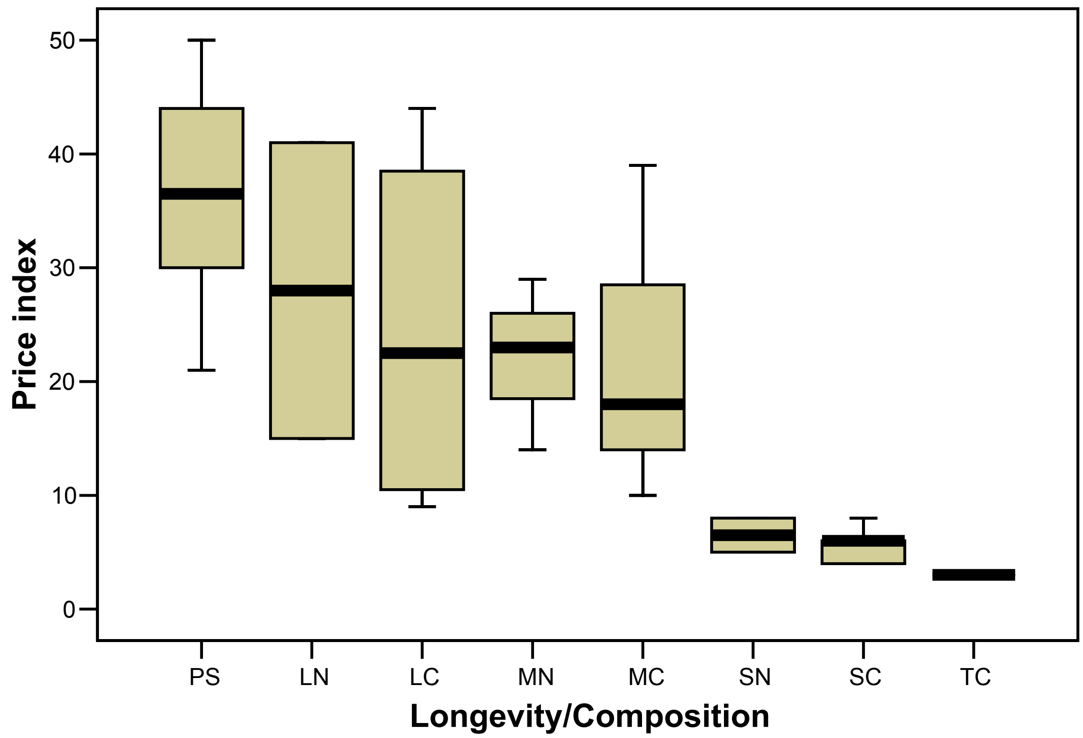


Figure 12: Price Index by Product Type, Channel APL.

It is difficult to compare the initial protection performance among product types for two reasons: the average performance is similar among product types, and the variances of performance within the same product groups are too large to generalize any tendencies. The research indicates that products with longer longevity continue to offer protection performance at higher shear stress (Figures 13 to 15). In temporary to mid-term product groups, only one product passed the test at the high shear stress condition (0 to 12 lb/ft^2), while, 25 products were approved at the low shear stress condition (0 to 2 lb/ft^2). In contrast, three of eleven long-term and permanent products withstood the highest shear stress.

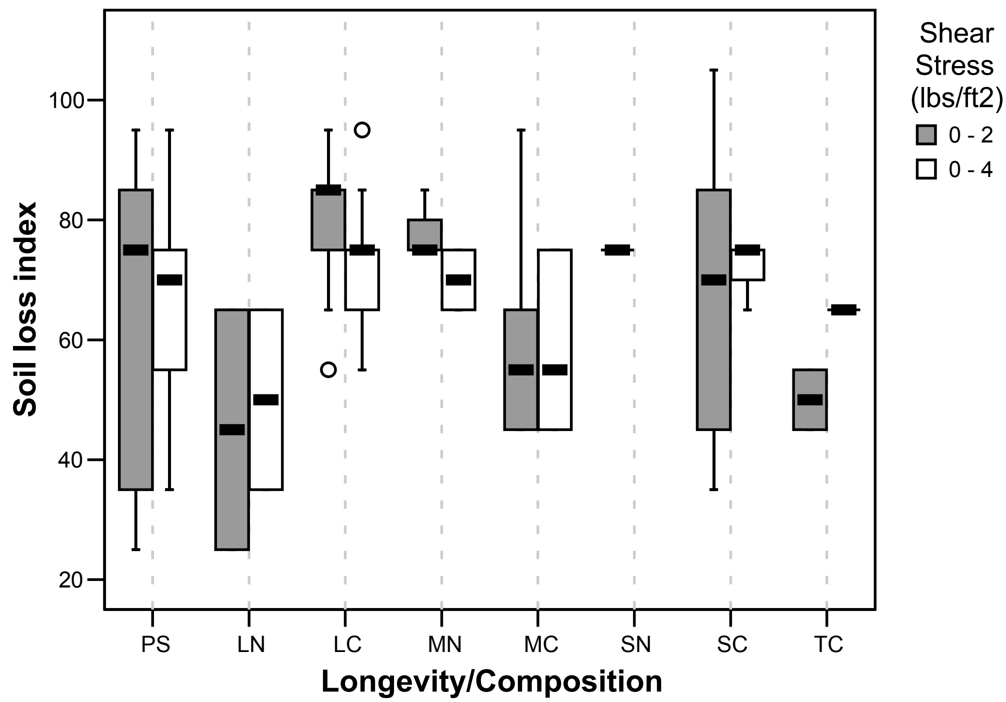


Figure 13: Soil Loss Index by Product Type @ Low Shear Stress.

