GEORGIA DOT RESEARCH PROJECT 11-22

FINAL REPORT

Categorization of Erosion Control Matting for Slope Applications

OFFICE OF DESIGN POLICY AND SUPPORT

OFFICE OF RESEARCH

RESEARCH & DEVELOPMENT BRANCH

1.Report No.: FHWA-GA-16-11-22	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Categorization Of Erosion Control Matting For Slope Applications	5. Report Date: December 2013 6. Performing Organization Code:	
7. Author(s): Susan E. Burns, Hyunwook Choo, Jong Muk Won	8. Performing Organ. Report No.: RP 11-22; T.O. 02-101	
9. Performing Organization Name and Address: School of Civil & Environmental Engineering Georgia Institute of Technology 790 Atlantic Dr. Atlanta, GA 30332-0355	10. Work Unit No.: 11. Contract or Grant No.: RP 11-22; PI# 0010764	
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Research 15 Kennedy Drive Forest Park, GA 30297-2534	13. Type of Report and Period Covered: Final; 14. Sponsoring Agency Code:	
15. Supplementary Notes:		

16. Abstract: Erosion control is an important aspect of any Georgia Department of Transportation (GDOT) construction project, with the extreme negative impacts of high sediment loads in natural waterways having been well documented. Selection of a proper erosion control mat for protection of slopes on GDOT rights-of-way should be made with primary emphasis on the steepness of slope, which will govern the hydraulic stress to which the soil and vegetation are subject. Additional considerations to selection of erosion control matting include time to establish vegetation: are growing conditions, followed by selection of a product made out of synthetic or natural fibers. GDOT has 79 approved products, produced by 19 manufacturers listed in QPL-62 dated May 29, 2015. Due to the high number of products which a designer can specify, a spreadsheet-based selection tool was developed to specify which QPL listed erosion control products are appropriate for given conditions. A laboratory-based investigation of the erodibility of coarse-grained soils was performed. The evidence shows that mean particle size is the primary variable in determining the raindrop splash displacement of sands. The effect of particle shape and void ratio on raindrop splash was minimal.

17. Key Words: Erodibility, matting, turf reinforcement		18. Distribution Statement:	
19. Security Classification (of this report): Unclassified	20. Security Classification (of this page): Unclassified	21. Number of Pages: 53	22. Price:

Form DOT 1700.7 (8-69)

GDOT Research Project No. 11-22

Final Report

CATEGORIZATION OF EROSION CONTROL MATTING FOR SLOPE APPLICATIONS

By

Susan E. Burns, Ph.D., P.E.

Professor

Hyunwook Choo

and

Jong Muk Won

Graduate Research Assistants

Georgia Institute of Technology

Contract with

Georgia Department of Transportation

In cooperation with

U.S. Department of Transportation

Federal Highway Administration

July, 2015

The contents of this report reflect the views of the author(s) who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Georgia Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Table of Contents

List of Tables

List of Figures

Executive Summary

Erosion control is an important aspect of any Georgia Department of Transportation (GDOT) construction project, with the extreme negative impacts of high sediment loads in natural waterways having been well documented. A variety of erosion control products are available to reduce the transport of solids to receiving streams. For example, geotextiles made from natural or synthetic fibers, concrete, seed and sod, wood mulch, and soil binders are frequently used for erosion control. Currently the Department has only one category of slope matting material. Within this one category, all slope-matting materials are presumed to perform equally well, and this presumption may cause a contractor to select a slope mat material that may be inappropriate for the intended application. Misapplication can result in inadequate grass growth, excessive soil erosion, and exposure to violations of the NPDES permits. The focus of this investigation was examining the factors that distinguish different materials used in slope protection in order to categorize the materials for guidance in applications.

The work performed in this research project includes a literature review of current practices in erosion control on slopes and erodibility of coarse-grained soil particles. Selection of a proper erosion control mat for protection of slopes on GDOT rights-of-way should be made with primary emphasis on the steepness of slope, which will govern the hydraulic stress to which the soil and vegetation are subject. Additional considerations to selection of erosion control matting include time to establish vegetation: are growing conditions excellent (< 12 months to vegetation), good (1-2 years to vegetation), fair (1-3 years to vegetation), or poor (>3 years to vegetation). Finally, erosion control material is also important, with selection of a product made out of synthetic or natural fibers. The

RECP can be UV degradable, with a short field life (~1 year) or UV stabilized (long-term applications). GDOT has 79 approved products, produced by 19 manufacturers listed in QPL-62 dated May 29, 2015. Due to the high number of products which a designer can specify, a spreadsheet-based selection tool was developed to specify which QPL listed erosion control products are appropriate for given conditions.

A laboratory-based investigation of the erodibility of coarse grained soils was performed. The behavior of coarse grained soils under the erosive forces of raindrop impact is primarily a function of raindrop size, drop velocity, porosity, sand particle size, and particle shape. Consequently, five different sand particles were studied in a laboratory-scaled experimental investigation to quantify the influence of drop characteristics and soil particle characteristics on the detachment and transport of soil particles. The evidence shows that mean particle size is the primary variable in determining the raindrop splash displacement of sands. An increase in sand particle size resulted in an increase in the force resisting raindrop splash and a decrease in splash driving force. The effect of particle shape and void ratio on raindrop splash was minimal. Experimental results demonstrated that the threshold value between splash displacement and no displacement due to splash was observed at approximately 1 mm.

Acknowledgements

The author is pleased to acknowledge the contributions of Dr. Hyunwook Choo, and Mr. Jong Muk Won, who worked as graduate research assistants on this project. In addition, thanks to Mr. Jon D. Griffith, P.G., P.E., for his continued dedication and significant contributions in the formulation of this project and throughout the course of this work.

Part I: Erosion Control on Slopes

Introduction

Erosion control is an important aspect of any Georgia Department of Transportation (GDOT) construction project, with the extreme negative impacts of high sediment loads in natural waterways having been well documented. A variety of erosion control products are available to reduce the transport of solids to receiving streams. For example, geotextiles made from natural or synthetic fibers, concrete, seed and sod, wood mulch, and soil binders are frequently used for erosion control. Currently the GDOT has only one category of slope matting material. Within this one category, all slope matting materials are presumed to perform equally well, and this presumption may cause a contractor to select a slope mat material that may be inappropriate for the intended application. Misapplication can result in inadequate grass growth, excessive soil erosion, and exposure to violations of the NPDES permits. The focus of this investigation was examining the factors that distinguish different materials used in slope protection in order to categorize the materials for guidance in applications.

A past research project at GDOT was focused on researching the behavior, classification, and performance of rolled erosion control products (RECPs) used in permanent or semi-permanent applications for erosion control in channels. The types of channel protection studied includes turf reinforcement mat (TRM), riprap, and concrete linings (Burns, 2011). This project is a follow-up to the channel-lining investigation and was focused on erosion control measures applied to slopes, including application of short-term erosion control products in slope applications.

Background and Literature Review

The erosion control industry is highly competitive, with a wide variety of products frequently entering, and leaving the market, which leads to some discrepancies in terminology. For the purposes of this work, the following terminology will be used, as defined by the Erosion Control Technology Council (www.ectc.org):

1) **Rolled Erosion Control Products (RECPs)**: Temporary degradable or long-term non-degradable material manufactured or fabricated into rolls designed to reduce soil erosion and assist in the growth, establishment and protection of vegetation.
2) **Erosion Control Net (ECNs)**: Flat woven natural fiber or synthetic mesh used either as a component in RECPs or as a temporary RECP to anchor loose fiber mulches.
3) **Erosion Control Blankets (ECBs)**: Temporary degradable RECPs with matrices composed of processed natural or polymer fibers bound together.
4) **Turf Reinforcement Mats (TRMs)**: Long-term nondegradable synthetic RECP with 3-dimensional matrices designed for applications where discharges exceed the shear strength of natural vegetation.

Erosion control is an area of intense research with significant summary work on erosion control technologies being conducted in Iowa (Stevens, 2006) and Texas (McFalls, 2006). Work on RECPs has been focused on natural and geosynthetic matting, most commonly in combined performance with seed and sod (e.g., Rickson, 2006; Gyasi-Agyei, 2004). Active research is focused on the use of erosion control products and compost to achieve rapid growth of vegetation to facilitate the stabilization of steep slopes and reduce earthwork (e.g., Montana Department of Transportation, 2008; Nebraska Department of Roads, 2006).

In contrast to TRMs, the erosion control products installed on slopes are often short-term applications, intended to provide protection only until vegetation is established. The primary consideration in choice of a TRM is the shear stress observed at the soil/water interface within the channel, while slope protection relies much more heavily on the soil type, as well as on the steepness of the slope. Relevant factors to consider in the erosion potential for any soil include the impact of rainfall, with either a direct or deflected strike on the soil surface, where the important considerations include the relative rain drop size versus particle size and depth of overland flow. Additionally, the impact of overland flow in the form of surface water are also important considerations, and will have a different impact if the soil is saturated or unsaturated. Relevant factors include infiltration/hydraulic conductivity, interparticle forces, and flow velocity.

The establishment of vegetation or grass cover is known to be the most efficient way to reduce the erosion of soil in tilled or bare land (Gyasi-Agyei 2004; Morgan and Rickson 2004; Pimentel and Kounang 1998). The advantages of vegetative cover include the reduction of raindrop splash displacement of soil particles, slowed rates of water runoff, and filtration of sediment during transport. Unfortunately, construction processes typically include the removal of vegetative cover and the alteration of slope, as well as the removal of top soil, all of which will result in a significant increase in the erosion potential of soils on a slope. Previous studies have cited erosion rates at construction areas ranging from 20 to 500 ton of soil/ha/yr, which can result in deterioration of aquatic ecosystems, oxidation of biomass carbon from the soil, and landslide in the most extreme cases (Phillips et al. 1993; Pimentel and Kounang 1998).

