DOE/NV/0000939-17

Soil Stabilization Methods with Potential for Application at the Nevada National Security Site: A Literature Review

prepared by

Rose Shillito and Lynn Fenstermaker
Desert Research Institute
Nevada System of Higher Education

submitted to

Nevada Field Office
National Nuclear Security Administration
U.S. Department of Energy
Las Vegas, Nevada

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Publication No. 45255

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The work upon which this report is based was supported by the U.S. Department of Energy under Contract #DE-NA0000939. Approved for public release; further dissemination unlimited.

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EXECUTIVE SUMMARY

Nuclear testing at the Nevada National Security Site (NNSS) has resulted in large areas of surficial radionuclide-contaminated soils. Much of the radionuclide contamination is found at or near the soil surface, and due to the dry climate setting, and the long half-life of radioactive isotopes, soil erosion poses a long-term health risk at the NNSS. The objective of this literature review is to present a survey of current stabilization methods used for minimizing soil erosion, both by water and wind. The review focuses on *in situ* uses of fundamental chemical and physical mechanisms for soil stabilization. A basic overview of the physical and chemical properties of soil is also presented to provide a basis for assessing stabilization methods. Some criteria for stabilization evaluation are identified based on previous studies at the NNSS. Although no specific recommendations are presented as no stabilization method, alone or in combination, will be appropriate in all circumstances, discussions of past and current stabilization procedures and specific soil tests that may aid in current or future soil stabilization activities at the NNSS are presented. However, not all Soils Corrective Action Sites (CASs) or Corrective Action Units (CAUs) will require stabilization of surficial radionuclide-contaminated soils. Each Soils CAS or CAU should be evaluated for site-specific conditions to determine if soil stabilization is necessary or practical for a given specific site closure alternative. If stabilization is necessary, then a determination will be made as to which stabilization technique is the most appropriate for that specific site.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARS	Agricultural Research Service
BSC	biological soil crust
°C	degrees Celsius
CAS	Corrective Action Site
CAU	Corrective Action Unit
CCDAQ	Clark County Department of Air Quality
cm	centimeter
Cs	cesium
DOE	Department of Energy
EDTA	ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
°F	degrees Fahrenheit
ft	feet
g	gram
GIS	geographic information system
ha	hectare
hr	hour
in	inch
kg	kilogram
km	kilometer
kph	kilometer per hour
L	liter
lb	pound
m	meter
Mg	megagram
mi	mile
µm	micrometer
mm	millimeter
mph	miles per hour
MSL	mean sea level
NFO	Nevada Field Office
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
NRCS	Natural Resources Conservation Service
NRMCA	National Ready Mixed Concrete Association
PAM	polyacrylamide
PG	phosphogypsum

PI-SWERL	Portable In-Situ Wind Erosion Laboratory
PM-2.5	particulate matter with diameters less than 2.5 micrometers
PM-10	particulate matter with diameters less than 10 micrometers
PS	polysaccharide
Pu	plutonium
RECS	rolled erosion control system
s	second
U	uranium
U.S.	United States
USDA	U.S. Department of Agriculture
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WEPS	Wind Erosion Prediction System
yd	yard

INTRODUCTION

A history of nuclear testing at the Nevada National Security Site (NNSS) has resulted in a dispersion of radionuclide-contaminated soils over large areas that vary in concentrations of contaminants such as plutonium (Pu), cesium (Cs), Tridite (tritium glass), and uranium (U) products (Turner *et al*., 2003). Due to the dry climate of the NNSS, much of the radionuclide contamination is found at or near the soil surface, making the redistribution of contaminants over the landscape subject to soil erosion by both wind and water. The long half-life of isotopes such as Pu-239 (2.41×10^4 years) means that soil erosion poses a long-term health risk in and around the NNSS (Eisenbud and Gesell, 1997). However, past efforts to remove or treat contaminated soil have resulted in varying degrees of success (Papelis *et al*., 1996; Desotell *et al*., 2008).

The arid environment of the NNSS presents both challenges and opportunities for stabilizing contaminated soils. Due to a lack of water and the resultant low-density vegetation cover, soils in arid environments tend to be particularly sensitive to disturbance, and remain so, long after being disturbed. Persistently low soil moisture increases the susceptibility of these usually low-cohesion soils to wind suspension or to scour and re-deposition from infrequent and brief, but intense, rainstorms (Whitford, 2002; Cornelis, 2006). Arid soils tend to be alkaline (pH > 7.4), which makes most metals—including heavy metal contaminants—insoluble in water and immobile in soils. This alkalinity is also associated with the sometimes detrimental accumulations of soluble salts (e.g., sodium salts near dry lake beds) that can affect vegetation growth, as well as the infiltration capacity and runoff characteristics of the soil (Brady and Weil, 2002). Desert, or rock, pavements tend to form between widely spaced vegetation, which act as sources of runoff during rainstorms. These pavements are also associated with increased soil moisture (Brady and Weil, 2002; Parsons *et al*., 2009). Physical and biological soil crusts are common in arid environments and play a significant role in stabilizing the soil surface from wind erosion. The effect of crusts on point infiltration is less certain, but overall it is considered to be favorable to infiltration (Dixon, 2002; Belnap, 2006). The presence of vegetation, even if dead, can also contribute to soil stability. For example, vegetation can effectively decrease local wind velocities, as well as support microbial communities that increase soil cohesion and infiltration (Whitford, 2002).

The objective of this literature review is to present a survey of *in situ* soil stabilization methods that are applicable to the NNSS and surrounding areas. Given the unique circumstances of the NNSS, a series of concerns and criteria for soil stabilization gleaned from prior studies specific to the NNSS are identified that may facilitate the selection, design, and assessment of soil stabilization methods and activities. A basic discussion of the physical and chemical properties of soils and soil erosion is presented. Scientific literature, reports, and the Internet were searched for practices established, used, or recommended for soil stabilization in semi- and arid areas both locally (e.g., Nevada, Southern California, Arizona, New Mexico, and Colorado) and globally (e.g., Afghanistan, China, Israel, and Saudi Arabia). Particular attention was given to stabilizing contaminated soils. Two general classes of soil stabilization emerged: physiochemical soil additives and mechanical methods, both of which are discussed in this review. Subclasses are defined based on fundamental physical, chemical, or mechanical processes involved in stabilization. Specific products or materials are not recommended, but are presented as illustrative examples. No single method will be applicable in all circumstances, but it is likely that combinations of methods may be appropriate in some locations. However, not all Soils Corrective Action Sites (CASs) or Corrective Action Units (CAUs) will require stabilization of surficial radionuclide-contaminated soils. Each Soils CAS or CAU should be evaluated for site-specific conditions to determine if soil stabilization is necessary or practical for a given specific site closure alternative. If stabilization is necessary, then a determination will be made as to which stabilization technique is the most appropriate for that specific site.

NNSS AND SOIL STABILIZATION CONCERNS

The northern part of the 3,500 square kilometer (km^2; 1,351 square mile, mi^2) NNSS is within the Great Basin Desert. Toward the south, the NNSS transitions to the Mojave Desert, which is the driest region in North America. The terrain includes mountains, mesas, and playa (dry) lakes in two closed hydrographic basins surrounded by sizable alluvial fans. Elevations on the NNSS range from 2,268 meters (m; 7,500 feet, ft) mean sea level (MSL) in the mountains and mesas of the north central NNSS to 823 m (2,700 ft) MSL in the southwest corner of the NNSS. At higher elevations, temperatures are cold in the winter and mild in the summer. At lower elevations, daily temperatures can exceed 40 degrees Celsius (°C; 104 degrees Fahrenheit, °F) in the summer with daily air temperature ranges of 22°C to 33°C (40°F to 60°F). Precipitation on the NNSS varies from an annual average of 320 millimeters (mm; 12.6 inches, in) to an annual average of 127 mm (5.0 in) at higher and lower elevations, respectively (United States Department of Energy [U.S. DOE], 2011). Average monthly wind speeds range from about 8 kilometers per hour (kph; 5 miles per hour, mph) to 20 kph (13 mph). Wind gusts in excess of 97 kph (60 mph) have been recorded at NNSS meteorological stations and are usually associated with strong cold fronts in the spring or thunderstorms in the summer (Soule, 2006). The combination of aridity and temperature extremes has resulted in sparsely vegetated basins (desert shrub plant communities) to moderately vegetated mountains (mixed coniferous forest plant communities) and both plant density and precipitation increase with increasing elevation (Fenstermaker, 2012). Most contaminated soils sites are associated with the lower elevation, sparsely vegetated areas in the central transitional portion of the NNSS between the Mojave and Great Basin Deserts.

Stabilization methods for agricultural soils have been extensively studied and have primarily focused on preserving the soil to maintain or improve crop yields. However, these methods generally are not applicable for non-agricultural purposes in arid environments where the soils are considered unsuitable due to the high soluble salt content and the lack of water. Research on non-agricultural soil stabilization methods is highly specialized and proprietary, and not abundant. Nevertheless, soil stabilization studies on the NNSS and similar sites exist. Additionally, examination of these studies can yield insight into the applicability and assessment of stabilization effectiveness. For example, there are three basic approaches to decrease wind and water erosion: 1) reduce soil movement by keeping the soil in place; 2) reduce the erosivity of the wind or water to levels below those necessary to move or suspend soil particles; and 3) reduce the erodibility of the soil itself by altering the soil structure, changing the physiochemical properties of the soil, or improving and retaining soil moisture (Nwankwo, 2001; Cornelis, 2006). Most soil stabilization methods involve keeping the soil in place.