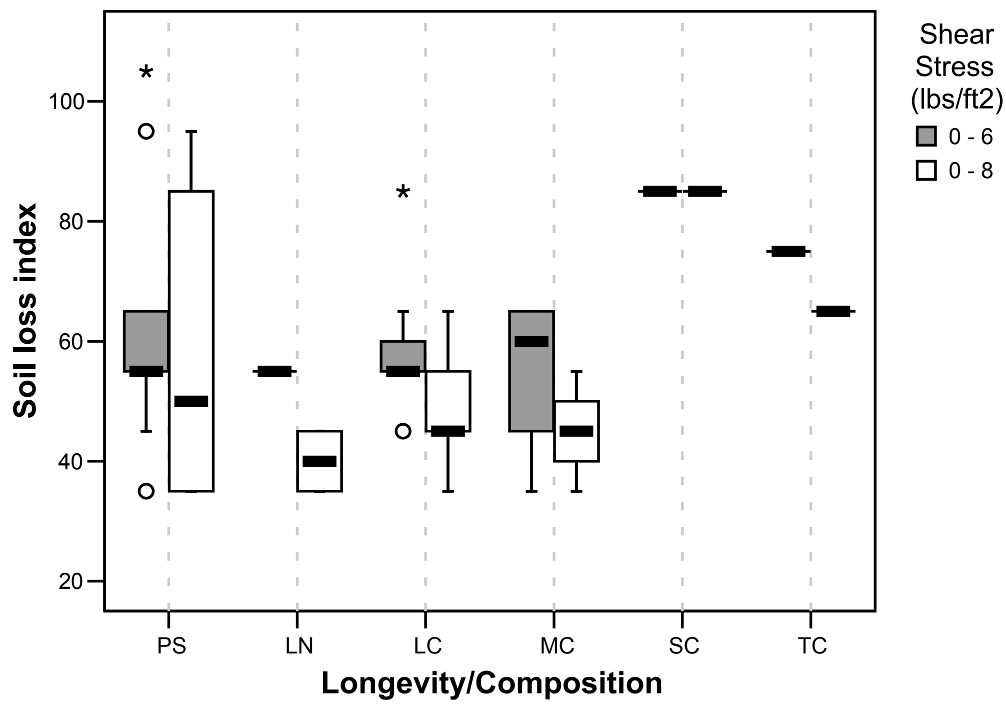


Figure 14: Soil Loss Index By Product Type @ Mid Shear Stress.

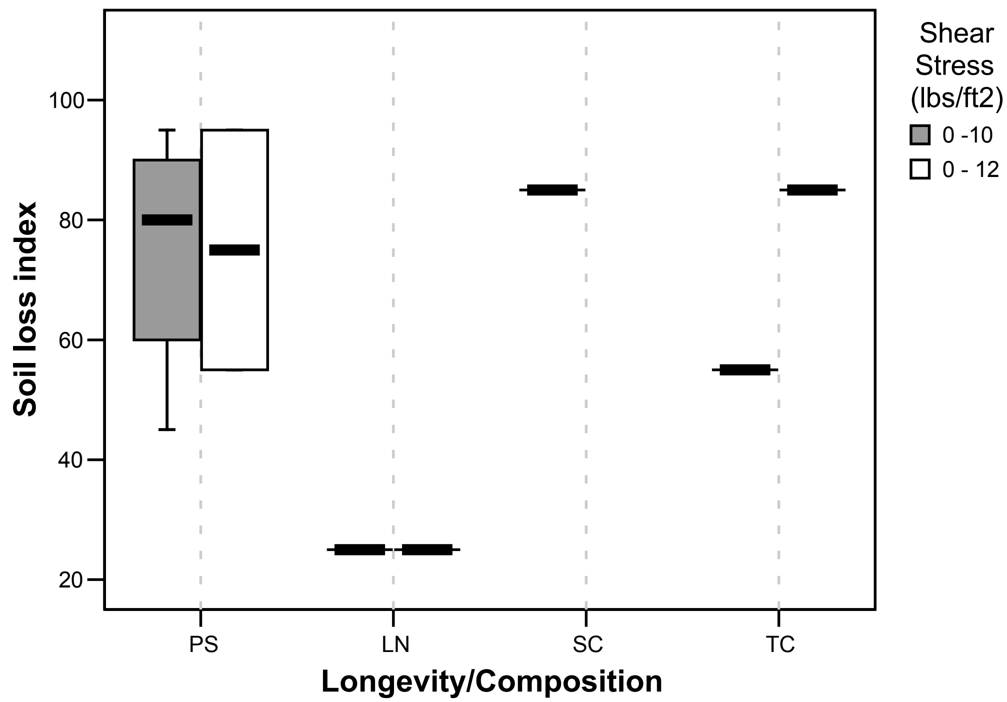


Figure 15: Soil Loss Index by Product Type @ High Shear Stress

COST-PERFORMANCE ANALYSIS

Lifetime Performance of Erosion Control Products

The descriptive analysis above indicates that it is difficult to estimate the performance of erosion control products only with soil loss test results. When selecting an erosion control product, we have three expectations: (1) soil loss will decrease by using the more durable product; (2) more durable products are more expensive; and (3) expensive products are expected to perform better than inexpensive products. The soil loss data did not satisfy expectations (1) and (3) although the durability and price are positively correlated. It may be because the soil loss data does not reflect the change of performance over time.

By applying the concept of product longevity to the soil loss data, this study calculated the lifetime product performance, which estimates the potential soil amount protected by the product over time. The lifetime performance shows a good correlation with price in both slope and channel products (Figures 16 and 17). It appears that current market prices well represent the product performance.