Geosynthetic materials can be used as cover on bare soil to decrease the erosion rate of soils in construction areas and to allow time for the establishment of grass cover or other vegetation. Generally, geotextiles for erosion control can be separated into natural and synthetic materials based on their composition, and can be divided into three categories based on their shape: 3-dimensional erosion meshes, erosion blanket (or mat), and honeycomb-shaped webs. Erosion control blankets are considered the most cost-effective temporary material (Theisen 1992), and are commonly implemented as biodegradable blankets to minimize erosion of soils on slopes until permanent vegetation can be established (Gyasi-Agyei 2004; Rickson 2006). In contrast, non-degradable synthetic mats (or blankets), such as turf reinforcement mats, can act as a permanent composite structure of mat and vegetation allowing a mutually reinforcing, additional resistance against erosion (GMA 2002; Morgan and Rickson 2004; Theisen 1992). Carroll et al. (1991) reported that this synergistic method can provide twice the erosion resistance when compared to methods with vegetation only. Consequently, synthetic geosynthetic materials are used for applications where the required erosion resistance is very high, while degradable erosion blankets are more suitable for the cases of moderate to low erosion resistance.

Many previous studies have compared the erosion control performance of bare soils to soils that are covered with a RECP only, without any established vegetation; consequently, the boundaries indicating high, moderate, and low resistances are quantitatively unclear. This leads to difficulties in the selection of proper methods: the required level of erosion protection will be a function of many variables, such as soil type, slope angle, and climate. As a result, the selection of materials has been relatively subjective. Generally, the application of a turf reinforcement mat provides the most resistance to erosion, and will be the conservative method for ensuring the minimization of the adverse effects of erosion. However, TRMs are approximately ten times more expensive than natural products (Ingold 1996; Rickson 2006), and many applications cannot justify their use due to the increased cost of construction. In contrast, the selection of a natural material erosion blanket will lower the construction cost; however, this method cannot guarantee performance at extreme conditions (i.e., shear stress induced by water flow which is greater than the strength of vegetation). In addition, the most important factor determining the performance of erosion control materials is the development of good contact between the blanket (or mat) and the soil (Morgan and Rickson 2004). It is important to note that there are a number of different types of soils and RECPs, which means that coupling (or contact) between the RECP and the soil will vary with the conditions of application.

In addition to the use of RECPs for erosion control, other hydraulic erosion control products, known as hydromulching or hydroseeding, are frequently used. The hydroseeding method involves spraying a slurry containing seed, fertilizer, agricultural lime, wood fiber (or paper fiber or mulch), tackifier, and green pigment onto the slope to establish the vegetation (Faucette et al. 2006; GASWCC 2000; Morgan and Rickson 2004). The hydroseed method is a mature technology, and is a listed practice in the *Manual for Erosion and Sediment Control in Georgia* (GASWCC, 2000). Additionally, GDOT also has a specification for hydroseeding in their grassing specification (GDOT

Standard Specification Section 700 Grassing); however, there is no specific description in terms of application of the method in slope erosion control (Section 218). The hydroseed method may not be applicable in all cases because the loss of seed during installation is high (more than 60%); however, the application method is relatively easy, and the estimated cost is less expensive than the installation of RECPs; consequently, it is one of the most common erosion control methods applied on engineered slopes (Morgan 2005; Morgan and Rickson 2004). There have been several studies on the performance of the hydroseed method; however, as was the case for RECPs, these previous studies simply compared the results of modified soils with those of unmodified soils, and did not provide any specified guidelines for the proper selection of this method in a variety of operational conditions.

Study Objectives

The eight research tasks within this study are the following:

1) Review of literature on current erosion control measures used by state DOTs for slope stabilization
2) Examination of the specifications currently used for selection of slope protection materials, and development of updated specifications, if necessary, including resistance to hydraulic loading (peak flow, duration of flow, length of preceding dry days, etc.)
3) Development of a calculator that categorizes the optimum level of erosion protection needed for a given slope configuration
4) Development of guidelines for quantitative comparison and evaluation of RECP material properties and durability, including performance aspects like resistance

to shear, interaction with a variety of Georgia soil types, stability when exposed to UV light

5) Evaluation of RECP test methods using ASTM test methods to quantitatively compare performance; these tests allow standard categorization of a wide variety of RECPs (lab based). Preference will be given to methods that can be performed by commercial labs.
6) Revision of GDOT Standard Specification Section 218, Blanket for Fill Slopes, as a special provision to be incorporated into the GDOT Standard Specifications.
7) Development of an erosion index for Georgia soils that is fundamentally based, reflects geochemical effects in addition to gravitational (particle size) effects, but that is still easily implemented on a field scale; continued work from TRM investigation.
8) Development of an implementation plan to describe how erosion control technologies can best be applied in construction applications.

The eight research tasks were sorted into the following comprehensive categories:

(1) Perform background and literature review (Research Task 1)

(2) Review of Specifications and Test Methods Governing Erosion Control. This category will evaluate tests that will allow categorization of ECBs by level of required erosion protection, longevity with respect to UV radiation, length of time required for establishment of vegetation, and erosion control material properties. (Research Task 2, 4, and 5).

(3) Revision of GDOT Standard Specification Section 218, Blanket for Fill Slopes. This task was completed by GDOT staff, and is not detailed in this report. (Research Task 6).

(4) Development of a selection tool to specify which QPL listed erosion control products are appropriate for given conditions. (Research Task 3 and 8).

(5) Test the erodibility of soils in a laboratory environment to better understand the detachment and transport mechanisms that are important in the movement of soil particles in the field. (Research Task 7).

Part I of this report covers the first four tasks listed above, while Part II of the report details the experimental investigation into erosion of sands. These laboratory experiments were performed with a specially designed rainfall simulator, used for the performance of controlled tests. Tests were performed in three major categories:

(1) Tests on soil particle detachment (to test the effect of raindrop splash), which is known as the most critical factor in soil detachment (Morgan 2005).

(2) Tests on sediment transport (to test the effect of runoff velocity and runoff depth), which is known as the most critical factor determining the amount of sediment transport (Morgan 2005). Runoff depth may also have some minor effect on sediment transport it was tested, too.

(3) Tests on combined effect of particle detachment and sediment transport were also performed.

GDOT Specifications Governing Erosion Control Measures

GDOT Standard Specifications for Construction of Transportation Systems were updated and approved by the State Transportation Board on April 13, 2013. The sections relevant to erosion control on slopes include:

- Section 218 – Blanket Fill for Slopes
- Section 711 – Turf Reinforcement Matting
- Section 712 – Fiberglass Blanket
- Section 713 - Organic and Synthetic Material Fiber Blanket
- Section 714 – Jute Mesh Erosion Control
- Section 716 – Erosion Control Mats (Slopes)

Currently, for applications on slopes, Section 716 recommends the application of fiberglass blankets (Section 712), organic and synthetic material fiber blankets (Section 713), and jute mesh (Section 714). Section 713 utilizes the following definition for a synthetic material fiber blanket: a machine produced uniform blanket of ultraviolet degradable polypropylene staple fibers reinforced with ultraviolet degradable polypropylene netting.

Erosion control products for slope applications

Within the last decade, the erosion control industry has grown rapidly and expanded to include a wide variety of RECPs designed to meet more demanding slope applications. These new products are stronger, more durable, and more resilient than the products currently described in Section 713 for synthetic fiber blankets. Most significantly, a variety of products are now available to provide mechanical reinforcement for applications on steep slopes (up to 1H:1V), or in applications where the time to establish vegetation is exceedingly long. These products are known as Turf Reinforcement Mats (TRMs), which are long-term nondegradable synthetic RECPs with 3-dimensional matrices designed for applications where discharges exceed the shear strength of natural vegetation.

Recommended Characteristics for Products Used in Slope Applications

Applicable ASTM Tests

Multiple ASTM standards are used to quantify the material properties of RECPs, as well as bench top and field scale engineering behavior of these geosynthetics:

- D 570 - Standard Test Methods for Water Absorption of Plastics.
- D 4354 - Practice for Sampling of Geosynthetics for Testing.
- D 4355 - Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus).
- D 4439 - Terminology for Geotextiles.
- D 4595 - Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method.
- D 4759 - Practice for Determining the Specification Conformance of Geosynthetics.
- D 4873 - Guide for Identification, Storage, and Handling of Geotextiles.
- D 5035 - Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Force).

- D 6475 - Test Method for Measuring Mass Per Unit Area of Erosion Control Blankets.
- D 6524 – Standard Test Method for Measuring the Resiliency of Turf Reinforcement Mats (TRM's)
- D 6525 - Standard Test Method for Measuring Nominal Thickness of Permanent Erosion Control Products.
- D 6566 - Standard Test Method for Measuring Mass per Unit Area of Turf Reinforcement Mats.
- D 6567 – Standard Test Method for Measuring Light Penetration of Turf Reinforcement Mats.
- D 6575 – Test Method for Stiffness of Geosynthetics Used as Turf Reinforcement Mats.
- D 6818 - Test Method for Ultimate Tensile Properties of Turf Reinforcement Mats.

Of these recommended ASTM specifications, the following are the most critical tests for detailing the properties of erosion control products in the field:

- D 4355 - Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus).
- D 6475 - Test Method for Measuring Mass Per Unit Area of Erosion Control Blankets.
- D 6525 - Standard Test Method for Measuring Nominal Thickness of Permanent Erosion Control Products.

- D 6566 - Standard Test Method for Measuring Mass per Unit Area of Turf Reinforcement Mats.
- D 6818 - Test Method for Ultimate Tensile Properties of Turf Reinforcement Mats.