In 2004, the U.S. Navy sponsored a study on the NNSS to test the effectiveness of an emulsion application to suppress dust emissions and keep the soil in place (Etyemezian *et al*., 2006). The hydrologic and ecologic effects of this same emulsion were then tested at the Yuma Proving Ground in Arizona (Young *et al*., 2007). In a follow-on study, runoff effects of the emulsion on small plots on the NNSS were observed (Desotell *et al*., 2008). Based on these studies, the following needs were defined:

- <u>Dust suppression</u>: minimize “depositional” dust suspended at low wind velocities and “erosional” dust moved during periods of high wind velocities;

- <u>Infiltration and runoff control</u>: ensure that dust suppression measures do not decrease infiltration into the soil or increase runoff; and

- <u>Ecological consequences of the treatment</u>: as soil erosion decreases with vegetation cover, ensure the effect of the treatment on the post-treatment growth, amount, diversity, and density of native and invasive flora, including biotic soil crusts, are not adversely affected; and ensure the application or by-products are not toxic to flora and fauna.

The effectiveness of a soil treatment to prevent erosion depends not only on the environment (climate, geomorphology, soils, and vegetation), type of contaminant, and disturbance, but also on the product or practice applied. Based on the NNSS soil stabilization reports (Young *et al*., 2007; Etyemezian *et al.*, 2006; Desotell *et al*., 2008), the following product or method evaluation criteria and use considerations were identified:

- cost;
- application method;
- toxicity;
- expected lifetime of treatment;
- effective area of application;
- off-site effects of treatments;
- effectiveness on surface type (disturbed or undisturbed);
- effective temperature range;
- effective soil moisture;
- timing of application; and
- appearance and color (dark colors increase soil temperatures).

PHYSICAL AND CHEMICAL PROPERTIES OF SOILS AND STABILIZATION

Soil is usually considered a three-phase system consisting of (1) soil particles, (2) the pores (air) between the particles, and (3) the liquid water that, to varying degrees, fills and flows through the pores. Soil mineral particle designations depend on industry applications and definitions (Figure 1), but are composed of—in order of decreasing size—sands, silts, and clays, with sands usually defined as particles with diameters less than or equal to 2 mm (0.08 in) (Schoeneberger *et al*., 2012). The U.S. Department of Agriculture (USDA) further designates various proportions of soil particles into textural classes (e.g., loam) and subclasses (e.g., fine sandy loam) based on the percentage of sand, silt, and clay (Figure 2). The overwhelming majority of soil stabilization and conditioning research and applications have been developed based on the soil textural classes shown in Figure 2.

The size of the soil particles themselves can be problematic for human health. The U.S. Environmental Protection Agency (EPA), which determines air quality standards, includes particulate matter of effective diameters less than 10 micrometers (PM-10) (µm; 4.0×10^{-4} in) as one of six principal pollutants affecting air quality. Particles of this size can enter human respiratory systems, affect breathing, damage lung tissue, and lead to premature death. The EPA further defined fine particles (particles less than 2.5 µm [PM-2.5], 9.8×10^{-5} in) as an additional concern for human health. Primary particulate matter directly emitted from a natural or anthropogenic source (e.g., PM-10 and PM-2.5) is frequently suspended by wind in arid environments (U.S. EPA, 2013a).

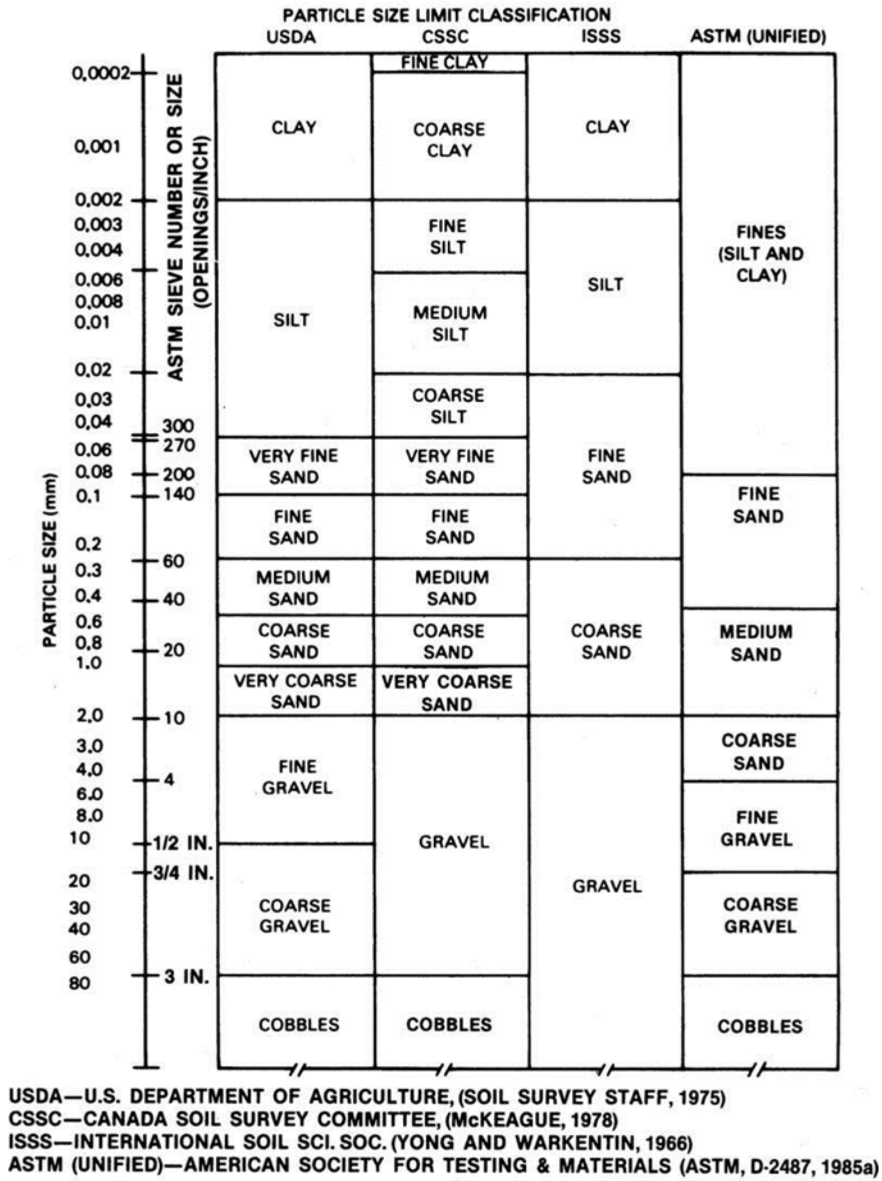

Figure 1. Summary of common soil classification systems.

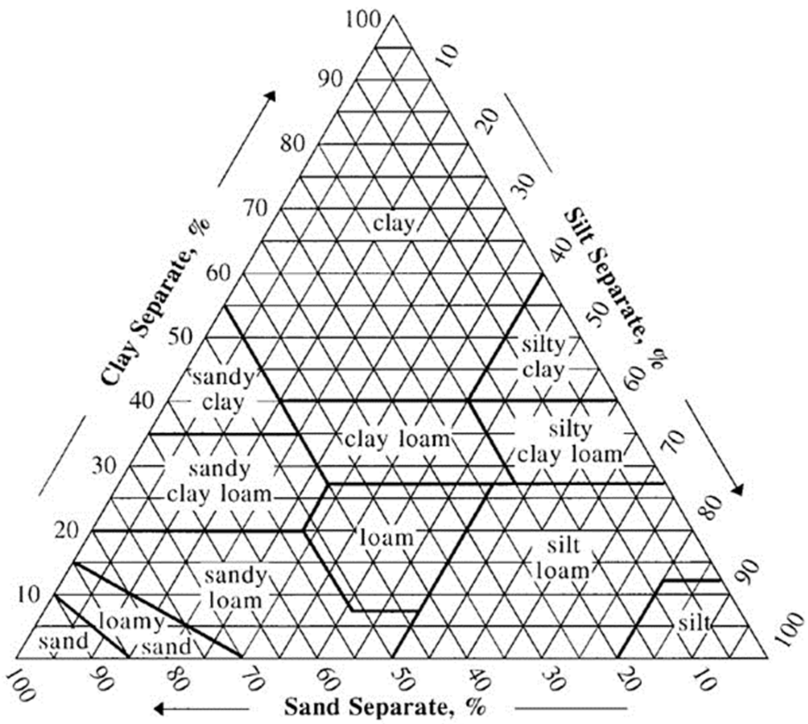

Figure 2. Textural triangle showing percentages of clay (< 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.0 mm) in the basic USDA textural classes.

Clay-sized particles—the fraction of soil less than 2 µm (3.9×10^{-5} in)—play an overwhelming role disproportionate to their size in the physical and chemical characteristics of the bulk soil. Below this size, molecular interactions between the particles, fluids, and other materials become important. Specifically, clay minerals are products of weathering or low temperature reactions, resulting in the formation of aluminosilicates, which are layered crystalline minerals comprised of sheets of silica-oxygen tetrahedra and aluminum-oxygen or hydroxyl octahedra. Isomorphic substitution, where one element replaces another in the mineral without changing the crystalline structure, and breakage of the aluminosilicate sheets tends to result in net negative charges on these particles (Bohn *et al*., 1979). Because of their electrochemical properties and large surface area, clay minerals in large part determine the chemistry and structure of a soil, and even the physical behavior of the soil. For example, in environments where sodium is a readily available cation, the substitution of sodium in the clay mineral structure can disperse the soil by breaking aggregates into individual particles, block the pores, and inhibit infiltration into an otherwise dry soil (Donahue *et al*., 1977). This situation is frequently associated with playas in arid environments. Because interlayers can accommodate water molecules, some clays expand when wet, which leads to cyclical soil shrinking and swelling. Many chemical soil stabilization and soil remediation additives (e.g., chelating agents) operate at this physiochemical level to either increase or decrease the mobility of nutrients or contaminants in the soil. Although water can adhere to soil particles due to the effects of surface tension forces active at liquid-solid interfaces, the larger silt and sand particles are generally considered chemically inert.