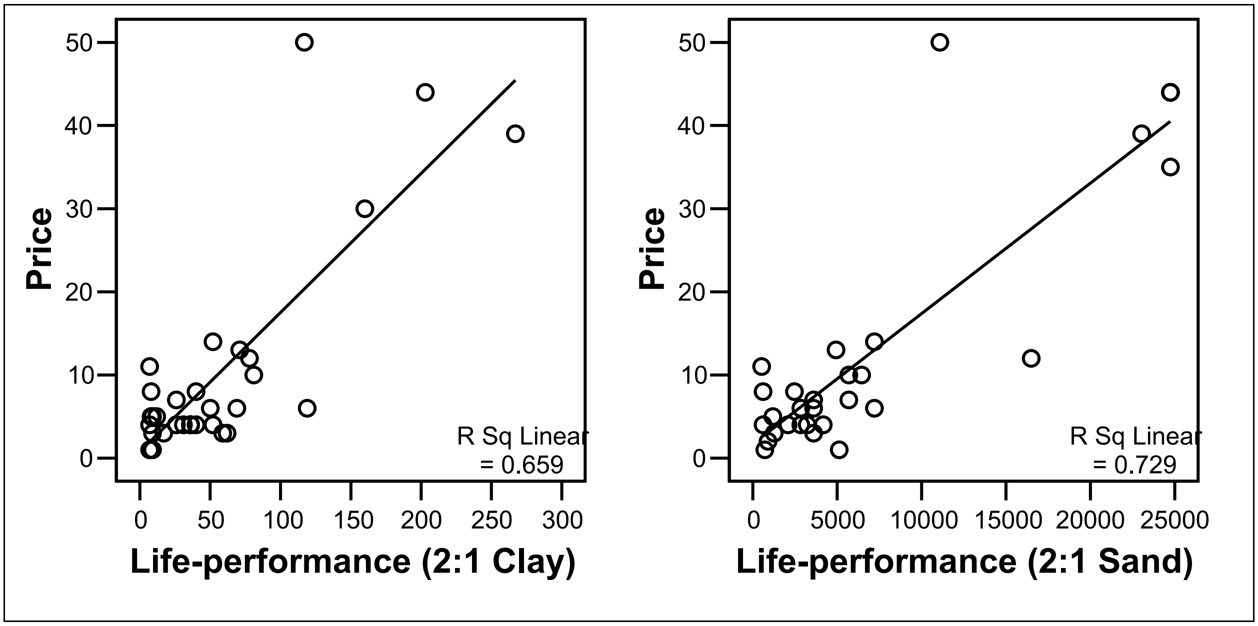


Figure 16: Correlation between Price and Life-Performance of Slope Protection Products.

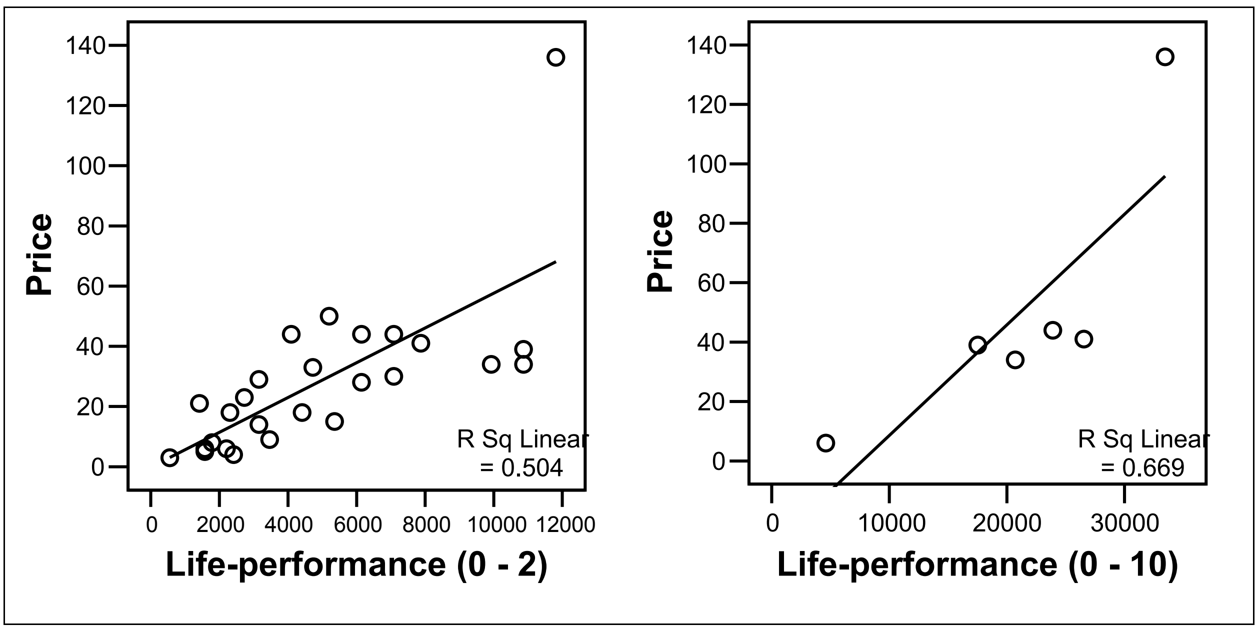


Figure 17: Correlation between Price and Life-Performance of Channel Protection Products.

Cost-Performance Index of Slope Protection Products

To identify appropriate products for designated conditions such as slope steepness, soil type, and the expected duration of vegetation establishment, this study calculated the cost-performance index considering many possible scenarios (i.e., temporary, short-term, mid-term, long-term, and permanent) by each slope and soil type. The researchers selected appropriate products for each scenario employing the following rules, which are listed in order of priority.