These five specifications focus on material properties including mass and thickness (ASTM D6475, D6525, and D6566), and the ability of the erosion control product to withstand exposure to UV light (ASTM D4355). The product tensile strength and elongation until tensile stress are covered in ASTM D6818.

Application to Slopes

Selection of the proper erosion control product depends on the slope of the surface to be protected. Selection of a TRM for channel lining is made based on the maximum shear stress generated by the design flow at the interface between the soil and the erosion control product. However, the choice of which RECP to apply to a roadside slope does not include a shear stress calculation but is simply based on slope steepness and the length of time required to establish a good stand of vegetation. For example:

- Steepness of slope (typically 3H:1V or 2H:1V; but also 1.5H:1V or as high as 1H:1V in extreme cases)
- Length of time required to establish full, permanent vegetation (short-term ≤ 12 months; medium-term = 1-2 years; long-term > 2 years
    - Short term applications can use photodegradable RECPs
    - Long term typically represent applications with difficult growing conditions, such as clay soils

Product Descriptions

A summary of the relevant material components to be included in RECPs used in slope applications is given in Table 1.

Table 1. Recommended Material Attributes for RECPs in Slope Applications

Slope	Product Materials	Time to vegetate	UV Degradable
Shallow	• Geosynthetic net • Organic fill	< 12 months	Yes
Shallow	• Geosynthetic net • Organic fill	1-2 years	Short term stabilized
Moderate	• Geosynthetic net • Organic fill	1-3 years	Short term stabilized
Steep	• Geosynthetic	>3 years	Stabilized
Steep	• 3D geosynthetic	>3 years	Stabilized
Steep, high strength/ durability	• 3D geosynthetic	> 3 years	Stabilized

RECP Selection Tool

The GDOT separates erosion control products into the following categories on the Qualified Products List (QPL):

QPL-24 Bituminous Treated Roving

QPL-25 Fiber Mulch

QPL-49 Turf Reinforcement Matting

QPL-62 Organic and Synthetic Material Fiber Blanket

Of these materials, the erosion control items in QPL-49 and QPL-62 are the most difficult to specify due to the large number of approved products within those categories. Previous research (Burns, 2011) developed a web-based application designed to calculate the hydraulic shear stress exerted on the lining of a channel, and return the level of protection that is required for the channel lining (http://liningdesign.ce.gatech.edu/), with specification for products on QPL-49 Turf Reinforcement Matting. The current project focuses on the selection of the products listed in QPL-62 Organic and Synthetic Material Fiber Blanket.

Seventy-nine (79) approved products manufactured by nineteen companies are shown on the Qualified Products List (QPL-62 (Table 2)) dated May 29, 2015. Erosion control for slope applications are differentiated based on location of application (slope, shoulders, or waterways) and material type (natural or synthetic fiber). In addition to these parameters, the steepness of the slope and UV degradability are also important parameters for selection. (Note that turf reinforcement matting is strictly specified for channel lining, with conditions that range from low to high shear stress (QPL-49)).

Table 2. QPL-62:Organic and Synthetic Material Fiber Blanket, May 29, 2015

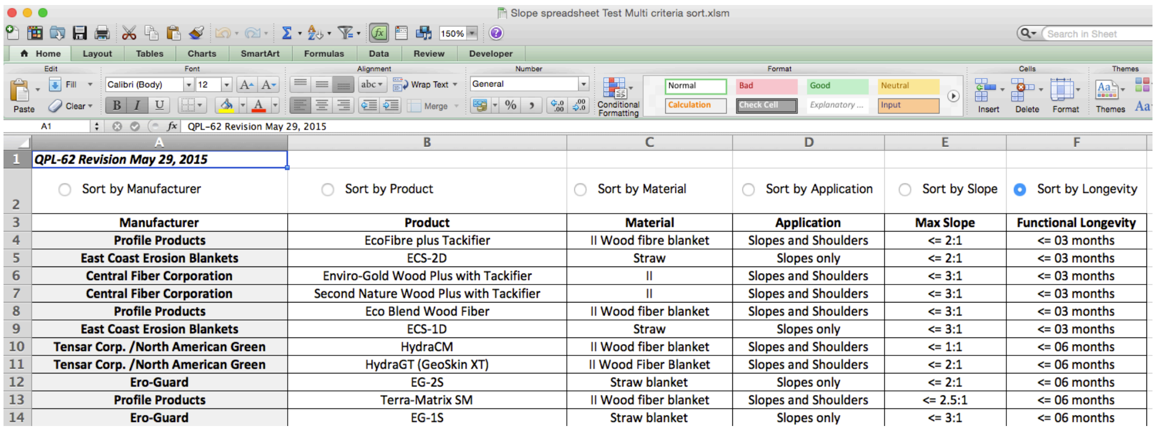
American Excelsior Company		
AEC Premier Straw – single net	Straw blanket	Slopes only
AEC Premier Straw Double Net	Straw blanket	Slopes only
Curlex II Natural aspen	Excelsior blanket	Slopes only
Curlex II QuickGRASS green	Excelsior blanket	Waterways Only
Curlex III Natural aspen	Excelsior blanket	Waterways Only
Curlex I QuickGRASS green	Excelsior blanket	Slopes Only
Curlex Enforcer	I Wood fiber blanket	Slopes and Shoulders
Curlex Net Free	Excelsior blanket	Slopes Only
Bindex BFM	II Wood fiber blanket	Slopes and Shoulders
Central Fiber Corporation		
Enviro Gold Wood Plus with Tackifier	II	Slopes & Shoulders
Second Nature Wood Plus with Tackifier	II	Slopes & Shoulders
Spraymatt Bonded Fiber Matrix	II Wood fiber blanket	Slopes & Shoulders
East Coast Erosion Blankets		

HY-C2	II Wood Fiber Blanket	Slopes & Shoulders
HY-C3	II Wood Fiber Blanket	Slopes & Shoulders
HY-C4	II Wood Fiber Blanket	Slopes & Shoulders
ECS-1 single net	Straw blanket	Slopes only
ECS-2 double net	Straw blanket	Slopes only
ECSC-2 double net	Straw blanket	Slopes only
ECX-1 single net	Excelsior blanket	Slopes only
ECX-2 double net	Excelsior blanket	Waterways and Slopes
ECC-3	Coconut blanket	Waterways and Slopes
ECS-2D	Straw	Slopes only
ECS-1D	Straw	Slopes only
ECC-2	Coconut	Slopes only
Ero-Guard		
EG-1S	Straw blanket	Slopes only
EG-2S	Straw blanket	Slopes only
Erosion Tech		
ET-RS1 Single Net	Straw blanket	Slopes only
ET-RS2 Double Net	Straw blanket	Slopes only
ETC-100	Coconut Blanket	Waterways only
ETX-2	Excelsior blanket	Waterways and Slopes
Greenfix America		
CF072 B	Coconut blanket	Waterways only
CF072 RR	Coconut blanket	Waterways only
GREENSOLUTIONS		
GREENSOLUTIONS SINGLE NET STRAW (SNS-1)	Straw Blanket	Slopes only
GREENSOLUTIONS DOUBLE NET STRAW (DNS-2)	Straw Blanket	Slopes only
Mat Inc.		
Soil Guard Bonded fiber matrix	II Wood fiber blanket	Slopes and Shoulders
Flex Guard	II Wood fiber blanket	Slopes and Shoulders
Spray Guard	II Wood fiber blanket	Slopes and Shoulders
Mid America Erosion Control Products,		

Inc.		
MA-S1	Straw blanket	Slopes only
MA-S2	Straw blanket	Slopes only
Tensar Corp. /North American Green		
S-75	Straw blanket	Slopes only
S-150	Straw blanket	Slopes only
C 125	Coconut blanket	Waterways only
HydraCM	II Wood fiber blanket	Slopes and Shoulders
HydraGT (GeoSkin XT)	II Wood Fiber Blanket	Slopes and Shoulders
HydraCX	II Wood Fiber Blanket	Slopes and Shoulders
Profile Products		
Futterra Green	I Wood fiber blanket	Slopes and Shoulders
Futterra Natural	I Wood fiber blanket	Slopes and Shoulders
Flexterra FGM	II Wood fiber blanket	Slopes and Shoulders
Hydro-Blanket M-BFM	II Wood fiber blanket	Slopes and Shoulders
Terra-Matrix SM	II Wood fiber blanket	Slopes and Shoulders
EcoAegis BFM	II Wood fiber blanket	Slopes and Shoulders
EcoMatrix	II Wood fibre blanket	Slopes only
EcoFibre plus Tackifier	II Wood fibre blanket	Slopes and Shoulders
ProMatrix	II Wood fiber blanket	Slopes and Shoulders
Eco Blend Wood Fiber	II Wood fiber blanket	Slopes and Shoulders
Propex Operating Company, LLC		
Landlok SuperGro	Synthetic fiber blanket	Slopes only
Landloc S-1	Straw blanket	Slopes only
Landloc S-2	Straw blanket	Slopes only
Robex LLC		
Robex Shield RS-1	Straw blanket	Slopes only
Robex Shield RS-2	Straw blanket	Slopes only