Many reactions in the soil are pH-dependent, a function of clay mineral chemistry. Arid-land soils tend to be uniquely high in pH (pH > 7.4, "alkaline") due to the accumulation of salts and carbonates that in some cases reaching pH levels as high as 10, such as soils high in sodium (Monger *et al*., 2012). Although most plant nutrients tend to be more mobile (water soluble and available to the plant) at neutral to slightly alkaline pH levels, metals—including heavy metals and some radionuclide contaminants—tend to be *less* mobile at higher pH levels. Metals become more tightly bound (sorbed) to clay minerals as pH increases (Donahue *et al*., 1977; Knox *et al.*, 2001; Gavrilescu *et al*., 2009). Therefore, the effects on soil pH are an important consideration regarding the effectiveness of stabilization additives for contaminated soils.

Many soil stabilization efforts attempt to physically bind soil particles. Organic matter also chemically and physically affects the soil by providing additional exchange sites, increasing water holding capacity, and adding other material (e.g., roots, hyphae, and polysaccharides) that physically bind particles together. Glomalin, an exudate of arbuscular mycorrhizal fungi that form mutualistic relationships with plant roots, may be a primary, persistent, heat-resistant "superglue" that binds soil particles together (USDA-Agricultural Research Service [ARS], 1997). The relatively low net primary productivity (vegetation) in arid environments means a decrease in roots (and glomalin), which may contribute to the decreased structural stability of arid soils (USDA-ARS, 1997; Treseder and Turner, 2007; Clark *et al*., 2009). Aside from physically covering the soil and protecting the surface from rainfall impact and wind, the role of vegetation in soil stabilization cannot be overestimated.

SOIL EROSION

Wind and water are the primary causes of soil erosion and the resultant types of erosion are summarized in Figure 3. Wind suspends soil particles of varying size at differing velocities and these particles strike the soil surface downwind, causing the suspension of more soil particles. When emitted, windborne dust can originate from "depositional" (i.e., a light layer of loose material) or "erosional" (i.e., direct breakup of the soil surface) material. The nominal difference between these two origins is associated with sustained wind speeds of 6.5 m s^{-1} (21 ft s^{-1}) in unvegetated areas (Etyemezian *et al*., 2006). Water erosion is a progressive process starting with splash erosion of soil particles from individual raindrop impacts (Julien, 1998; Parsons *et al.*, 2009). As the soil surface becomes saturated or water builds up above the soil surface, interrill or sheet flow occurs and more soil particles are displaced. Depending on a number of factors including slope length, angle, and variations in soil erodibility, rills (small microchannels approximately 2.5-5.1 cm [1.0-2.0 in] wide by 7.6 cm [3.0 in] deep) will form and as water movement within the rills increases in duration and velocity, gullies will develop. Channel erosion is a larger scale form of water erosion where water flow within a streambed may erode the channel bed or banks. Additional sources of erosion occur due to seepage, gravity and ice (freeze/thaw or ice movement over land; Rivas, 2006).

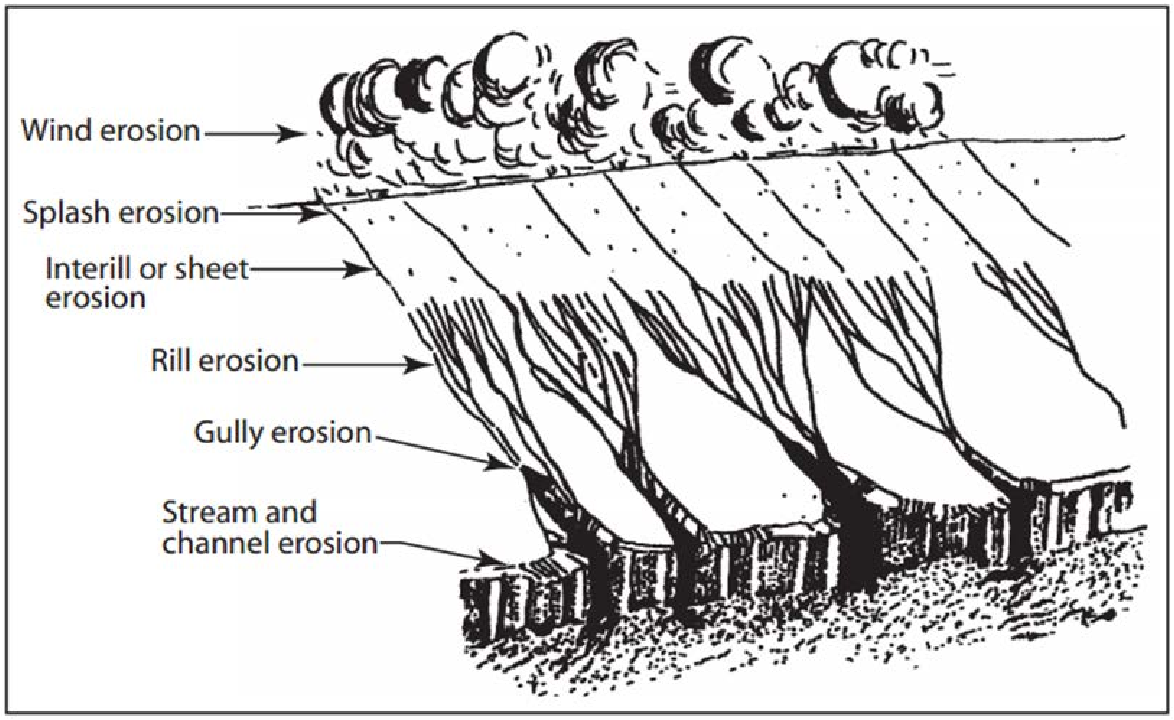

Figure 3. Schematic depicting the processes and types of soil erosion (from Rivas, 2006).

The erosion potential of a soil was first estimated by the Universal Soil Loss Equation (USLE) (Wischmeier, 1959; Wischmeier and Smith, 1965; Wischmeier *et al.*, 1971; and Wischmeier, 1976), which was developed to define how various factors impact erosion on agricultural land. This and other equations based on it predict average soil loss due to erosion from the erosive potential of rainfall, soil erodibility, topography or slope, crop management, and conservation practices. Control of any of these factors will result in reduced erosion. Therefore, most soil stabilization efforts have been designed to reduce water erosion by protecting the soil surface and increasing infiltration; reduce or break up the length of a slope; increase vegetative cover; and employ conservation measures, such planting crops or native plants along a topographic contour, mulching, and terracing (Schwab *et al.*, 1971).

A model developed to specifically assess water erosion potential for natural areas is the Water Erosion Potential Project (WEPP; Foster and Lane, 1987; http://www.ars.usda.gov/Research/docs.htm?docid=10621, accessed 9/29/13). In addition to topographic spatial variability, model parameters include weather generation; frozen soils; snow accumulation and snow melt; irrigation; infiltration; overland flow hydraulics; water balance; plant growth; residue decomposition; and soil disturbance by tillage, consolidation, and erosion and deposition. However, WEPP does not include a factor for soil loss due to wind erosion; therefore, it can only be used to estimate soil loss due to water erosion.

Wind erosion potential can be estimated using models such as the Wind Erosion Prediction System (WEPS; http://www.weru.ksu.edu/weps/wepshome.html, accessed 9/29/13), which was developed to estimate wind erosion from a single crop field or a few adjacent fields. Alternatively, water and wind erosion potential can be directly measured with devices such as rainfall simulators and the Portable In-Situ Wind Erosion Lab (PI-SWERL) developed by the Desert Research Institute (Etyemezian *et al.*, 2007).

Geospatial predictions of erosion thresholds are also being modeled through the development of geographic information system (GIS) applications. Dietrich *et al.* (1992) discuss digital terrain model analysis to predict geographic locations with the highest erosion potential. This type of modeling allows land managers to target limited resources on areas predicted to have the highest erosion potential. Selection of the proper treatment must be based on site characteristics and predicted erosion potential. An effective approach is the six-step process defined by Rivas (2006): 1) evaluate the project site for existing and future potential erosion, 2) establish objectives, 3) collect site-specific data, 4) define erosion potential, 5) evaluate alternative treatments, and 6) select and perform the treatment(s). Figure 4 is an example field form for initial site erosion assessment that could be modified for specific projects or environments. The following sections provide a literature review of both physiochemical and mechanical treatment alternatives to consider depending on the outcome of the site evaluation.

Site Visit Information for Erosion Control Treatment Selection					
Name:				Date:	
Location:				Project:	
Weather:					
GPS Coordinate:				Altitude:	
Soil					
Moisture Condition:	Wet ___	Damp ___	Dry ___	Frozen __	Snow ___
Depth:	Deep ___	Moderate ___		Shallow ___	
Rock Type:	Extensive __				
Rock Cover:	Extensive __	Moderate ___	Light ___	Localized __	Random ___
Soil Texture:	Gravel		Sand		
	Gravel w/ silt	Gravel w/ clay	Loamy sand	Sandy clay loam	
	Silt	Clay	Organic	Other:	
Vegetation					
Description:					
Plant species (photos):					
Topography					
Slope Type:	Cut slope	Fill slope	Natural	Other:	
Slope Angle:	Min:	Max:	Typical:		
Slope Length:	Min:	Max:	Typical:		
Slope Aspect:					
Erosion Processes					
<u>Gravity Erosion</u>					
Mass-movement:	Present	Likely	Not likely	Undetermined	
Shallow-mass movement:	Present	Likely	Not likely	Undetermined	
Dry-ravel:	Present	Likely	Not likely	Undetermined	
<u>Water Erosion</u>					
Live Channels:	Present	Not present		Width ____	Depth ____
Coastline:	Present	Not present		Severity:	
Gullies:	Present	Likely	Width ____	Depth ____	Severity ___
Rills:	Present	Likely	Width ____	Depth ____	Severity ___
Interrill:	Present	Likely	Severity		
Seepage:	Present	Likely	Severity		
<u>Wind Erosion</u>					
Slope on top of ridge?	Yes / No	Slope exposed to predominant wind?			Yes / No
Observed wind speed:	Strong ___	Moderate ___	Light ___	None:	
Expected wind speed:	Max _____	Min ____	Typical:		
Slope on flat ground?	Yes ____	No ___	Wind comments:		
General Comments:					

Figure 4. Example of a site evaluation form (from Rivas 2006).