1. Every scenario should include at least one product.
2. An appropriate product should satisfy a minimum CPI level of 0.5.
3. Price should be reasonable. The acceptable price is set as the larger value of twice the mean price or minimum price of products listed in the adjacent, higher, longevity category. Table 15 shows the thresholds of acceptable price for slope protection products.

Table 15: Acceptable Price Threshold for Slope Protection Products.

Longevity	Mean Price ($/100 ft^2)	Acceptable Price Threshold ($/100 ft^2)
Permanent	40	No limit
Long	13	34
Mid	8	16
Short	5	10
Temporary	5	10

The overall results indicate that temporary products are better suited for temporary projects; likewise, long-term products are more useful for long-term projects.

Cost-Performance Index of Channel Protection Products

After calculating the CPI of channel protection products for every scenario, the selection of appropriate products is made according to the rules explained above. Table 16 shows the threshold of acceptable price for channel products.

Table 16: Acceptable Price Threshold for Channel Protection Products

Longevity	Mean Price ($/100 ft^2)	Acceptable Price Threshold ($/100 ft^2)
Permanent	37	No limit
Long	26	52
Mid	22	44
Short	6	18
Temporary	6	9

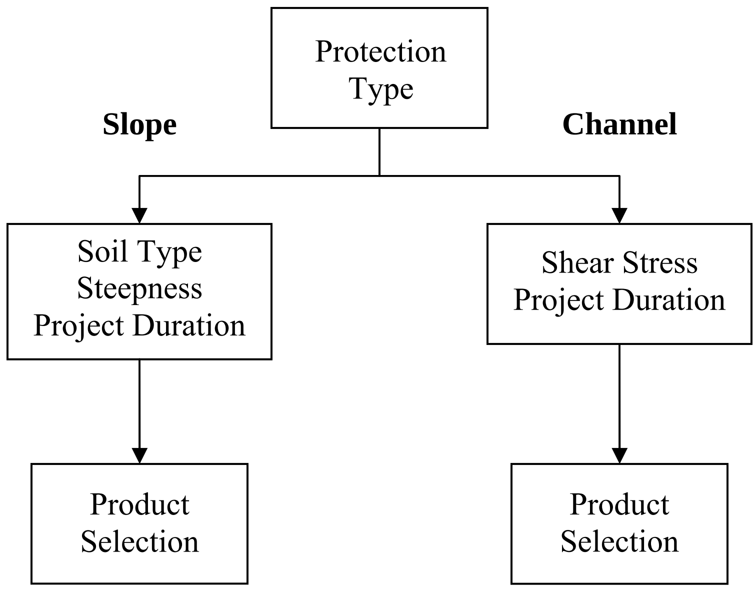
Affordable long-term channel products can be widely used for temporary to mid-term projects. Permanent products are frequently recommended for longer term projects.

USER'S GUIDE TO SUGGESTED APL

In order to use the suggested APL, site- or project-specific information is needed, including:

(1) Protection type – slope or channel
(2) Soil type – clay or sand
(3) Stress – steepness of slope or shear stress of flow in channel
(4) Anticipated project duration

The selection process of products follows the decision tree below. Each box lists the needed data for making a decision to move forward to the next step.



An example below is used to illustrate each slope and channel product selection process.

A 12-month highway expansion project includes a 3:1 slope that is adjacent to a drainage swale at the bottom of the slope. The swale has a depth of 12 inches and 5% longitudinal slope. The soil type is clay.

To protect the slope, products approved for 3:1 clay that will last 12-month should be selected. Hence, select any product from the "Short-term (12 months)" column of the "Clay 3:1" table.

To protect the channel, estimating shear stress is needed. The shear stress (τ) on an open channel can be calculated using $\tau = \gamma ds$, where γ is fluid specific gravity, d is the depth of the flow and s is the longitudinal slope of the channel. The shear stress of the drainage swale is calculated: $\tau = \gamma ds = 62.4 \text{ lb/ft}^3 \times 1\text{ft} \times 0.05 = 3.1 \text{ lb/ft}^2$. Therefore, select any product from the "Short-term (12 months)" column of the "Shear Stress: 0 ~ 4" table.

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APPENDIX A
Suggested Approved Products List after the Cost-Performance Analysis, Slope Protection Products

Suggested Approved Products List after Cost-Performance Analysis, Slope Protection Products

Clay 2:1

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
Anti-wash	Curlex I	Econo Jute	Greenstreak Pec-Mat	Greenstreak Pec-Mat
Curlex I	Econo Jute	Greenfix CFS072R	Xcel CC-4	Landlok TRM 435
Earth Bound	Greenfix CFS072R	Landlok BonTerra ENCS2		Miramat TM8
EcoAegis	Greenfix WS05	Landlok BonTerra S2		Xcel PP5-10
Econo Jute	Greenfix WSO72	NAG SC150		
EnviroGuard Plus	Landlok 407GT	Xcel CC-4		
Futerra	Landlok BonTerra S2	Xcel CS-3 All Natural		
Greenfix CFS072R	NAG S150			
Greenfix WS05	NAG S75			
Greenfix WSO72	NAG SC150			
Landlok 407GT	R-1 Regular			
Landlok BonTerra S2	Rhino Erosion King Double Net			
NAG S150	Xcel SS2 Superior			
NAG S75	Xcel Superior			
R-1 Regular				
Rhino Erosion King Double Net				
Rhino Erosion King Single Net				
Soil Guard				
SprayMatt				
SR-1				
SuperGro				
Xcel SS2 Superior				
Xcel Superior				

Suggested Approved Products List after Cost-Performance Analysis, Slope Protection Products (continued)