Rolanka International, Inc.		
StrawMat 1	Straw blanket	Slopes only
ExcelsiorMat 1	Excelsior blanket	Slopes only
ExcelsiorMat 2	Excelsior blanket	Waterways and Slopes
Southern Environmental Conservation		
SEC-S1	Straw blanket	Slopes only
SEC-S2	Straw blanket	Slopes only
C2	Coconut blanket	Waterways only
Verdyol Alabama, Inc.		
Verdyol Ero-Mat Standard	Straw blanket	Slopes only
Verdyol Ero-Mat High Velocity	Straw blanket	Slopes only
Verdyol Excelsior Green EX-1	Excelsior blanket	Slopes only
Verdyol Excelsior High Velocity	Excelsior blanket	Waterways and Slopes
Western Excelsior Corporation		
EXCEL S-2	Excelsior Blanket	Waterways and Slopes
EXCEL SR-1	Straw Blanket	Slopes only
EXCEL SS-2	Straw Blanket	Slopes only
EXCEL SD-3	Excelsior blanket	Waterways and Slopes
Winters Excelsior Company		
WinterStraw	Straw blanket	Slopes only
WinterStrawHV	Straw blanket	Slopes only
WintersChoice	Straw blanket	Slopes only
WintersFiber	Excelsior blanket	Slopes only
WintersFiberHV	Excelsior blanket	Waterways and Slopes
Winters Coir	Coconut blanket	Waterways only
US Erosion Control Products		
US- 1S	Straw blanket	Slopes only
US- 2S	Straw blanket	Slopes Only
US - 1X	Excelsior blanket	Slopes only
US - 2X	Excelsior blanket	Waterways and Slopes

Due to the high number of products from which to select, a spreadsheet-based selection tool was developed in this work to provide an ability to sort on the basis of five input parameters. The Excel spreadsheet selection tool was developed to provide guidance on the products from QPL-62 that meets the job specifications on the basis of the following criteria: Product, Material, Application, Maximum Slope, and Functional Longevity. Screenshots from the Excel tool are given in Figure 1 and Figure 2.



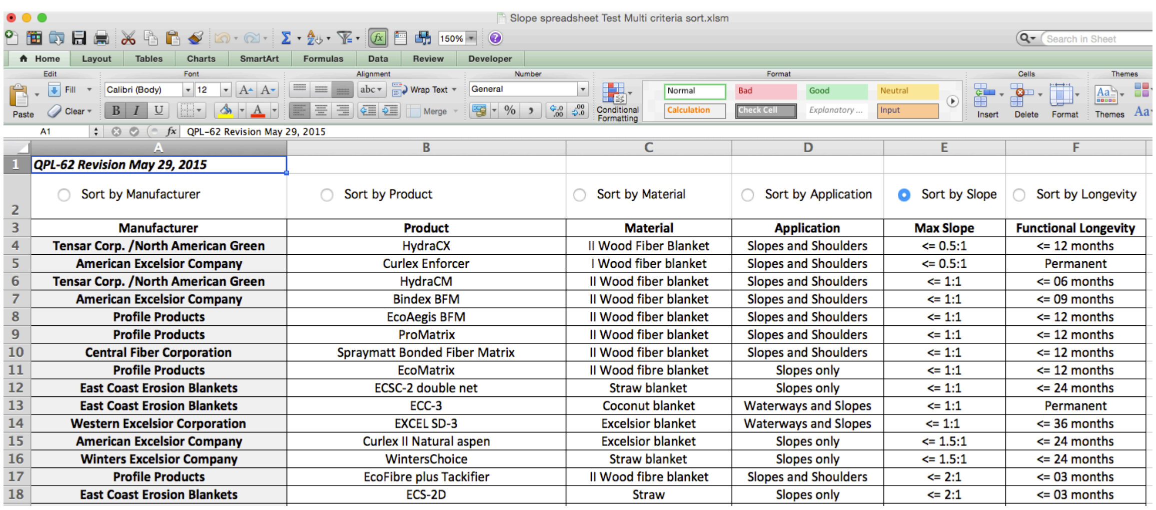
Slope spreadsheet Test Multi criteria sort.xlsm

QPL-62 Revision May 29, 2015

Sort by Manufacturer | Sort by Product | Sort by Material | Sort by Application | Sort by Slope | Sort by Longevity

Manufacturer	Product	Material	Application	Max Slope	Functional Longevity
Profile Products	EcoFibre plus Tackifier	II Wood fibre blanket	Slopes and Shoulders	<= 2:1	<= 03 months
East Coast Erosion Blankets	ECS-2D	Straw	Slopes only	<= 2:1	<= 03 months
Central Fiber Corporation	Enviro-Gold Wood Plus with Tackifier	II	Slopes and Shoulders	<= 3:1	<= 03 months
Central Fiber Corporation	Second Nature Wood Plus with Tackifier	II	Slopes and Shoulders	<= 3:1	<= 03 months
Profile Products	Eco Blend Wood Fiber	II Wood fiber blanket	Slopes and Shoulders	<= 3:1	<= 03 months
East Coast Erosion Blankets	ECS-1D	Straw	Slopes only	<= 3:1	<= 03 months
Tensar Corp. /North American Green	HydraCM	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 06 months
Tensar Corp. /North American Green	HydraGT (GeoSkin XT)	II Wood Fiber Blanket	Slopes and Shoulders	<= 2:1	<= 06 months
Ero-Guard	EG-2S	Straw blanket	Slopes only	<= 2:1	<= 06 months
Profile Products	Terra-Matrix SM	II Wood fiber blanket	Slopes and Shoulders	<= 2.5:1	<= 06 months
Ero-Guard	EG-1S	Straw blanket	Slopes only	<= 3:1	<= 06 months

Figure 1. Screenshot from erosion control selection tool sorted by longevity.



Slope spreadsheet Test Multi criteria sort.xlsm

QPL-62 Revision May 29, 2015

Sort by Manufacturer | Sort by Product | Sort by Material | Sort by Application | Sort by Slope | Sort by Longevity

Manufacturer	Product	Material	Application	Max Slope	Functional Longevity
Tensar Corp. /North American Green	HydraCX	II Wood Fiber Blanket	Slopes and Shoulders	<= 0.5:1	<= 12 months
American Excelsior Company	Curlex Enforcer	I Wood fiber blanket	Slopes and Shoulders	<= 0.5:1	Permanent
Tensar Corp. /North American Green	HydraCM	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 06 months
American Excelsior Company	Bindex BFM	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 09 months
Profile Products	EcoAegis BFM	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 12 months
Profile Products	ProMatrix	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 12 months
Central Fiber Corporation	Spraymatt Bonded Fiber Matrix	II Wood fiber blanket	Slopes and Shoulders	<= 1:1	<= 12 months
Profile Products	EcoMatrix	II Wood fiber blanket	Slopes only	<= 1:1	<= 12 months
East Coast Erosion Blankets	ECSC-2 double net	Straw blanket	Slopes only	<= 1:1	<= 24 months
East Coast Erosion Blankets	ECC-3	Coconut blanket	Waterways and Slopes	<= 1:1	Permanent
Western Excelsior Corporation	EXCEL SD-3	Excelsior blanket	Waterways and Slopes	<= 1:1	<= 36 months
American Excelsior Company	Curlex II Natural aspen	Excelsior blanket	Slopes only	<= 1.5:1	<= 24 months
Winters Excelsior Company	WintersChoice	Straw blanket	Slopes only	<= 1.5:1	<= 24 months
Profile Products	EcoFibre plus Tackifier	II Wood fibre blanket	Slopes and Shoulders	<= 2:1	<= 03 months
East Coast Erosion Blankets	ECS-2D	Straw	Slopes only	<= 2:1	<= 03 months

Figure 2. Screenshot from erosion control selection tool sorted by slope.

Implementation plan

The performance of erosion control products on slopes relies on selection of a RECP designed for the proper function. In terms of field implementation, the following criteria are recommended in order of importance for selection of an appropriate product:

1. *Slope*
    a. Shallow $\leq$ 4H:1V
    b. Moderate 3H:1V to 2H:1V
    c. Steep 1.5H:1V to 1H:1V
2. *Time to establish vegetation*
    a. Excellent vegetative conditions (< 12 months)
    b. Good vegetative conditions (1-2 years)
    c. Fair vegetative conditions (1-3 years)
    d. Poor vegetative conditions (>3 years)
3. UV degradability
    a. NonUV stabilized product
    b. Short term UV stabilized product
    c. Stabilized product
4. Material
    a. Synthetic fibers
    b. Natural fibers

On the basis of these ranked criteria, the selection tool can be used to select the appropriate products from the Qualified Products List.

Part II: Laboratory Based Investigation of Soil Erosion

Summary: Laboratory Investigation

The laboratory investigation was performed to quantify the importance of the soil properties of grain size, angularity, and relative density on the erodibility of sands. These soil properties were studied in relation to the size of raindrop impacting the eroding soil, in order to quantify the threshold values of energy versus soil type that would result in displacement and erosion. Sands were chosen as soil types frequently found in coastal areas, with susceptibility to erosion.

The results of the laboratory investigation demonstrated that mean particle size is the primary variable determining the raindrop splash displacement of sands. An increase in sand particle size resulted in an increase in the soil's resisting force, and a decrease in splash driving force. The effect of particle shape and void ratio on raindrop splash was minimal, with relatively little quantifiable impact of the displacement of soil particles. The experimental results demonstrated that the threshold value between splash displacement and no splash displacement was observed at approximately 1 mm.