PHYSIOCHEMICAL STABILIZERS

Information on commercially available chemical additives designed to stabilize soil and decrease susceptibility to erosion by wind and water is widely available. Nearly all of these products are proprietary and described as "…biodegradable…environmentally friendly…nontoxic…safe and effective…" with applications ranging from recreational use (baseball fields, golf course sand traps, and park paths) to industrial use (construction and development sites, military uses, and mining operations). Nevertheless, specific information regarding products that would be applicable for the entire NNSS is elusive. Special use reports (i.e., gray literature) exist that compare specific products and some scientific literature exists that focuses on the fundamental mechanisms and efficacy for specific conditions under which additives are developed and tested. Local jurisdictions have developed guidelines and even application recommendations for soil stabilization additives that are in compliance with federal and state regulations. All of these sources were used to develop the following discussion of physiochemical soil stabilizers, which provides a general overview of additive types and chemical mechanisms used to stabilize soils. Most commercially available products are blends of these components. Any recommendations or restrictions noted by local regulatory agencies are referenced.

Cement/Concrete/Lime

Products associated with cement have long been used to stabilize soil from wind and water erosion for purposes of road construction and contaminant encapsulation. The type of application determines the amount of cement used, but up to two percent cement added to soil can increase soil cohesion (strength). Soil minimally modified with cement is referred to as "cement-modified soil". Cement-modified soil can involve merely spreading cement onto prepared (tilled) on-site soil, adding water, and then compacting the soil (Ingles and Metcalf, 1973; Karol, 2003). Slightly hardened mixtures of cemented and uncemented material can form a semi-rigid pavement of relatively low strength (compared to most conventional cement mixtures) that is usually applicable for infrequent, light, and low-traffic areas. Cement stabilization of soil can be applied to both coarse (sandy) and fine (clayey) soils (Prusinski and Bhattacharja, 1999; Parsons and Milburn, 2003). The cement forms nodules that are larger than the constituent sand, silt, and clay particles, making them less susceptible to erosion.

Slightly higher mixtures of cement (5-11 percent) and soil that are compacted to a high density have been referred to as "soil cement" and have many applications, including use throughout the southwestern United States for channel bank protection applications (Choi and Hansen, 2005). Arid environment channel banks composed of loose soil material may erode during ephemeral flow events; therefore, channel bank protection is imperative through urban areas. Soil cement, which is impervious to water and can be easily applied, is designed to blend with the local environment and mimic the texture and color of the surrounding soils; thus, acting as bank protection. Pervious concrete pavements have been designed to provide a more rigid soil surface while allowing for water infiltration into the soil. In these applications, the concrete is comprised of only rock fragments held together by a binder paste of cement and water (Ghafoori and Dutta, 1995) (Figure 5). The National Ready Mixed Concrete Association (NRMCA) states that hardened pervious concrete porosities of 15-25 percent can be achieved, as can permeabilities of 0.34 centimeters second^{-1} (cm s^{-1}; 482 inches hour^{-1}, in hr^{-1}) (NRMCA, 2011). The EPA considers the use of pervious concrete pavements a Best Management Practice for storm water runoff and pollutant removal (U.S. EPA, 2013b). Although developed in warm climates, pervious concrete can be designed to withstand freeze-thaw conditions for increased durability (Tennis *et al*., 2004).

Also referred to as porous concrete, no-fines concrete, gap-graded concrete, or enhanced-porosity concrete, pervious concrete has been used for roadways, sidewalks, trails, and slope stabilization and also has been made into brick material. Proper functioning is dependent on optimal mix and bedding design (Scholz and Grabowiecki, 2007; Lian and Zhuge, 2010; EPA, 2013b). However, the effectiveness of pervious concrete is limited and subject to clogging (Tennis *et al*., 2004; Borgwardt, 2006). Scholz and Grabowiecki (2007) state that porous concrete pavement systems can lose permeability within three years of installation, but a study in Florida indicated porous concrete surfaces were functioning as designed 10 to 15 years after installation (Wanielista *et al*., 2007).

Figure 5. Example of water flow through pervious concrete (NRMCA).

Somewhat similar to cement, hydrated lime is also a traditional practice for stabilization of soils. Although hydrated lime [$Ca(OH)_2$, not calcium carbonate ($CaCO_3$) that is used for agricultural amendments or quicklime (CaO)] may be more effective than cement as a stabilizer in heavy clay soils, lime has little effect in sandy soils (Ingles and Metcalf, 1973; Akpokodje, 1985). Another calcium mineral, gypsum ($CaSO_4 \cdot 2H_2O$), has a long history of agricultural use as a soil amendment to ameliorate the effects of swelling clays or sodium dispersal, an effect wholly unrelated to cementation. Gypsum is used in sodic soils where calcium will substitute for sodium in the clay mineral structure, which results in flocculating the clay particles, opening soil pores, and allowing water infiltration into the soil (Graber *et al*., 2006). In a study of sodic clay soils in Australia, it took 145 days for 650 mm

(26 in) of ponded water to infiltrate more than 2 m (79 in) on a gypsum-treated soil compared to 379 days for 292 mm (11 in) of water to infiltrate the same depth on untreated soil (McIntyre *et al*., 1982). Agassi *et al*. (1995) reported that soil loss from the 25-m (82-ft) long, gypsum-treated plots was three to five times less than the soil loss for untreated plots due to increased infiltration on the treated plots.

Clay Mineral Additives

Because of their electrochemical properties, clay minerals have been used as amendments on unpaved roadways and to alter the physical properties of soils. The net negative charge on soil clay minerals can bind soil particles together, acting as "electrochemical glue." In a study of the effectiveness of bentonite (a naturally occurring montmorillonite clay mineral) as a dust palliative on Iowa and Texas roadways, Bergeson and Brocka (1996) found that additions of five to nine percent by weight of bentonite added and mixed to limestone roadbeds reduced dust emissions by 50-70 percent. The treatment was able to withstand manipulation by routine maintenance, but the effects were not immediate. Surface treatments of clay minerals require some moisture and may require reapplication every five years (Bolander and Yamada, 1999). Under prolonged dry conditions in arid environments, surface treated areas seldom will be dust free and may add suspendible material. As with cement additives, surface application of clay is equipment-intensive (Skorseth and Selim, 2000).

Water Absorbing Products (Deliquescents/Hygroscopic Salts)

Salts can be used as soil stabilization additives. These materials absorb moisture by increasing the surface tension between particles, which slows evaporation, keeps the soil surfaces moist, and forms crusts as the surfaces dry. All of these actions result in reduced potential for soil erosion by wind (Skorseth and Selim, 2000). The treated soil can be manipulated and still maintain its moisture content, but water must be periodically applied. The ability of minerals to absorb water is a function of temperature and humidity. Calcium chloride begins to absorb moisture at 29 percent relative humidity at 25°C (77°F) and at 20 percent relative humidity at 38°C (100°F). Sodium chloride requires at least 79 percent relative humidity to absorb water and is generally less effective for dust abatement. Magnesium chloride begins to absorb moisture at 32 percent relative humidity and is considered the most effective salt deliquescent for dry climates (Bolander and Yamada, 1999). The Clark County Department of Air Quality (CCDAQ) of Southern Nevada only allows magnesium chloride for dust control if used for less than one year and only on trafficked areas. Although corrosion-inhibiting additives may be added to the mix, magnesium chloride has the potential to be corrosive to steel and it is readily leached out of the surface during heavy rainstorms (Bolander and Yamada, 1999; CCDAQ, 2003). Clark County does not allow the use of magnesium chloride on non-trafficked areas or vacant land, near open bodies of water or drinking wellheads, natural washes, or near flood control channels.

Organic Petroleum Products

Petroleum-based materials have long been used to stabilize soil, but their use has decreased recently, even to the point of being banned at some locations. Known variously as road oil, bitumen, cutback asphalt, asphalt emulsions, modified asphalt emulsions, or mineral oils, the adhesive and waterproofing properties of these products allows for the continued, if limited, use for soil stabilization and dust control. For example, a foamed asphalt mixture of seven percent asphalt and two percent Portland cement was found to significantly increase the soil strength of marl (calcium-rich) sand dunes in Saudi Arabian oil fields (Asi *et al*., 2002). Nevertheless, the effectiveness of these products is independent of the chemical interaction with soils. The dilution, additives, and application rates depend on the specific situation, but use is considered an expensive measure due to the cost of the material and specialized application equipment (Ingles and Metcalf, 1973; Skorseth and Selim, 2000). Bolander and Yamada (1999) state that one to two treatments per season may be necessary, as well as follow-up treatments at reduced dilutions. In Clark County, petroleum products are allowed on trafficked areas only and dilution and recommended application rates have been developed for dust abatement. Petroleum products can discolor the land surface and produce unpleasant odors (CCDAQ, 2003).

Organic Non-petroleum Products

Like petroleum products, organic non-petroleum products have been used in the stabilization of soils due to their ability to bind soil particles together and resist the forces of wind and water. This class of products includes tall oil (or tallol, a by-product of wood pulping) and derivatives, resins, vegetable oils, animal fats, and even molasses extracts. Oily wastes (e.g., food-industry wastes and soybean oil) have many characteristics of light petroleum oils, provide a degree of bonding, and may even provide organic matter to the soil (Skorseth and Selim, 2000; Graber *et al.*, 2006). Cruse *et al*., (2000) found that a one percent soybean oil protein amendment increased soil shear strength and significantly decreased soil detachment. Although oils penetrate deeper into soils at higher temperatures, the effect of oil penetration on soil water infiltration rates is unknown. Borlander and Yamada (1999) recommend one treatment per season and note application rates of 1.1-2.3 liter m^{-2} (L m^{-2}; 0.23-0.50 gallons $yard^{-2}$, gal yd^{-2}) for dust abatement.