Clay 3:1

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
AEC Premier Straw	Curlex I	Bio-D-Mesh 60	Bio-D-Mesh 60	Greenstreak Pec-Mat
Anti-wash	Econo Jute	Econo Jute	Greenstreak Pec-Mat	Landlok TRM 435
Curlex I	Greenfix CFS072R	Greenfix CFS072R		Miramat TM8
Earth Bound	Greenfix WS05	Landlok BonTerra ENCS2		Xcel PP5-10
EcoAegis	Greenfix WSO72	Landlok BonTerra S2		
Econo Jute	Landlok 407GT	NAG SC150		
EnviroGuard Plus	Landlok BonTerra S1			
Greenfix CFS072R	Landlok BonTerra S2			
Greenfix WS05	NAG S150			
Greenfix WSO72	NAG S75			
Landlok 407GT	NAG SC150			
Landlok BonTerra S1	R-1 Regular			
Landlok BonTerra S2	Rhino Erosion King Double Net			
NAG S75	SNS1			
R-1 Regular	Xcel Regular			
Rhino Erosion King Double Net	Xcel SS2 Superior			
Rhino Erosion King Single Net	Xcel Superior			
SNS1				
Soil Guard				
SprayMatt				
SuperGro				
Xcel SS2 Superior				

Suggested Approved Products List after Cost-Performance Analysis, Slope Protection Products (continued)

Sand 2:1

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
Curlex I	Curlex I	Greenfix CFS072R	Xcel CC-4	Landlok TRM 435
EarthGuard Fiber Matrix	Geojute Plus 1	Landlok BonTerra CS2	Xcel PP5-8	Miramat TM8
EnviroGuard Plus	Greenfix CFS072R	Landlok BonTerra ENCS2		Xcel PP5-10
Futerra	Greenfix WS05	Landlok BonTerra S2		Xcel PP5-12
Geojute Plus 1	Greenfix WSO72	NAG SC150		Xcel PP5-8
Greenfix CFS072R	Landlok 407GT	Xcel CC-4		
Greenfix WS05	Landlok BonTerra CS2	Xcel CS-3 All Natural		
Greenfix WSO72	Landlok BonTerra S2	Xcel CS-3 Long Term		
Landlok 407GT	NAG S150			
Landlok BonTerra CS2	NAG SC150			
Landlok BonTerra S2	R-1 Regular			
NAG S150	Xcel CS-3 Long Term			
NAG SC150	Xcel SS2 Superior			
R-1 Regular	Xcel Superior			
Rhino Erosion King Single Net				
Soil Guard				
SuperGro				
Xcel CS-3 Long Term				
Xcel SS2 Superior				
Xcel Superior				

Suggested Approved Products List after Cost-Performance Analysis, Slope Protection Products (continued)

Sand 3:1

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
AEC Premier Straw	Geojute Plus 1	Econo Jute	Xcel CC-4	Landlok TRM 435
Curlex I	SNS1	Greenfix CFS072R	Xcel PP5-8	Miramat TM8
Earth Bound	Curlex I	Landlok BonTerra CS2		Xcel PP5-10
EarthGuard Fiber Matrix	Econo Jute	Landlok BonTerra ENCS2		Xcel PP5-12
Econo Jute	Greenfix CFS072R	Landlok BonTerra S2		Xcel PP5-8
EnviroGuard Plus	Greenfix WS05	NAG SC150		
Futerra	Greenfix WSO72	Xcel CC-4		
Geojute Plus 1	Landlok 407GT	Xcel CS-3 All Natural		
Greenfix CFS072R	Landlok BonTerra CS2	Xcel CS-3 Long Term		
Greenfix WS05	Landlok BonTerra S1			
Greenfix WSO72	Landlok BonTerra S2			
Landlok 407GT	NAG S150			
Landlok BonTerra CS2	NAG S75			
Landlok BonTerra S1	NAG SC150			
Landlok BonTerra S2	R-1 Regular			
NAG S150	Xcel CS-3 Long Term			
NAG S75	Xcel Regular			
NAG S75 BN	Xcel SS2 Superior			
NAG SC150	Xcel Superior			
R-1 Regular				
Rhino Erosion King Single Net				
SNS1				
Soil Guard				
Xcel CS-3 Long Term				
Xcel Regular				
Xcel SS2 Superior				
Xcel Superior				

APPENDIX B
Suggested Approved Products List After the Cost-Performance Analysis, Channel Protection Products

Suggested Approved Products List after Cost-Performance Analysis, Channel Protection Products

Shear stress: 0 ~ 2

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
Curlex II	Curlex Channel Enforcer 1	Curlex Channel Enforcer 1	Enkamat 7018	Greenstreak Pec-Mat
Landlok BonTerra S2	Curlex Channel Enforcer II	Greenstreak Pec-Mat	Greenstreak Pec-Mat	Landlok TRM 450
NAG S150	Curlex II	Koirmat 700	Koirmat 700	NAG C350 Three Phase
R-1 Regular	Landlok BonTerra C2	Landlok BonTerra C2	Landlok TRM 435	Pyramat
Rhino Erosion King Single Net	Landlok BonTerra S2	Landlok TRM 435	NAG C350 Three Phase	Xcel PP5-10
Xcel SS2 Superior	NAG S150	Pyramat	Pyramat	Xcel PP5-12
	R-1 Regular	Xcel CS-3 All Natural	StayTurf	Xcel PP5-8
	Xcel SS2 Superior	Xcel PP5-12	Xcel PP5-10	
			Xcel PP5-12	
			Xcel PP5-8	