Introduction: Particle Detachment

The rate of erosion of soil particles is dependent on multiple factors, including physical properties such as raindrop size, raindrop velocity, soil porosity, sand particle size, and particle shape. The manner in which water spreads after striking the soil surface also impacts the erosion of soil particles, and the impact of the raindrop splash will result in crater formation, which will impact the amount of water that either infiltrates the soil or spreads laterally. This objective of this portion of the investigation was to delineate a particle size threshold for the erodibility of sands as a function of raindrop size. The erosion of soil particles is a function of the impact produced by a falling drop (raindrop splash), and the transport that occurs with the runoff water. The impact of the raindrop splash is known as the most critical factor for determining detachment rate and erosion of soil particles (Ahn et al. 2013; Dunne et al. 2010; Morgan 2005; Park et al. 1982). After a particle has been detached by the drop impact, the particle can be transported by the resulting runoff water, and transported to a receiving stream, which contributes to the deterioration of aquatic ecosystems (Phillips et al. 1993; Pimentel and Kounang 1998). Studies on the effects of raindrop splashing on the susceptibility of soil to erosion involve a large number of forces, and a high level of complexity of the forces involved (e.g., Al-Durrah and Bradford 1981; Terry 1998). Consequently, most previous studies have focused on the effects of raindrop erosivity (i.e., the ability of the raindrop to erode soil) as a function of raindrop size, velocity, shape, kinetic energy, and momentum. However, studies focused on the erodibility of soils, which depends on soil type, particle size, water content, soil fabric, strength, stiffness, as a result of raindrop splashing are relatively limited (e.g., Al-Durrah and Bradford 1982b; Bryan et al. 1989).

Several studies on erosivity and erodibility have attempted to link splash rate with geotechnical strength parameters obtained from fall cone tests, assuming that the mechanisms of failure were similar (e.g., Al-Durrah and Bradford 1982b; Cruse and Larson 1977; Mouzai and Bouhadef 2011; Nearing and Bradford 1985). These studies have focused on fine-grained materials such as silts, clays, and sand-silt or sand-clay mixtures, but have not identified a clear relationship between geotechnical shear strength parameters and erosion due to splash rate.

For coarse-grained soils, the mathematical model describing the detachment of soil particles was initially expressed according to the following empirical power law relationship (Meyer 1981):

$$D_S = K \cdot E^n \tag{1}$$

where, D_S = splash detachment rate (mass of particle detached by raindrop); K = erodibility factor, which is the function of soil property; E = erosivity (typically modeled either as kinetic energy or momentum in the empirical relationship); n = empirical constant. However, later studies recognized that soil particles have a threshold resistance against detachment due to raindrop splash; therefore, Equation (1) was modified to employ the concept of a minimum threshold of erosivity to initiate the detachment of soil particles (Kinnell 2005; Sharma and Gupta 1989; Sharma et al. 1991):

$$D_S = K_a \cdot (KE - KE^*) \tag{2}$$

where, K_a = erodibility factor, indicating the slope of the linear relationship between splash rate (detachment) and applied kinetic energy; KE^* = critical (threshold) kinetic energy. Detachment of soil particles will not occur when the applied erosivity (e.g., kinetic energy) is smaller than critical erosivity. Once the applied erosivity exceeds the critical value, the splash rate of soil particles will increase at a rate proportional to the erodibility factor (K_a). Therefore, the critical erosivity and erodibility factor in Equation (2) are a function of the erodibility of soils, and reflect the resistance of a soil to detachment by raindrop splash (Sharma and Gupta 1989). Splash resistant soils will exhibit a higher critical erosivity (higher raindrop impact to dislodge), but smaller erodibility factor when compared to easily detachable soil particles.

The behavior of coarse-grained soils under the erosive forces of raindrop impact is primarily a function of raindrop size, drop velocity, porosity, sand particle size, and particle shape. Consequently, five different sand particle types were studied in a laboratory-scale experimental investigation to quantify the influence of drop characteristics and soil particle characteristics on the detachment and transport of soil particles.

Materials and Methods

Five different coarse grains (sand particles) were selected and tested in this study (Table 3). The materials were chosen to represent a range of particle sizes (0.177 - 1.16 mm), particle shapes (round to angular particles), and packing density/porosity (relative density = 30 ~ 70 %). The median grain sizes of the sand particles were determined according to ASTM D422, and the limiting void ratios (e_{max} and e_{min}) of the samples were obtained according to ASTM D4253 and ASTM D4254. The particle shape, including roundness, was quantitatively determined according to the method of Wadell (1932). All sand samples for the raindrop splash tests were air-dried and reconstituted by air pluviation into a cell that was 8.1 cm in diameter and 8.5 cm in height. Each testing sample was prepared to have initial relative densities of 30, 50, and 70 % by symmetric vibration, and tests were conducted on dry specimens (Table 4).

Table 3. Soil Properties

Properties	F-75	ASTM graded	ASTM 20/30	GS22 20/30	Coarse
d_{50} (mm)	0.177	0.36	0.72	0.72	1.16
G_s	2.65	2.65	2.65	2.65	2.65
e_{max}	0.820	0.762	0.742	0.973	0.781
e_{min}	0.537	0.514	0.502	0.685	0.556
R	0.75	0.80	0.90	0.23	0.32

Note: d_{50} = median grain size; G_s = specific gravity; e_{max} = maximum void ratio; e_{min} = minimum void ratio; R = roundness.

Table 4. Soil Testing Conditions

Type	D_r = 30 %	D_r = 50 %	D_r = 70 %
	n	N	n
F-75	0.424	0.404	0.383
ASTM graded	0.407	0.389	0.370
ASTM 20/30	0.401	0.383	0.365
GS22 20/30	0.470	0.453	0.435
Coarse	0.416	0.401	0.384

Note: D_r = relative density = $(e_{\max}-e)/(e_{\max}-e_{\min})$; n = porosity = $e/(1+e)$; e = void ratio = volume of void / volume of solid.

For the variable of water-drop erosivity (i.e., drop kinetic energy or drop momentum), three different-sized (3.39, 4.43, and 5.21 mm in diameter) water drops were released from the height of 1, 3, and 5 m (Table 5). The drop diameter (D) was determined by assuming a spherical shape and measuring the mass of 50 drops. The drop velocity (u) falling from three different heights was determined according to the method of Sharma and Gupta (1989) (Table 5):

$$u = \sqrt{(1 - \exp(-2 \cdot h \cdot g / u_t^2)) \cdot u_t^2} \qquad (3)$$

where, u_t = terminal velocity; h = drop height; g = gravity acceleration.

Table 5. Raindrop Variables

Type	Drop height = 1 m			Drop height = 3 m			Drop height = 5 m	
D (mm)	3.39	4.43	5.21	3.39	4.43	5.21	4.43	5.21
Drop u (m/s)	4.13	4.17	4.18	6.30	6.45	6.48	7.52	7.57
Drop KE (mJ)	0.174	0.396	0.646	0.405	0.948	1.557	1.287	2.123
KE'	0.245	0.217	0.211	0.570	0.520	0.510	0.706	0.695

Note: D = water-drop size; u = fall velocity at impact; KE = kinetic energy at impact; KE' = relative kinetic energy (KE at current velocity / KE at terminal velocity).

To measure the mass of splashed particles displaced due to the water drop, a splash collector with a 18 mm diameter hole was placed onto the target area of soil specimen (after the experimental methods of Al-Durrah and Bradford (1981) and Nearing and Bradford (1985)) (Figure 3). The released single water drops traveled through the

PVC pipe to minimize the effect of air drift, and the drops landing near the corner of target area were excluded from data analysis. Before beginning each test, the inside of sampler was sprayed with deionized water to provide a viscous layer or to increase in particle detainment, and the collected splash displaced sand particles were oven-dried and weighed after finishing each test.

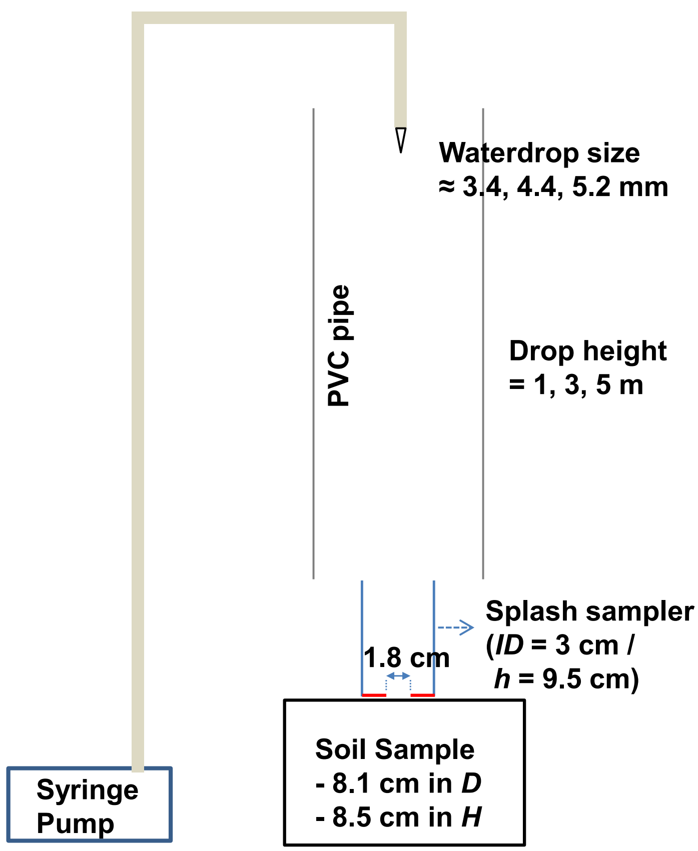


Figure 3. Test setup for splash measurement after the method of Al-Durrah and Bradford (1981): D and H = diameter and height of soil sample, respectively; ID and h= inner diameter and height of splash sampler, respectively.

Results

As water-drop impact energy increased, the erosivity of the raindrop increased and the measured mass of the splashed particles increased for all five sands, as was anticipated (Figure 4). The lateral flow velocity of the fluid and the projected cross sectional area of the particle were the primary factors in determining the driving force causing lateral movement of sand particles. Therefore, with an increase in drop velocity (controlled by adjusting drop heights), there was an accompanying increase in lateral flow velocity, resulting in an increase in rain splash driving force. This also corresponded to increased mass of splashed or displaced particles. In addition, an increase in water-drop size also caused a decrease in the infiltration ratio, leading to an increase in the area of particles affected by lateral movement of water (or fluid pressure). Consequently, it is notable that kinetic energy, which is a function of drop velocity and drop size (mass), also impacts the splash rate (Figure 4). The total mass of splashed particles increased with a decrease in individual sand particle size.