The paper industry produces a large amount of organic-matter-rich waste, most of which is incinerated or landfilled (Graber *et al*., 2006). When mixed with proprietary blends of other additives and water, tree resins (tree sap obtained from trees or tall oil from the pulping process) have been lauded for their ability to cement and waterproof the soil surface. However, some product formulations can be acidic and require care in handling (Birst and Hough, 1999). Lignin, the material that binds wood fibers together in trees, and its derivatives (e.g., lignosulfonate) have proven effective as soil binders and can allow for increased compaction and plasticity of treated surfaces. In two separate Canadian studies, paper mill sludge-treated soils showed increased hydraulic conductivities and soil aggregate stabilities (Chow *et al.*, 2003; Price and Voroney, 2007). A four- to six-fold decrease in runoff on treated plots was noted in an Ohio mine reclamation study (Shipitalo and Bonta, 2008). The U.S. Army Corps of Engineers concluded that a pine sap emulsion and calcium lignosulfonate both withstood heavy vehicle traffic on unpaved roads in desert systems (Birst and Hough, 1999). Lignin derivatives may require one to two treatments per season, whereas tall oil derivatives may require one treatment every few years (Bolander and Yamada, 1999). These products can cause corrosion of aluminum and its alloys. The binding effectiveness of both tall oil and lignin derivatives may be reduced or completely destroyed by heavy rain (Bolander and Yamada, 1999; Etyemezian *et al*., 2006). The CCDAQ allows the use of lignin derivatives and tall oil emulsions for dust abatement on roadways and provides sample application rates. The lignin derivatives are not allowed on vacant land. As with petroleum-based products, food-industry wastes and paper mill sludges can discolor the land surface and produce unpleasant odors (CCDAQ, 2003).

Polymer Products

Polymers, both natural and synthetic, are probably the most ubiquitous constituent of soil stabilization additives besides water. Polymers are large, long-chain molecules with a high charge density composed of small, repeating units (monomers). Due to the size and structure of polymers, they can affect the physical and chemical characteristics of a soil (Ben-Hur, 2006; Graber *et al*., 2006).

Polymers can be cationic, anionic, or nonionic. Anionic polymers are the most common form used in soil amendments and can promote the formation of larger floccules that settle out of solution in the presence of cations. As only a small part of the anionic polymer is involved in adsorption, the remaining polymer tail can form bridges between particles. This effect was demonstrated by Aggasi and Ben-Hur (1992) by the addition of the cation source phosphogypsum (PG) to a polysaccharide (PS) treatment, which showed that soil loss rates were significantly decreased compared to untreated plots (Figure 6). The net effect is one of strengthening soil aggregates, increasing infiltration, and decreasing runoff; therefore, reducing erosion (Ben-Hur and Keren, 1997; Ben-Hur, 2006; Graber *et al*., 2006). No mechanical characteristics of the treated soil surface (e.g., cohesion) were given in these studies.

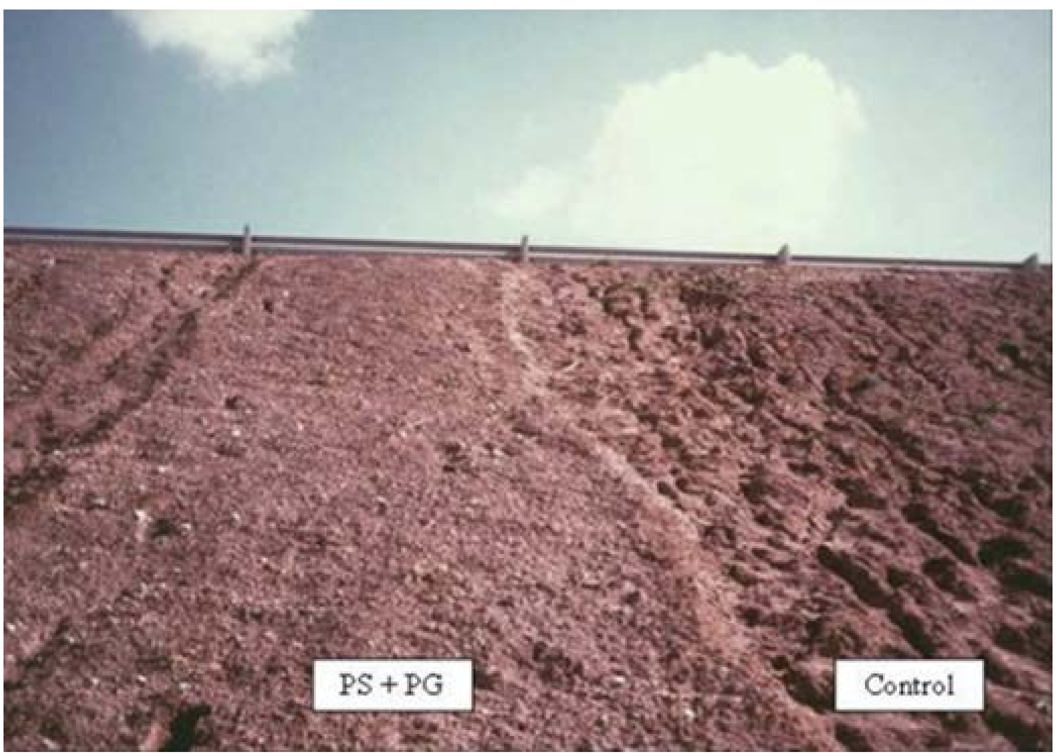

Figure 6. Soil surface of untreated (Control) plot and a plot treated with polysaccharide (PS) and phosphogypsum (PG) in 1990 (from Agassi and Ben-Hur, 1992).

Polymers have also proven effective at stabilizing sand surfaces against wind erosion (Yang *et al*., 2007; Meng *et al*., 2013). The application of polyvinyl acetate and vinyl acrylic, by-products of the adhesive manufacturing process, is a common dust abatement practice (Bolander and Yamada, 1999). The CCDAQ allows the use of these polymers for dust control on both trafficked and non-trafficked areas (CCDAQ, 2003). Of recent interest is a polymer blend dust palliative, named Envirotac II, used by U.S. Marines in Iraq and Afghanistan to reduce dust from aircraft activity and provide a cohesive surface in arid environments (Keating, 2003). Recently, the U.S. Forest Service approved the use of Envirotac II at eleven areas within the Cleveland National Forest in Southern California to be used as aircraft landing sites (Okula, 2013). Although highly lauded, the product can ruin clothing and equipment (Fisher, 2008). Envirotac II is considered noncombustible, but can burn when dried and may thermally break down, yielding acrylamide polymers (Envirotac II, 2013). After use in Tombstone, Arizona, the City subsequently applied a tar emulsion pavement sealer to control dust as the applied Envirotac product was not maintained and proved ineffective over the one-and-half-year period after application (Littlejohn, 2009). No infiltration parameters were available for treated sites. Ultimately, the effectiveness of any particular polymer formulation is dependent upon the type of polymer, as well as the physiochemical properties of the soil upon which it is applied and the application objective.

Polyacrylamide (PAM) was an early polymer developed by Monsanto in the 1950s as Krilium, a flocculant designed to increase infiltration into agricultural soils (Nwankwo, 2001). A flocculant ionically (electrochemically) binds small particles together. In soils, it acts primarily on clay particles. Polyacrylamide can be incorporated into the soil in dry form to increase the water holding capacity of the soil or can be added to irrigation water to increase infiltration and reduce erosion (Lentz *et al*., 1992; Green *et al*., 2004). At high concentrations, PAM can be effectively used to seal the soil. This is a method considered to reduce transmission losses from unlined canals (Young *et al*., 2009). The addition of cationic PG to anionic PAM increased the infiltration rate into and decreased runoff from arable soils in Israel (Yu *et al.*, 2003). However, one environmental concern is that PG is derived from phosphate rock that can contain naturally occurring radionuclides (Graber *et al*., 2006). Several studies indicate the effectiveness of PAM application depends not only on the molecular weight and charge density of the polymer and concentration, but also on the soil texture (Levy and Agassi, 1995; Green *et al*., 2000; Vaucher *et al*., 2003; Chatterjee *et al*., 2009). Although PAM is nontoxic, the unpolymerized acrylamide monomer constituent is a neurotoxin possibly present in small amounts that has been shown to be carcinogenic to rats and mice, and therefore requires careful handling. However, “cross-linked” PAM reduces the presence of the acrylamide monomer (Jenkins *et al*., 1996; Rice, 2005; Lentz, 2007). Nevertheless, the use of PAM is an established practice for erosion control (Natural Resources Conservation Service [NRCS], 2001).

Chelates

Chelates are compounds used in soils to complex with metals. Geologically, chelates are peptides or sugars in humic acids (soil organic matter) that remove metals from minerals. In agricultural practices, chelates have been used to remove adsorbed metals from clay minerals and make metal micronutrients more available to plants. A common chelating agent (ligand) is ethylenediaminetetraacetic acid (EDTA), but other natural and synthetic ligands exist (e.g., citric acid) (Wuana *et al*., 2010). Metal chelation is an important technique used in heavy metal soil contamination remediation and phytoremediation (Blaylock *et al*., 1997; Wasay *et al*., 1998; Peters, 1999; Mulligan, 2001). Contaminated soils can be treated *ex situ* (e.g., removed, treated, and washed) or *in situ* (e.g., in place) to make metal contaminants more soluble for plant uptake. Specifically, chelates are frequently used in the remediation of radionuclide-contaminated soils (Chao *et al.*, 1998; Peters, 1999), although phosphate-induced metal stabilization of radionuclide-contaminated soils also has been documented (Conca *et al*., 2000). Young *et al*. (2007) studied the ability of a proprietary organic emulsion to stabilize soils containing depleted U through chelation. Short-term and limited mobilization occurred, possibly due to the low-pH emulsion, but no hydrologic or ecosystem effects of the emulsion were noted within the study period. The chemistry of the soil and treatment is critical to the efficacy of chelation. Although there is no direct effect of the process on either wind or water erosion, theoretically chelates can be used as a constituent in soil stabilization measures.