Shear stress: 0 ~ 4

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
Landlok BonTerra C2	Curlex Channel Enforcer 1	Curlex Channel Enforcer 1	Enkamat 7018	Greenstreak Pec-Mat
NAG S150	Curlex Channel Enforcer II	Curlex Channel Enforcer II	Greenstreak Pec-Mat	Landlok TRM 435
R-1 Regular	Koirmat 700	Enkamat 7018	Koirmat 700	Landlok TRM 450
	Landlok BonTerra C2	Greenstreak Pec-Mat	Landlok BonTerra C2	Miramat TM8
	NAG S150	Koirmat 700	Landlok TRM 435	NAG C350 Three Phase
	R-1 Regular	Landlok BonTerra C2	Miramat TM8	Pyramat
		Landlok TRM 435	NAG C350 Three Phase	Xcel PP5-10
		NAG C125 BN	Pyramat	Xcel PP5-12
		NAG C350 Three Phase	StayTurf	Xcel PP5-8
		NAG SC150 BN	Xcel PP5-10	
		Pyramat	Xcel PP5-12	
		StayTurf	Xcel PP5-8	
		Xcel PP5-10		
		Xcel PP5-12		
		Xcel PP5-8		

Suggested Approved Products List after Cost-Performance Analysis, Channel Protection Products (continued)

Shear stress: 0 ~ 6

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
Landlok BonTerra C2 R-1 Regular	Curlex Channel Enforcer II Koirmat 700 Landlok BonTerra C2 R-1 Regular	Curlex Channel Enforcer II Enkamat 7018 Greenstreak Pec-Mat Koirmat 700 Landlok BonTerra C2 Landlok TRM 435 NAG C350 Three Phase Pyramat Xcel PP5-10 Xcel PP5-8	Enkamat 7018 Greenstreak Pec-Mat Koirmat 700 Landlok BonTerra C2 Landlok TRM 435 NAG C350 Three Phase Pyramat Xcel PP5-10 Xcel PP5-8	NAG C350 Three Phase Pyramat Greenstreak Pec-Mat Landlok TRM 435 Xcel PP5-10 Landlok TRM 450 Xcel PP5-8

Shear stress: 0 ~ 8

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
R-1 Regular	R-1 Regular	Pyramat	Landlok TRM 435 NAG C350 Three Phase Pyramat StayTurf Xcel PP5-10 Xcel PP5-12 Xcel PP5-8	Pyramat NAG C350 Three Phase Landlok TRM 435 Landlok TRM 450 Xcel PP5-10 Xcel PP5-8 Xcel PP5-12

Shear stress: 0 ~ 10

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
R-1 Regular	R-1 Regular	Xcel PP5-8	StayTurf Xcel PP5-10 Xcel PP5-12 Xcel PP5-8	Landlok TRM 450 Xcel PP5-12 Xcel PP5-8 Xcel PP5-10

Shear stress: 0 ~ 12

Temporary (3 months)	Short-term (12 months)	Mid-term (24 months)	Long-term (36 months)	Permanent (54 months)
StayTurf	StayTurf	StayTurf	StayTurf Xcel PP5-12	Landlok TRM 450 Xcel PP5-12

APPENDIX C
TxDOT APPROVED PRODUCT LIST
SEPTEMBER 2006

TxDOT/TTI Approved Product List (APL)

September 2006

CLASS 1 "SLOPE PROTECTION"

Type A - Slopes 1:3 or Flatter - Clay Soils:

- AEC Premier Straw
- Airtrol
- Anti-wash/Geojute
- BioD-Mesh 60
- Carthage Mills Veg Net
- C-Jute
- Contech Standard
- Contech Standard Plus
- Contech Straw/Coconut Fiber Mat w/Kraft Net
- Contech C-35
- Curlex 1
- Curlex™-LT
- Earth Bound
- EcoAegis™
- Econo-Jute
- ECS Excelsior Blanket Standard
- ECS High Velocity Straw Mat
- ECS Standard Straw
- EnviroGuard Plus
- Enviro-Matrix
- Enviro-Shield
- Formula 480 Liquid Clay
- Flexterra FGM
- Futerra
- Grass Mat
- Greenfix CFS072R
- Greenfix WS05
- Greenfix WSO72
- Landlok S2
- Landlok CS2
- Landlok 407
- Landlok TRM 435
- Miramat TM8
- Multimat 100
- North American Green S150
- North American Green S75
- North American Green S75 BN
- North American Green SC150
- North American Green S150 BN
- Maccaferri MX287
- Pennzsuppress®
- Poplar Erosion Blanket
- Rhino Erosion King Single Net
- Rhino Erosion King Double Net
- SEC-S2
- Soil Guard
- Soil Saver
- SprayMat
- Landlok SuperGro
- S 31 Single Net Straw ECB
- S 32 Double Net Straw ECB
- Terra-Control
- TerraJute
- Terra-Mulch
- Verdyol Ero-Mat
- Verdyol Excelsior High Velocity
- Verdyol Excelsior Standard

Green Solutions DNS2

GreenSolutions SNS1

GeoTech TechMat™ SCKN

Green Triangle Regular

Green Triangle Superior

Greenstreak Pec-Mat

Hydro Blanket

Landlok S1

Webtec Terraguard 44P

Excel R-1

Excel S-2

Excel CC-4

Excel CS-3 All Natural

Excel SS-2

Excel SR-1

Excel PP5-10

CLASS 1 "SLOPE PROTECTION" (continued)

Type B - 1:3 or Flatter - Sandy Soils:

- AEC Premier
- C-Jute
- Carthage Mills Veg Net
- Contech Standard
- Contech Standard Plus
- Contech Straw/Coconut Fiber Mat w/Kraft Net
- Contech C-35
- Curlex 1
- Curlex LT
- Earth Bound
- EarthGuard Fiber Matrix
- ECS Standard Straw
- ECS Excelsior Blanket Standard
- ECS High Velocity Straw Mat
- EnviroGuard Plus
- Flexterra FGM
- Futerra
- Greenfix CFS072R
- Greenfix WS05
- Greenfix WSO72
- GreenSolutions SNS1
- Geojute Plus 1
- GeoTech TechMat™ SCKN
- Green Triangle Regular
- Green Triangle Superior
- Landlok S1
- Landlok S2
- Landlok CS2
- Landlok 407
- Landlok TRM 435
- Maccaferri MX287
- Miramat 1000
- Miramat TM8
- Multimat 100
- North American Green S75
- North American Green S75 BN
- North American Green S150
- North American Green SC150
- North American Green® S150 BN
- Poplar Erosion Blanket
- Rhino Erosion King Single Net
- SEC-S2
- Soil Guard
- S 31 Single Net Straw ECB
- S 32 Double Net Straw ECB
- Terra-Control
- TerraJute
- Verdyol Ero-Mat
- Verdyol Excelsior Standard
- Webtec Terraguard 44P
- Excel R-1
- Excel S-2
- Excel CC-4
- Excel CS-3 All Natural
- Excel CS-3
- Excel SS-2
- Excel 5-8
- Excel PP5-10
- Excel PP5-12

CLASS 1 "SLOPE PROTECTION" (continued)

Type C - Slopes Steeper than 1:3 - Clay Soils:

- Airtrol
- Anti-Wash/Geojute
- Carthage Mills Veg Net
- C-Jute
- Contech Standard Plus
- Contech Straw/Coconut Fiber Mat w/Kraft Net
- Contech C-35
- Curlex 1
- Earth Bound
- Eco-Aegis
- Econo Jute
- ECS High Velocity Straw Mat
- ECS Standard Straw
- EnviroGuard Plus
- Formula 480 Liquid Clay
- Flexterra FGM
- Futerra
- Greenfix CFS072R
- Greenfix WS05
- Greenfix WSO72
- GreenSolutions DNS2
- Green Triangle Superior
- GeoTech TechMat™ SCKN
- Greenstreak Pec-Mat
- Hydro Blanket
- Landlok S2
- Landlok CS2
- Landlok 407
- Landlok TRM 435
- Maccaferri MX287
- Miramat TM8
- Multimat 100
- North American Green S150
- North American Green S75
- North American Green SC150
- North American Green® S150 BN
- Pennzsuppress®
- Poplar Erosion Blanket
- Rhino Erosion King Single Net
- Rhino Erosion King Double Net
- SEC-S2
- SprayMat
- Soil Guard
- Soil Saver
- Landlok SuperGro
- S 32 Double Net Straw ECB
- TerraJute
- Verdyol Excelsior High Velocity
- Webtec Terraguard 44P
- Excel S-2
- Excel CC-4
- Excel CS-3 All Natural
- Excel SS-2
- Excel SR-1
- Excel PP5-10

CLASS 1 “SLOPE PROTECTION” (continued)

Type D - Slopes Steeper than 1:3 - Sandy Soils:

C-Jute
Carghage Mills Veg Net
Contech Standard Plus
Contech Straw/Coconut Fiber Mat
w/Kraft Net
Contech C-35
Curlex 1
EarthGuard Fiber Matrix
ECS High Velocity Straw Mat
ECS Standard Straw
EnviroGuard Plus
Futerra
Greenfix CFS072R
Greenfix WS05
Greenfix WSO72
Geojute Plus 1
GeoTech TechMat™ SCKN
Green Triangle Superior
Landlok S2
Landlok CS2
Landlok 407
Landlok TRM 435
Maccaferri MX287
Miramat 1000
Miramat TM8
North American Green S150
North American Green SC150
North American Green S150
BN
Rhino Erosion King Single Net
SEC-S2
Soil Guard
S 32 Double Net Straw ECB
TerraJute
Webtec Terraguard 44P
Excel S-2
Excel CC-4
Excel CS-3 All Natural
Excel CS-3
Excel SS-2
Excel PP5-10
Excel PP5-12

CLASS 2 - "FLEXIBLE CHANNEL LINER"

Type E - Shear Stress Range 0 - 96 Pascal (0 - 2 Pounds Square Foot):

Contech TRM C-45
Contech C-35
Contech C50
Contech Coconut/Poly Fiber Mat
Contech Coconut Mat w/Kraft Net
Curlex II Stitched
Curlex III Stitched
Curlex Channel Enforcer 1
Curlex Channel Enforcer II
Earth-Lock
Earth-Lock II
ECS High Impact Excelsior
ECS Standard Excelsior
ECS High Velocity Straw Mat
Enkamat 7018
Enkamat 7020
Enkamat Composite 30
Enkamat Composite NPK**
Enviromat
Geotech TechMat™ CP 3-D
Geotech TechMat™ CKN
Greenfix CFG 2000
Greenstreak Pec-Mat
Koirmat™ 700
Landlok C2
Landlok CS2
Landlok S2
Landlok TRM 435
Landlok TRM 450
Landlok TRM 1051
Maccaferri MX287
Miramat TM8
Multimat 100
North American Green C125 BN
North American Green C350 Three Phase
North American Green SC150 BN
North American Green S350
North American Green P350
North American Green S150
Pyramat
Recyclex TRM
Rhino Erosion King Single Net
Rhino Erosion King Double Net
StayTurf
SureTurf ST 1000
Webtec Terraguard 44P
Webtec Terraguard 45P
Excel CC-4
Excel CS-3
Excel CS-3 All Natural
Excel PP5-8
Excel PP5-10
Excel PP5-12
Excel R-1
Excel SD-3
Excel SS-2