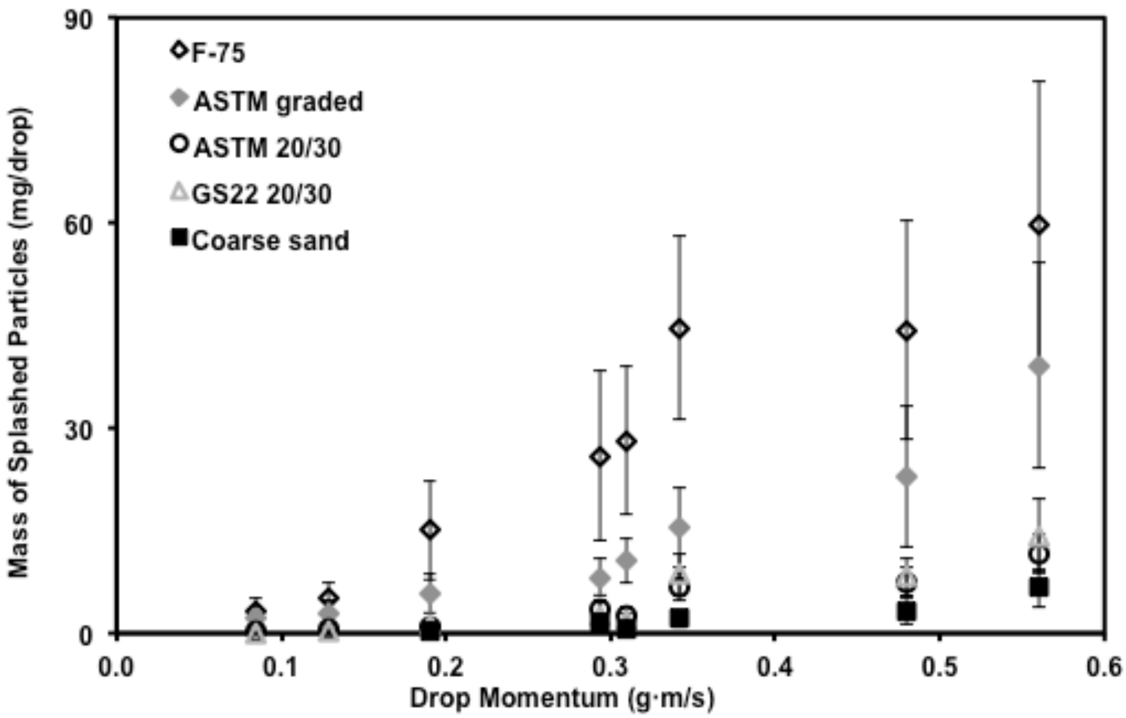


Figure 4. Variation of splashed particles of 5 different sands as a function of drop kinetic energy: d_{50} of F-75 = 0.177 mm; ASTM graded = 0.36 mm; ASTM 20/30 = 0.72 mm; GS22 20/30 = 0.72 mm; and Coarse sand = 1.16 mm.

Analysis and Discussion

Effect of Particle Size

Figure 5 shows the variation of mass of splashed particles as a function of mean sand particle size under two selected kinetic energies (~ 1.56 and 2.12 mJ). It is clear that the splash rate of sand particles decreased with an increase in sand particle size at a given erosivity (i.e., kinetic energy or increased raindrop size). As the size of individual sand particle increased, each particle had more mass and correspondingly more resistance to the splash driving forces, which resulted in a decrease in splash rate. Mean particle size is the primary variable determining the resistance of a soil particle against raindrop splash. Additionally, with an increase in sand particle size, there is an accompanying increase in hydraulic conductivity, leading to a decrease in the volume fraction of lateral flow, which also results in a decrease in raindrop splash driving force. In summary, an increase in the sand particle size results in an increase in the raindrop splash resisting force, and a decrease in the splash driving force, which results in mean particle size as the primary variable controlling the extent of raindrop splash of sands (Dunne et al. 2010; Fox et al. 2007; Furbish et al. 2007; Huang et al. 1982).

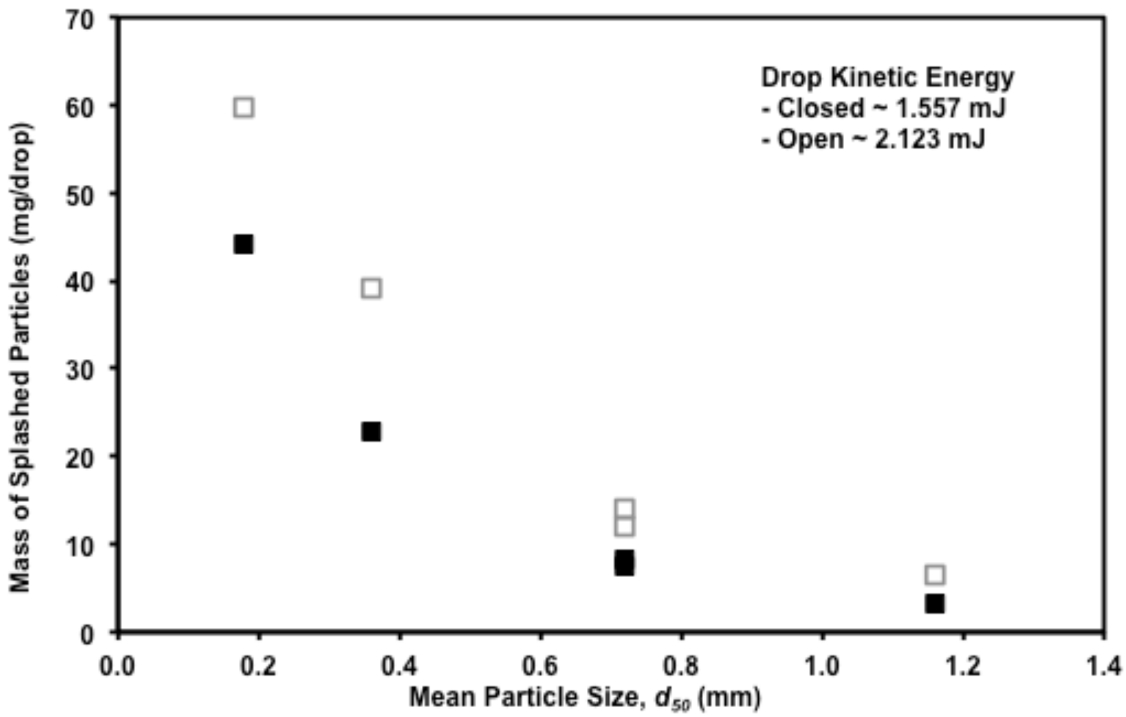


Figure 5. Effect of mean particle size on raindrop splash at selected drop kinetic energies: closed figures = drop *KE drop* of 1.557 mJ; open figures = drop *KE* drop of 2.123 mJ.

Effect of Particle Shape and Void Ratio

Figure 6 shows the variation of the mass of splashed sand particles for two different sands as a function of relative density (or porosity, which is related to relative density) at three different kinetic energies. These sands were chosen for comparison because the particles have very similar size distributions (e.g., d_{50}), but distinct particle shapes (Table 3). An increase in particle angularity will result in an increase in the resistance of particles against lateral movement of splashed water. This means that angular sands will displace less, when compared to the displacement of rounded sand particles. However, increase in particle angularity will also result in a more irregular infiltration flow path, with an increase in tortuosity (T_0), which will result in an increase in the volume fraction of lateral flow. Previous studies have also noted a decrease in hydraulic conductivity with an increase in particle angularity (Fair and Hatch 1933; Sperry and Peirce 1995). Consequently, these two conflicting mechanisms may cancel each other, and result in minimal effect of particle shape on raindrop splash of coarse-grained particles.

Both hydraulic conductivity and infiltration ratio are direct functions of a soil's intrinsic permeability, which is a function of grain size, size distribution, shape, and arrangement. As permeability increases, the infiltration ratio increases and the splash driving force decreases. As porosity (or void ratio) increase, an increase in the infiltration ratio and a decrease in the splash driving force tend (but not always) to occur. However, the data demonstrated that the effect of varying the initial relative density was negligible on the displacement of splashed particles (Figure 6). Soils experiencing shear failure have undergone large strain displacement, which results in the development of critical state conditions and rearrangement of soil particles (e.g., Atkinson 2007; Wood 1990). An initially loose sand (D_r ~ 30 %) will contract during raindrop impact while an initially dense sand (D_r ~ 70 %) will expand during the impact. Consequently, sand particles with different initial state variables (e.g., void ratio) will have similar critical state porosity, which results in a minimal effect of initial void ratio on raindrop splash.