Sludge/Biosolids

Sludge and biosolids have long been used in agricultural practices and still continue to be used, but now their use in restoration (e.g., for strip mine remediation) is increasing (Graber *et al*., 2006). Although the benefits of using a readily available soil treatment for vegetative growth are well-known, the potential hazards associated with toxic heavy metals, disease pathogens, and contaminated water associated with biosolids also have been documented. Biosolids can produce odors, especially under conditions of high heat and elevated pH. Although the odors are not associated with adverse human health effects (U.S. EPA, 2000), this concern has moderated their use in the United States (Epstein, 2003). Use of biosolids in arid and semiarid areas has been documented as a nutrient source and stabilization measure (García-Orenes *et al*., 2005; Artiola, 2006). Specifically, sewage sludge appears to improve several properties that decrease erosion in arid soils, such as an increase in soil aggregate stability and water holding capacity (Singh and Agrawal, 2008). In a study on both burnt loam and sandy loam soils on a 16 percent slope in Spain, the application of thermally dried sludge decreased runoff by 32 percent and 26 percent, respectively, as well as decreased sediment transport and increased infiltration (Ojeda *et al.*, 2003). However, a decrease in soil pH associated with sewage sludge could adversely affect metal contaminants sorbed onto soil particles, making them more mobile in the environment. The potential for soil stabilization exists with the use of sludge and biosolids, but so does the potential to introduce and increase contaminants on already contaminated arid soils. As part of the Clean Water Act, the U.S. EPA has established numeric standards for metals and operational standards for microbial organisms for sewage sludge and biosolids used as soil amendments (U.S. EPA, 2009). The standards are reviewed every two years. There is an emerging interest in the environmental effects of pharmaceuticals, steroids, and hormones found in biosolids and wastewater, but no standards have yet been determined.

MECHANICAL STABILIZATION METHODS

Mechanical stabilization methods involve applying solid materials to the soil surface or embedding materials at some depth into the soil. In an evaluation of new erosion control technology, the California Department of Transportation evaluated 37 practices and 262 erosion control products, revealing the breadth of available erosion control methods (Caltrans, 2003). The number of peer review publications discussing mechanical stabilization methods for arid soils in natural settings is limited (Sutherland, 1998); therefore, civil engineering gray literature was reviewed. These publications focus on stabilization methods for man-made structures, such as bridge abutments, overpasses, roads, and constructed road and channel banks. Mechanical stabilization typically includes the application of materials such as rock and plant-material mulch, as well as revegetation, the installation of barriers, geotextile surface reinforcement, artificial vegetation, and the alteration of soil surface slope for more severe cases. The success of these different methods in preventing soil erosion is dependent on a number of biotic and abiotic factors, such as the presence of vegetation and biological soil crusts (BSC), physical characteristics such as soil texture and surface slope, and weather conditions. The presence of vegetation and BSC can mitigate the impact of intense precipitation and high wind events, thus reducing both wind and water erosion (Marqués *et al.*, 2005; Belnap, 2006). In one case, a greater than 50 percent reduction in water erosion was found for an arid site in Spain that was revegetated with *Atriplex halimus*, a Mediterranean Saltbush similar to *Atriplex* species within the Mojave Desert (Marqués *et al.*, 2005). The erodibility of agricultural soils was determined to increase with decreasing soil particle size (e.g., a silt loam soil had an erodibility factor 23 times larger than the erodibility factor for a gravelly loam) (Wischmeier and Smith, 1965). Erodibility varies depending on the season of the year and is higher in the spring in colder climates due to freeze-thaw action (Renard *et al.*, 1991). Rock fragments at the soil surface act like a mulch and decrease erodibility (Renard *et al.*, 1991). Slope alteration practices either reduce the slope percent or break the slope into reduced length segments to lessen potential runoff and erosion. Although weather modification is somewhat limited (e.g., increased precipitation via cloud seeding), it is possible to add wind breaks and vegetation to modify surface roughness and boundary layer conditions, and thus reduce strong wind and high intensity rainfall striking the soil surface.

Soil Compaction

Soil compaction is commonly used in preparation for construction projects (such as roads and buildings) to strengthen and stabilize the soil and the area surrounding the construction project (Gray, 2002). Soil compaction is commonly performed with heavy equipment that applies vibration, impact or soil compression, rolling, or kneading to reduce soil pore space, and therefore increase soil strength. Compaction is not a technique commonly used to prevent erosion because it reduces infiltration (70 to 99 percent reduction), which results in higher runoff on sloped soil surfaces (Gregory *et al.*, 2006). In agriculture settings there are concerns that compaction reduces the ability of roots to penetrate the soil, which limits plant growth (Goldsmith *et al.*, 2001). However, others have found that even with 90 percent compaction, it is possible to revegetate compacted soils successfully depending on the plant species (Schor, 1980; Schor, 1992), as demonstrated in Figure 7.

Figure 7. An example of successful revegetation on a canyon fill project where soils were compacted to 90 percent. The left photo is after grading and the right photo, after an intense rain event, shows how the stabilization and revegetation efforts protected the project area from water erosion (photos of Hollywood Hills, California, from Gray, 2002).

Soil Grading and Backfill

Carretier *et al.* (2012) examined erosion rates based on slope and climate variability in the Andes of central Chile. It was confirmed that slope plays a primary role in erosion and that the high intensity storms associated with decennial and millennial events enhance erosion rates. Across ecosystem moisture gradients, Carretier *et al.* (2012) found that erosion from less-frequent (i.e., higher return interval) storm events increases with increasing aridity. Therefore, in areas where slopes are greater than 30 percent, it may be necessary to excavate and backfill soils to prevent or reduce erosion to acceptable levels (Kearley and McCallister, 2000). Depending on vegetation cover and soil texture and structure, soil grading and backfilling also may be necessary to stabilize landforms with slopes less than 30 percent. If the ultimate goal for mechanically stabilizing a slope is to limit erosion until vegetation can cover the slope, then it is important to consider the slope aspect and percent slope despite precipitation amounts or the application of irrigation. Bochet *et al.* (2009) examined the effect of aspect and slope on vegetation colonization for a semiarid location in eastern Spain. The maximum slope on which revegetation occurred decreased from north to south aspects, i.e., the maximum slope for north, east, west, and south facing slopes was 70 percent, 56 percent, 51 percent and 46 percent, respectively. Furthermore, as stated in a U.S. Forest Service *Erosion Control Treatment Selection Guide* (Rivas, 2006), it is crucial to both characterize soil texture and structure and to define the type of erosion (rill, gully, gravity, etc.) that is to be mitigated to ensure proper treatment selection. Figure 8 depicts common grading strategies to stabilize sloping land, and Table 1 describes functions, uses, and limitations of grading treatments.

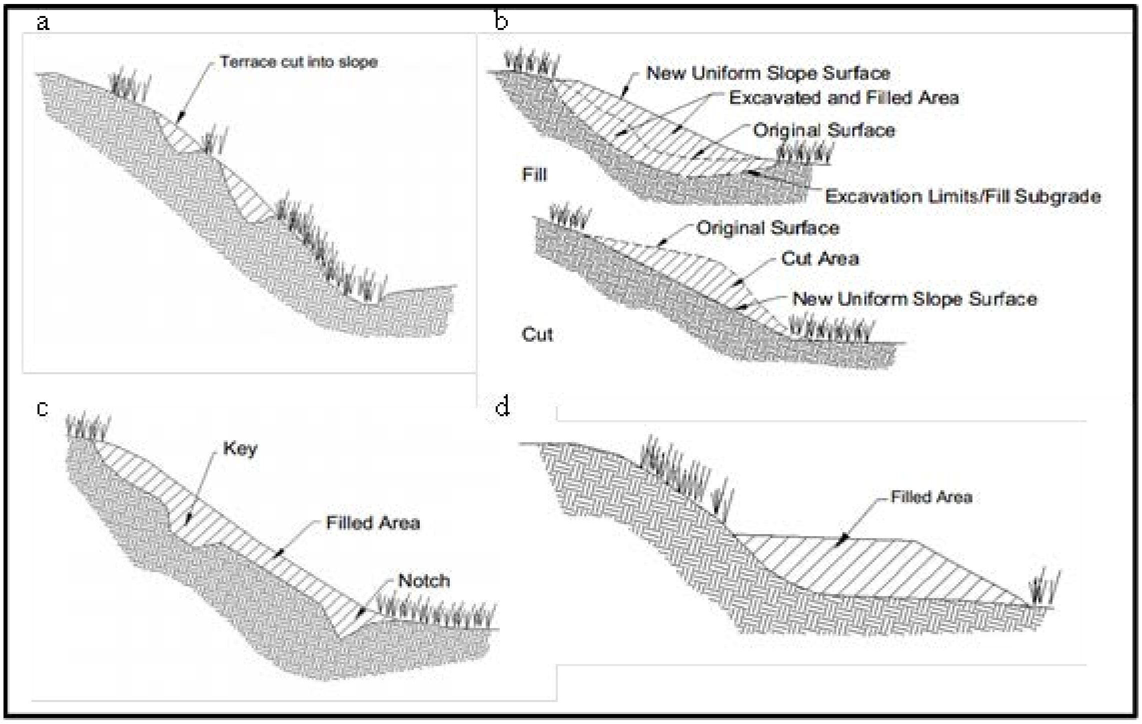

Figure 8. Examples of different types of excavation and infilling used to stabilize slopes. Graph (a) illustrates excavation of soil to form terraces, (b) illustrates slope shaping by excavation and filling of a non-uniformly sloped area (top) and excavation to produce a more uniform and overall reduced slope area, (c) illustrates a method termed “slope keying” that prevents slipping of added fill, and (d) is an example of “counter-weighting” a toe slope to prevent downhill sliding along a slope. (All figures are from Kearley and McCallister, 2000).