CLASS 2 - “FLEXIBLE CHANNEL LINER” (continued)

Type F - Shear Stress Range 0 - 192 Pascal (0 - 4 Pounds Per Square Foot):

- Curlex II Stitched
- Curlex III Stitched
- Curlex Channel Enforcer 1
- Curlex Channel Enforcer II
- Contech C50
- Contech TRM C-45
- Contech C-35
- Contech Coconut/Poly Fiber Mat
- Contech Coconut Mat w/Kraft Net
- Earth-Lock
- Earth-Lock II
- ECS High Impact Excelsior
- ECS High Velocity Straw Mat
- ECS Standard Excelsior
- Enkamat 7018
- Enkamat Composite 30
- Enviromat
- Geotech TechMat™ CP 3-D
- Geotech TechMat™ CKN
- Greenfix CFG 2000
- Greenfix CFO 72RR
- Greenstreak Pec-Mat
- Koirmat™ 700
- Landlok® C2
- Landlok® CS2
- Landlok® TRM 435
- Landlok TRM 450
- Landlok TRM 1051
- Landlok S2
- Maccaferri MX287
- Miramat TM8
- Multimat 100
- North American Green C125 BN
- North American Green C350 Three Phase
- North American Green SC150 BN
- North American Green S350
- North American Green P350
- North American Green S150
- Pyramat
- Recyclex TRM
- Rhino Erosion King Double Net
- SS Superior Straw
- StayTurf
- SureTurf ST 1000
- Webtec Terraguard 44P
- Webtec Terraguard 45P
- Excel CC-4
- Excel PP5-8
- Excel PP5-10
- Excel PP5-12
- Excel SD-3
- Excel R-1

CLASS 2 - "FLEXIBLE CHANNEL LINER" (continued)

Type G - Shear Stress Range 0 - 287 Pascal (0 - 6 Pounds Square Foot):

Contech TRM C-45
Contech C-35
Contech C50
Contech Coconut/Poly Fiber Mat
Curlex Channel Enforcer II
Earth-Lock
Earth-Lock II
Enkamat 7018
Enkamat Composite 30
Geotech TechMat™ CP 3-D
Greenfix CFG 2000
Greenstreak Pec-Mat
Koirmat™ 700
Landlok BonTerra® CP2
Landlok TRM 1051
Landlok TRM 1060
Landlok TRM 435
Landlok TRM 450
Multimat 100
North American Green C350 Three
Phase
North American Green S350
North American Green® P350
Pyramat
Recyclex TRM
StayTurf
SureTurf ST 1000
Webtec Terraguard 44P
Webtec Terraguard 45P
Excel PP5-8
Excel PP5-10
Excel PP5-12

CLASS 2 - "FLEXIBLE CHANNEL LINER" (continued)

Type H - Shear Stress Range 0 - 383 Pascal (0 - 8 Pounds Square Foot):

Contech TRM C-45
Contech C-35
Contech C50
Contech Coconut/Poly Fiber Mat
Geotech TechMat™ CP 3-D
Landlok TRM 435
Landlok TRM 450
Landlok TRM 1051
Multimat 100
North American Green C350 Three
Phase
North American Green S350
North American Green P350
Pyramat
Recyclex TRM
StayTurf
SureTurf ST 1000
Webtec Terraguard 44P
Webtec Terraguard 45P
Excel PP5-8
Excel PP5-10
Excel PP5-12

CLASS 2 - "FLEXIBLE CHANNEL LINER" (continued)

Type I - Shear Stress Range 0 - 479 Pascal (0 - 10 Pounds Square Foot):

Landlok TRM 450

StayTurf

SureTurf ST 1000

Recyclex TRM

Excel PP5-8

Excel PP5-10

Excel PP5-12

CLASS 2 - "FLEXIBLE CHANNEL LINER"

Type J - Shear Stress Range 0 - 575 Pascal

(0 -12 Pounds Square Foot):

Landlok TRM 450

Recyclex TRM

StayTurf

SureTurf ST 1000

Excel PP5-12

MULCHES 4:1 OR FLATTER SLOPES

Clay or Tight Soils:

- Agri-Fiber
- American Fiber Mulch
- American Fiber Mulch(Hydro-Stick)
- Conweb Hydro Mulch
- Enviro-Gro Fiber Mulch
- Evercycle Hydro-Mulch
- Fiber Mulch
- Excel Fibermulch II
- GeoSkin Cotton Hydro Mulch
- Hydro-Lok
- Hydro Straw
- Lay-Low Mulch
- Lonestar Hydro-Grass
- Oasis Fiber Mulch
- Pennzsuppress
- Pro Mat
- Pro Mat (with RMBplus)
- Pro Mat X
- Second Nature Regenerated Wood
- Second Nature Wood Fiber Blend
- Second Nature Recycled Paper Fiber
- Second Nature Recycled Straw Tack
- Silva Fiber Plus

Sandy or Loose Soils:

- American Fiber Mulch
- American Fiber Mulch (with Hydro-Stick)
- American Fiber Mulch with Stick Plus
- Conwed Hydro Mulch
- Enviro-Gro
- Evercycle™ Hydro-Mulch
- Excel Fibermulch II
- GeoSkin Cotton Hydro Mulch
- Hydro-Lok
- Hydro Straw
- Lay-Low Mulch
- Lonestar Hydro-Grass
- Oasis Fiber Mulch
- Pennzsuppress
- Pro Mat
- Pro Mat (with RMB Plus)
- Pro Mat X
- Pro Mat XL
- Second Nature Regenerated Wood Fiber Mulch
- Second Nature Wood Fiber Blend
- Second Nature Recycled Paper Fiber
- Second Nature Recycled Straw Tack