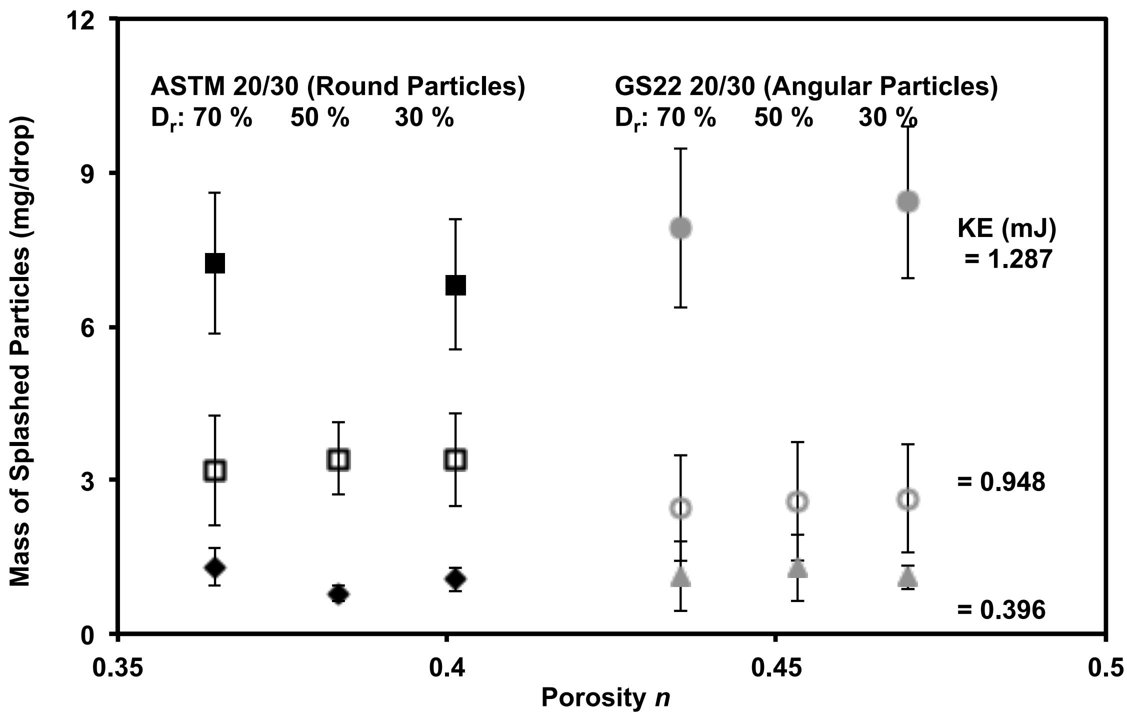


Figure 6. Effect of particle shape and relative density (or porosity) on raindrop splash at three different kinetic energies. Note, particle shape effect = comparison of ASTM 20/30 sand with GS22 20/30 sand; porosity effect = comparison of different initial relative densities.

Critical Threshold Erosivity

Figure 7 shows the variation of critical erosivity and the erodibility factor as a function of mean particle size. Three different soil variables (mean particle size, particle shape, and relative density) were tested in this study, and the data clearly demonstrated that mean particle size is the primary variable determining splash rate of sand particles (Figure 5 and Figure 6). When the two soil property-related variables of erodibility factor and threshold erosivity were plotted with mean particle size, a linear relationship was observed (Equation (2)). As discussed previously, as mean particle size increased, splash resisting force of soil particles also increased due to the increase in the mass of particles, while splash driving force decreased due to the increase in infiltration ratio. Consequently, threshold kinetic energy (minimum required erosivity to initiate motion of particles) increased with an increase in particle size, but the erodibility factors (K_a, factor determining the rate of splash once applied erosivity exceeds the critical value) decreased with an increase in particle size. Additionally, it was observed that the measured threshold kinetic energies of tested materials ranged from a low critical value of close to zero for very fine sand (d_{50} = 0.177 mm), which means raindrop splash can happen regardless of magnitude of raindrop, to a high value of approximately 0.5 mJ for coarse sand (d_{50} = 1.16 mm). These values are in line with values determined in previous studies of silty sand to clayey silt, which reported a range of critical kinetic energy of 0.1 ~ 0.6 m in raindrop splash tests (Sharma et al. 1991).

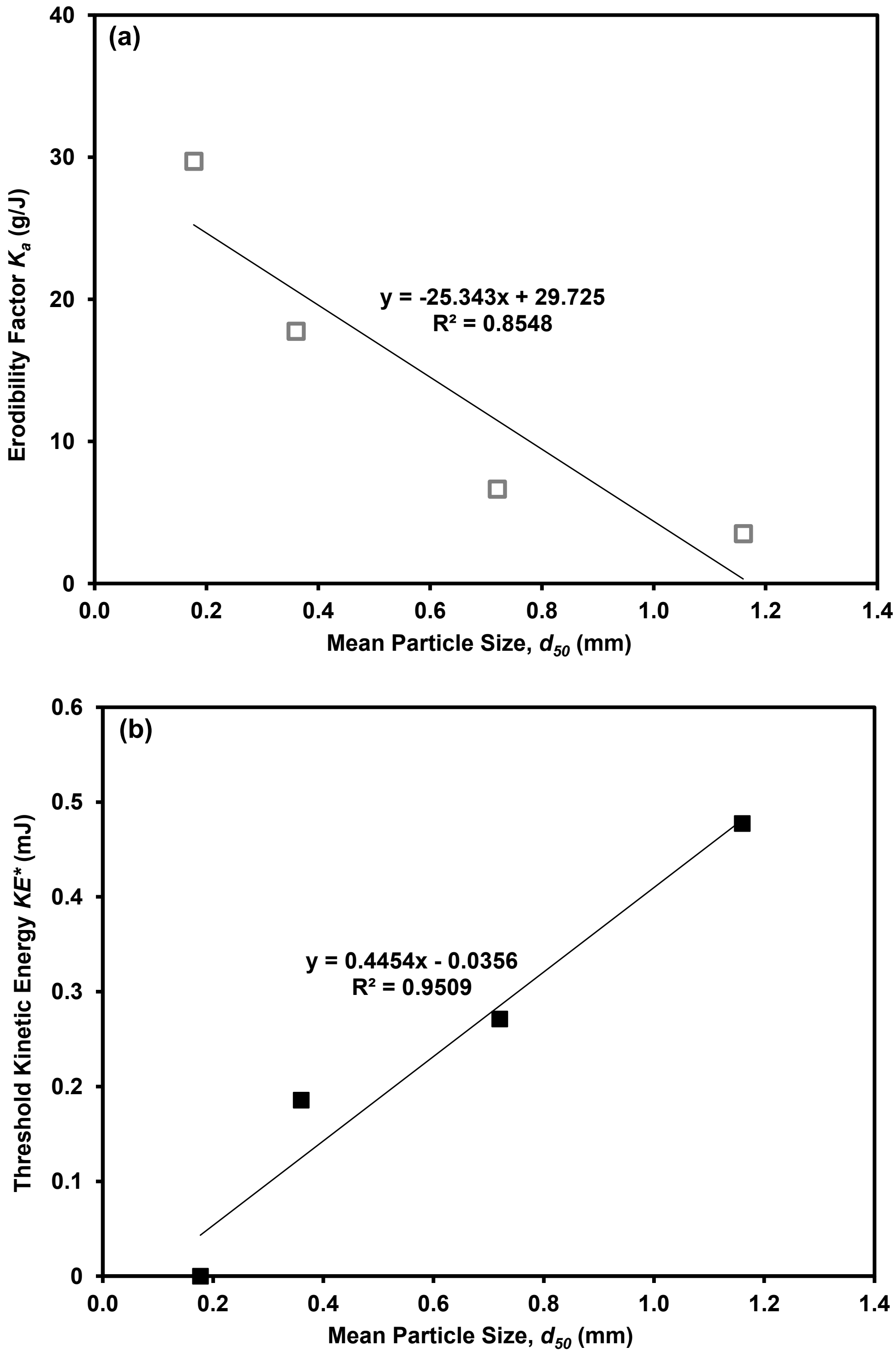


Figure 7. Variation of critical erosivity and erodibility factor as a function of mean particle size: (a) erodibility factor K_a; (b) threshold kinetic energy KE^*; Note, K_a and KE^* = Equation (2).

Soil Erosion: Summary

This study was a quantitative examination of the intrinsic resistance of coarse-grained particles to raindrop splash through laboratory experimentation. In addition, the splash erosion rate was evaluated by employing both the influence of erosivity, which accounts for the properties of the impacting raindrop, and erodibility, which accounts for the properties of the soils that are impacted. The primary findings from this study demonstrated that:

1. The concept of relative scales (i.e., relative size of the ratio of raindrop size D (external excitation) to particle size d_{50} (internal scale)) was employed to account for the dependency of crater size on sand particle size.
2. Splashing of sand particles due to water-drop impact was investigated using the concepts of force equilibrium: driving forces causing lateral motion of a soil particle can be expressed by drag force, and resisting force to splash can be expressed by frictional interaction between particles.
3. It was found that mean particle size is the primary variable determining the raindrop splash displacement of sands. An increase in sand particle size resulted in an increase in raindrop splash resisting force and a decrease in splash driving force. The effect of particle shape and void ratio on raindrop splash was minimal.
4. Experimental results demonstrated that the threshold value between splash and no splash was observed at approximately 1 mm.

Conclusions

The work performed in this research project included a literature review of current practices in erosion control on slopes and erodibility of coarse-grained soil particles.

Selection of a proper erosion control mat for protection of slopes on GDOT rights-of-way should be made with primary emphasis on the steepness of slope, which will govern the hydraulic stress to which the soil and vegetation are subject. Additional considerations to selection of erosion control matting include time to vegetation: are growing conditions excellent (< 12 months to vegetation), good (1-2 years to vegetation), fair (1-3 years to vegetation), or poor (>3 years to vegetation). Finally, erosion control material is also important, with selection of a product made out of synthetic or natural fibers. The RECP can be UV degradable, with a short field life (~1 year) or UV stabilized (long-term applications). GDOT has 79 approved products, produced by 19 manufacturers listed in QPL-62 dated May 29, 2015. Due to the high number of products which a designer can specify, a spreadsheet based selection tool was developed to specify which QPL listed erosion control products are appropriate for given conditions.