Table 1. Grading erosion control treatments: functions, typical uses, and limitations (from Rivas, 2006).

Function	Typical uses	Limitation
Grading and shaping		
• Flattens slope for stability. • Modifies soil surface and topography to control runoff and establish vegetation. • Optimizes slope angles and shapes for reduced water erosion and sediment yield.	• To improve final appearance, improve stability, enhance vegetation establishment, and reduce erosion. • To reduce costs and increase effectiveness of treatments.	• May reduce vegetation establishment if surface is compacted on sites with high silt and clay content. • May have limited options due to topography. • Final grading should be compatible with the land use objectives.
Soil roughening		
• Reduces and detains runoff and improves vegetation establishment.	• To loosen the soil for improved soil properties for improved vegetation establishment.	• May not be suitable for steep slopes. • May temporarily increase erosion prior to vegetation establishment.
Tracking (tracking cleated construction equipment up and down or across a slope)		
• Roughens the soil surface to reduce runoff, increases infiltration, traps sediment, and promotes seed germination and growth.	• To reduce erosion and sediment yield, particularly for sandy slopes, if the cleats are parallel to the contour.	• May compact the surface if used on clay and silt soils. • Increases erosion if used with cleats perpendicular to the contour. • May increase time to finish slopes. • May not be suitable for steep slopes.
Terraces (berm or bench-like earth embankment with a nearly level plain bounded by rising and falling slopes); based on slope, terraces are either level (placed on contour) or graded (sloped to drain)		
• Improves infiltration, reduces effects of interrill and rill erosion and assists vegetation establishment. • Reduces slope distance.	• On long, steep, stable cut and fill slopes 2H:1V or steeper. • To prevent erosion with paved on-contour terrace drainage ditches.	• May be susceptible to instability if not well compacted. • May be difficult in rocky, hard soils. • May reduce sediment yield, but not erosion.

Table 1. Grading erosion control treatments: functions, typical uses, and limitations (from Rivas, 2006) (continued).

Function	Typical uses	Limitation
Constructed wattles (a constructed, linear feature placed in contact with the soil surface, generally on contour, that breaks a longer slope into a series of shorter slopes, such as small rock walls, woven wooden fences, or logs)		
• Retains seeds and soil, slows runoff. • Breaks a long slope into a series of smaller slopes. • Improves conditions for plant establishment immediately upslope of wattle.	• To shorten slope distance, retain sediment, and reduce rill formation. • For long-term protection after vegetation is established. • On gentle or steep slopes (up to 1H:1V). • In combination with soil bioengineering, such as a bender board fence, to help establish vegetation for steep dry sites. • Log wattles for fire rehabilitation.	• May require maintenance to remain effective. • May require skilled, time-consuming labor to install. • Has limited sediment capture capability. • Should not be used on creeping or slumping soils or for high flows. • May be ineffective for interrill erosion.

Soil Reinforcement and Barriers

To protect the soil surface against water erosion a number of materials (rocks, geotextiles, and roll erosion control) have been developed and used to reinforce soil surfaces. Early examples of soil reinforcement include the construction of walls, such as the Great Wall of China and the ziggurat of Dur-Kurigatzu in Iraq (Elton and Patawaran, 2004). Soil was reinforced with plant materials that were embedded in either a mixture of clay and gravel (Great Wall of China) or layers of sand and gravel (ziggurat). Although a number of soil reinforcement techniques were subsequently developed for construction-related projects, using rocks and plant material to reinforce soils against erosion is still a common technique to provide strong erosion control (Figure 9) (Kearley and McCallister, 2000).

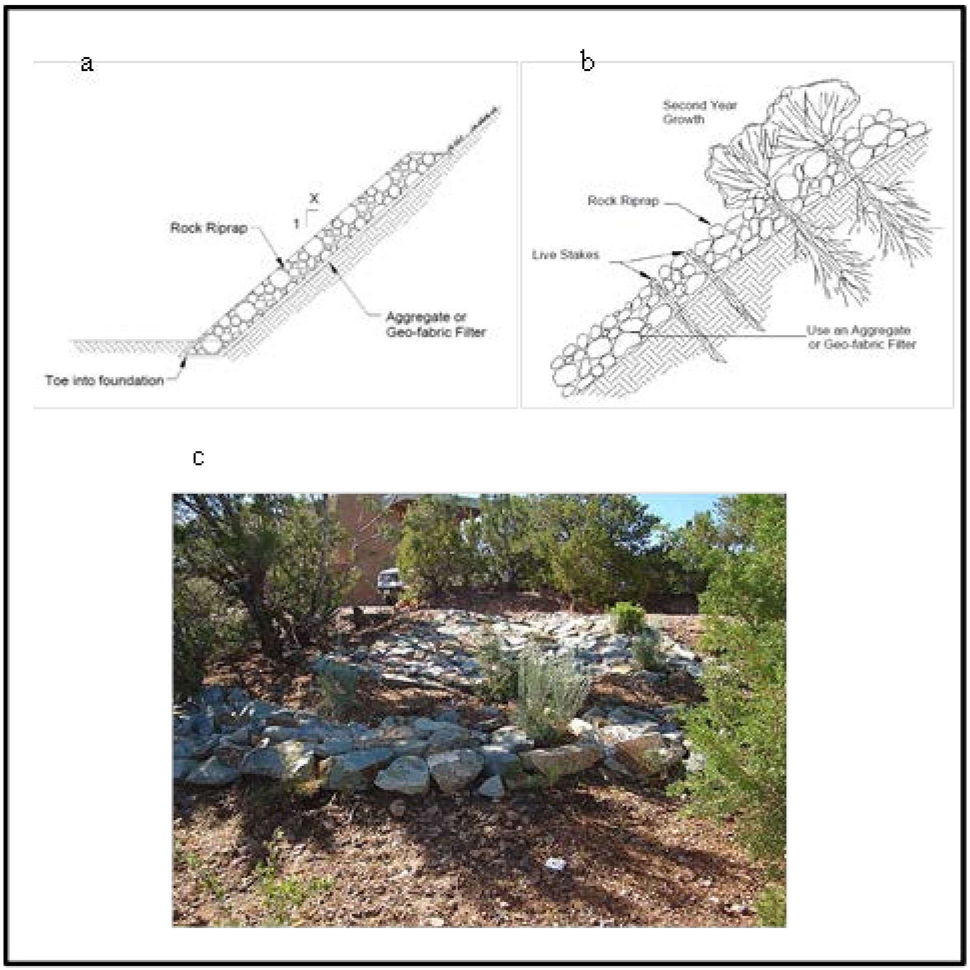

Figure 9. Examples of natural soil reinforcement materials being used to stabilize soil from water and gravity erosion: (a) mixed rock or riprap revetment, (b) vegetation riprap revetment, and (c) a photograph of a vegetation and light riprap revetment. (Illustrations (a) and (b) are from Kearley and McCallister, 2000; (c) is from the California Department of Transportation website www.dot.ca.gov, accessed September 29, 2013).

The placement of rock on sloped soil surfaces to protect against water erosion is termed "revetment." In arid environments, intense precipitation events have a significant impact on soil erosion from sloped areas (Carretier *et al.*, 2012); therefore, the use of strong reinforcement—such as rock revetment, riprap, or a similar technique—may be appropriate.

Depending on the project and site characteristics, other types of erosion control may work better than rock, such as geosynthetics and blankets or mats (Rivas, 2006; Kearley and McCallister, 2000). Collectively, these anthropogenic materials are called rolled erosion control systems (RECS) because they are typically sold in rolls for ease of storage and installation. Geosynthetics are polymer products that are used to stabilize soil on a variety of slopes. Selection of the appropriate treatment is based on site variables, such as slope and soil texture (Rivas, 2006). According to the International Geosynthetics Society, there are several categories of geosynthetics (http://www.geosyntheticssociety.org/Resources/Documents/Classification/English.pdf), but only a few are commonly used to prevent soil erosion in natural settings (Figure 10):

- Geotextiles: woven, nonwoven, knitted, or stitch-bonded fibers. They are permeable and are typically composed of synthetics, such as polypropylene or polyester (http://www.geosynthetica.net/underwriters/supertex-inc/ (Products) http://www.archiexpo.com/prod/colbond-geosyntetics/geotextiles-erosion-control-2105-440794.html).
- Geogrids: materials that have an open grid-like, square appearance (http://www.fs.fed.us/eng/pubs/htmlpubs/htm08232813/page02.html).
- Geonets: similar to geogrids, but are composed of polymeric ribs with acute angles (http://www.geo-synthetics.com/drainage_geocomposites.html).
- Geocells: three-dimensional networks of interconnected cells manufactured from ultrasonically welded, high-density polyethylene or novel polymeric alloy strips (http://www.alibaba.com/product-gs/600348245/slope_protection_geocells_with_the_new.html).