A laboratory-based investigation of the erodibility of coarse-grained soils was performed. The behavior of coarse-grained soils under the erosive forces of raindrop impact is primarily a function of raindrop size, drop velocity, porosity, sand particle size, and particle shape. Consequently, five different sand particles were studied in a laboratory-scale experimental investigation to quantify the influence of drop characteristics and soil particle characteristics on the detachment and transport of soil particles. It was found that mean particle size is the primary variable determining the raindrop splash displacement of sands. An increase in sand particle size resulted in an increase in raindrop splash resisting force and a decrease in splash driving force. The effect of particle shape and void ratio on raindrop splash was minimal. Experimental results demonstrated that the threshold value between splash and no splash was observed at approximately 1 mm.

References

Ahn, S., Doerr, S. H., Douglas, P., Bryant, R., Hamlett, C. A. E., McHale, G., Newton, M. I., and Shirtcliffe, N. J. (2013). "Effects of hydrophobicity on splash erosion of model soil particles by a single water drop impact." *Earth Surface Processes and Landforms*, 38(11), 1225-1233.

Al-Durrah, M., and Bradford, J. M. (1981). "New Methods of Studying Soil Detachment Due to Waterdrop Impact." *Soil Science Society of America Journal*, 45(5), 949-953.

Al-Durrah, M. M., and Bradford, J. M. (1982a). "The Mechanism of Raindrop Splash on Soil Surfaces." *Soil Science Society of America Journal*, 46(5), 1086-1090.

Al-Durrah, M. M., and Bradford, J. M. (1982b). "Parameters for Describing Soil Detachment Due to Single Water-Drop Impact." *Soil Science Society of America Journal*, 46(4), 836-840.

Atkinson, J. (2007). *The mechanics of soils and foundations*, Taylor and Francis.

Burns, S.E. (2011). Categorization of Erosion Control Matting, GDOT Project No. 07-25, Georgia Department of Transportation, May.

Bryan, R. B., Govers, G., and Poesen, J. (1989). "The Concept of Soil Erodibility and Some Problems of Assessment and Application." *Catena*, 16(4-5), 393-412.

Carrier, W. D. (2003). "Goodbye, Hazen; Hello, Kozeny-Carman." *Journal of Geotechnical and Geoenvironmental Engineering*, 129(11), 1054-1056.

Carroll, G. J., Rodencal, J., and Theisen, M. S. "Evaluation of Turf Reinforcement Mats and Erosion Control and Revegetation Mats under High Velocity Flows." *Proceedings of the XXII Annual Conference of the IECA*, Orlando, FL, 131-145.

Cho, G. C., Dodds, J., and Santamarina, J. C. (2006). "Particle shape effects on packing density, stiffness, and strength: Natural and crushed sands." *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5), 591-602.

Choo, H., Qian, Z., Sturm, T., and Burns, B. (In preparation). "Impact of Packing Density, Particle Angularity, and Uniformity Coefficient on the Erodibility of Coarse-Grained Particles."

Cruse, R. M., and Larson, W. E. (1977). "Effect of Soil Shear-Strength on Soil Detachment Due to Raindrop Impact." *Soil Science Society of America Journal*, 41(4), 777-781.

Das, B. M. (2001). *Principles of Geotechnical Engineering*, Brooks/Cole Pub Co.

Das, B. M. (2010). *Principles of Foundation Engineering*, Cengage Learning.

Dunne, T., Malmon, D. V., and Mudd, S. M. (2010). "A rain splash transport equation assimilating field and laboratory measurements." *Journal of Geophysical Research-Earth Surface*, 115.

Engel, O. G. (1955). "Waterdrop Collisions with Solid Surfaces." *Journal of Research of the National Bureau of Standards*, 54(5), 281-298.

Epema, G. F., and Riezebos, H. T. (1983). "Fall Velocity of Waterdrops at Different Heights as a Factor Influencing Erosivity of Simulated Rain." *Catena*, 1-17.

Fair, G. M., and Hatch, L. P. (1933). "Fundamental factors governing the streamline flow of water through sand." *Journal of the American Water Works Association*, 25(11), 1551–1565.

Faucette, L. B., Risse, L. M., Jordan, C. F., Cabrera, M. L., Coleman, D. C., and West, L. T. (2006). "Vegetation and soil quality effects from hydroseed and compost blankets used for erosion control in construction activities." *Journal of Soil and Water Conservation*, 61(6), 355-362.

Fox, D. M., Darboux, F., and Carrega, P. (2007). "Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions." *Hydrological Processes*, 21(17), 2377-2384.

Furbish, D. J., Hamner, K. K., Schmeeckle, M., Borosund, M. N., and Mudd, S. M. (2007). "Rain splash of dry sand revealed by high-speed imaging and sticky paper splash targets." *Journal of Geophysical Research-Earth Surface*, 112(F1).

GASWCC, G. S. a. W. C. C. (2000). "Manual for Erosion and Sediment Control in Georgia." G. D. o. N. Resources, ed., 536.

GMA, G. M. A. (2002). *Handbook of Geosynthetics*, Geosynthetic Materials Association.

Ghadiri, H. (2004). "Crater formation in soils by raindrop impact." *Earth Surface Processes and Landforms*, 29(1), 77-89.

Ghadiri, H., and Payne, D. (1981). "Raindrop Impact Stress." *Journal of Soil Science*, 32(1), 41-&.

Gyasi-Agyei, Y. (2004). "Optimum use of erosion control blankets and waste ballast (rock) mulch to aid grass establishment on steep slopes." *Journal of Hydrologic Engineering*, 9(2), 150-159.

Huang, C., Bradford, J. M., and Cushman, J. H. (1982). "A Numerical Study of Raindrop Impact Phenomena - the Rigid Case." *Soil Science Society of America Journal*, 46(1), 14-19.

Ingold, T. (1996). "Technical specification and market study of potentially important jute geotextiles." Silsoe College, Cranfield University.

Kinnell, P. I. A. (2005). "Raindrop-impact-induced erosion processes and prediction: a review." *Hydrological Processes*, 19(14), 2815-2844.

Lambe, T. W., and Whitman, R. V. (1969). *Soil Mechanics*, Wiley.

Meyer, L. D. (1981). "How Rain Intensity Affects Interhill Erosion." *Transactions of the Asae*, 24(6), 1472-1475.

Mihara, Y. (1952). *Raindrops and Soil Erosion*, National Institute of Agricultural Sciences, Tokyo.

Mitchell, J. K., and Soga, K. (2005). *Fundamentals of Soil Behavior*, John Wiley & Sons.

Morgan, R. P. C. (2005). *Soil Erosion and Conservation*, Blackwell publishing.

Mouzai, L., and Bouhadef, M. (2011). "Shear strength of compacted soil: effects on splash erosion by single water drops." *Earth Surface Processes and Landforms*, 36(1), 87-96.

Nearing, M. A., and Bradford, J. M. (1985). "Single Waterdrop Splash Detachment and Mechanical-Properties of Soils." *Soil Science Society of America Journal*, 49(3), 547-552.

Nearing, M. A., Bradford, J. M., and Holtz, R. D. (1986). "Measurement of Force Vs Time Relations for Waterdrop Impact." *Soil Science Society of America Journal*, 50(6), 1532-1536.

Park, S. W., Mitchell, J. K., and Bubenzer, G. D. (1982). "Splash Erosion Modeling - Physical Analyses." *Transactions of the Asae*, 25(2), 357-361.

Morgan, R. P. C. (2005). *Soil Erosion and Conservation*, Blackwell publishing.

Morgan, R. P. C., and Rickson, R. J. (2004). *Slope Stabilization and Erosion Control: A Bioengineering Approach*, Taylor & Francis.

Phillips, D. L., White, D., and Johnson, B. (1993). "Implications of Climate-Change Scenarios for Soil-Erosion Potential in the USA." *Land Degradation and Rehabilitation*, 4(2), 61-72.

Pimentel, D., and Kounang, N. (1998). "Ecology of soil erosion in ecosystems." *Ecosystems*, 1(5), 416-426.

Rickson, R. J. (2006). "Controlling sediment at source: an evaluation of erosion control geotextiles." *Earth Surface Processes and Landforms*, 31(5), 550-560.

Santamarina, J. C., Klein, K. A., and Fam, M. A. (2001). *Soils and waves : particulate materials behavior, characterization and process monitoring*, J. Wiley & Sons, Chichester, England ;.

Sharma, P. P., and Gupta, S. C. (1989). "Sand Detachment by Single Raindrops of Varying Kinetic-Energy and Momentum." *Soil Science Society of America Journal*, 53(4), 1005-1010.

Sharma, P. P., Gupta, S. C., and Rawls, W. J. (1991). "Soil Detachment by Single Raindrops of Varying Kinetic-Energy." *Soil Science Society of America Journal*, 55(2), 301-307.

Sperry, J. M., and Peirce, J. J. (1995). "A Model for Estimating the Hydraulic Conductivity of Granular Material Based on Grain Shape, Grain-Size, and Porosity." *Ground Water*, 33(6), 892-898.

Terry, J. P. (1998). "A rainsplash component analysis to define mechanisms of soil detachment and transportation." *Australian Journal of Soil Research*, 36(3), 525-542.

Terzaghi, K. (1943). *Theoretical Soil Mechanics*, Wiley, New York.

Theisen, M. S. (1992). "The Role of Geosynthetics in Erosion and Sediment Control - an Overview." *Geotextiles and Geomembranes*, 11(4-6), 535-550.

Wadell, H. (1932). "Volume, shape, and roundness of rock particles." *Journal of Geology*, 40(5), 443-451.

White, F. M. (1974). *Viscous Fluid Flow*, McGraw-Hill, New York.

Wood, D. M. (1990). *Soil behaviour and critical state soil mechanics*, Cambridge University Press.