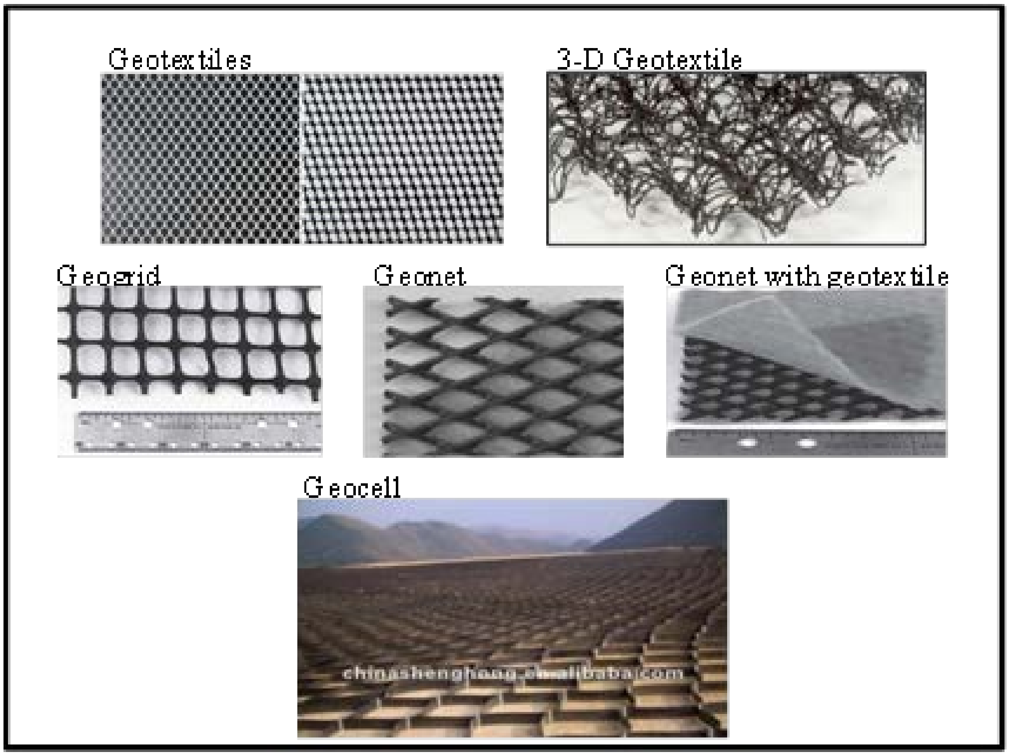

Figure 10. Examples of geosynthetics.

Carroll *et al.* (1992) compared geosynthetics to mulch and organic blankets and found the use of ultraviolet-stabilized fiber provided a much longer life. In arid environments where plant establishment requires time, nondegradable erosion control materials are likely to provide longer soil erosion protection. Strength is an advantage of geosynthetics. Latha and Murthy (2006) evaluated the strength (stress and strain) of geotextile, geogrid, and geofilm products. All three geosynthetics significantly improved the cohesion of sandy soil compared to untreated sand. The geotextile and geofilm imparted significantly higher cohesion strength than the geogrid product. Geofilms should not be considered an appropriate erosion control material for soil stabilization at contaminated-soil sites on the NNSS because the impermeability of films prevents infiltration and revegetation. However, if the goal is to prevent leaching of contaminants within the soil profile in addition to erosion, then a geofilm may be an appropriate treatment.

A study performed to assess the load-bearing capabilities of sand reinforced with geosynthetics yielded results that also indicate geosynthetics will reduce soil erosion and can help prevent slope failures (Kearley and McCallister, 2000). Most geosynthetics are well-suited to slopes up to 50 percent and are manufactured with ultraviolet resistant properties, which make them less likely to degrade over time. Geosynthetic materials are not suitable for some locations because the soil surface must be smooth for proper installation, the material must be covered with soil or gravel, and the installation may entrap burrowing wildlife (Rivas, 2006). The cost of geosynthetics is considered medium to high depending on the type of geosynthetic material (Caltrans, 2003) and the cost to cover the material with soil or gravel. Because geosynthetic materials are now engineered for increased longevity, over the long term the initial purchase and installation costs may be more cost effective than short-term degradable products.

Erosion control mats or blankets (i.e., degradable RECS) are typically composed of natural fibers (such as straw, coconut fiber, wood fiber, jute, etc.) or synthetic materials held together by netting that may be synthetic or biodegradable (Carroll *et al*., 1992). Figure 11 provides an example of three natural-fiber erosion control blankets that are commonly used to inhibit soil erosion. Other types of blankets include jute netting and biodegradable netting. Although less costly, netting does not provide the same level of soil stabilization as blankets or mats because rain drops can impact soil within the net interspaces (Sutherland, 1998).

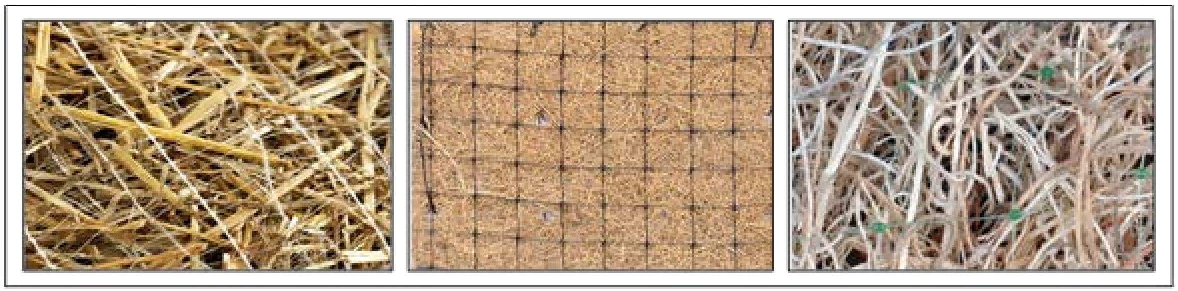

Figure 11. Examples of straw, coconut, and aspen wood fiber erosion control blankets, respectively, are depicted from left to right.

Natural erosion control blankets have several beneficial properties, such as retaining seeds to provide time for germination and establishment, slowing runoff and thereby reducing rill formation, and creating improved conditions for plant establishment above the blanket (Rivas, 2006). The limitations of this material are the possibility of runoff flowing under the blanket (if the upslope blanket edge is not buried under soil), photodegradation of the natural material resulting in loss of erosion protection potential after two to three years, and required maintenance.

When selecting the appropriate RECS treatment to protect against erosion, a number of factors must be taken into account. Products are specifically designed to function better on gently sloped or relatively flat surfaces, so the slope of the project site is one of the first criteria for proper treatment selection (Rivas, 2006; Sutherland 1998). Soil properties (texture, structure, nutrients, and moisture status), anticipated weather conditions, and whether seeds will be planted are three other important criteria for RECS selection. The structure and composition of RECS play a direct role in their effectiveness and ability to reduce erosion. As depicted in Figure 12 some natural RECS provided significantly better performance and protection against splash erosion than most synthetic RECS, although the effectiveness of natural RECS may decline over time depending on degradability and site conditions (Rivas, 2006).

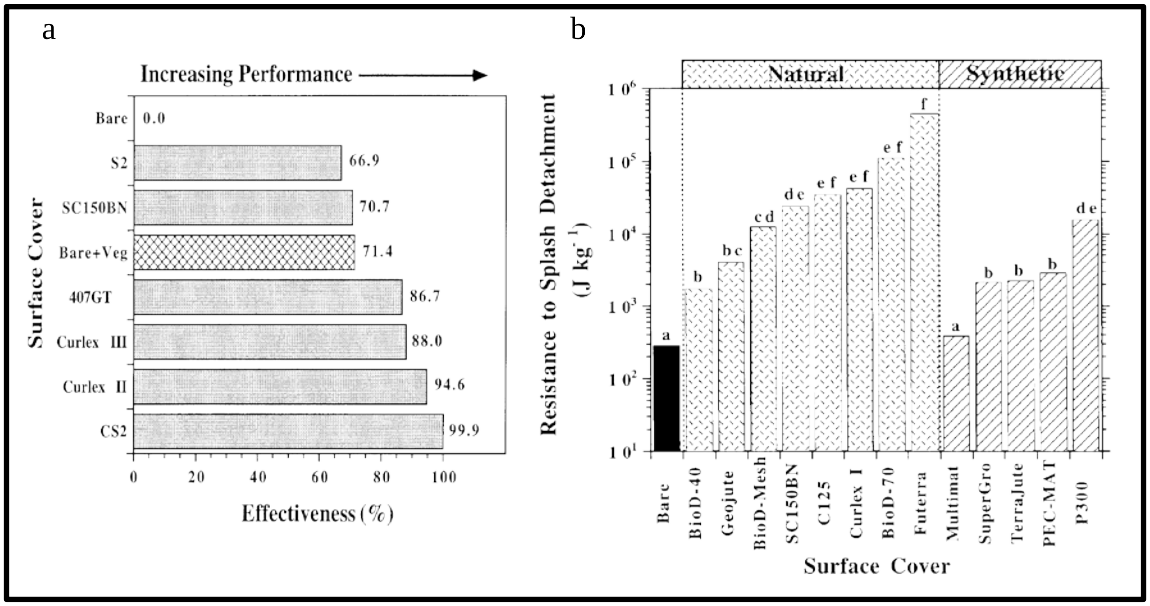

Figure 12. Graph depicting erosion performance and erosion resistance: (a) comparison of the performance of bare soil at a 50 percent slope in Southern California versus several natural and synthetic RECS for three natural rain events, where natural RECS include all Curlex products (aspen fibers), S2 (straw), CS2 (70/30 straw and coconut fiber), and SC150BN (straw and coconut mattress fiber); 407GT (photodegradable polypropylene) is a synthetic RECS; and (b) differences in resistance to splash detachment of soil particles for bare soil versus natural and synthetic RECS receiving simulated rainfall with intensity of 120 mm hr^{-1} for a one hour duration; bars with the same letter are not significantly different (α=0.5) and BioD-Mesh represents BioD-Mesh 60, BioD-40 represents BioD-Mat 40, BioD-70 represents BioD-Mat 70, Multimat represents Multimat 100, and TerraJute1 is also known as LANDLOK 407GT (formerly POLYJUTE 407GT). Both graphs are from Sutherland (1998).

Barriers such as silt fences and rock or wooden walls (wattles) are commonly used in addition to RECS to reduce wind or water erosion by placement perpendicular to prevailing winds or perpendicular to a slope to reduce long slope lengths (Kearley and McCallister, 2000; Rivas, 2006). Proper selection of material, installation, and maintenance are required for barriers to be effective. For example, a geotextile silt fence should not be used in areas where high velocity runoff is anticipated (Kearley and McCallister, 2000). Figure 13 provides an example of a properly installed silt fence using a geotextile fabric vertically placed between stakes that are no more than 3 m (10 ft) apart. Although installation of barriers increases the initial cost of soil erosion control measures, they can significantly reduce the overall cost of erosion protection by ensuring the success of surface cover measures.

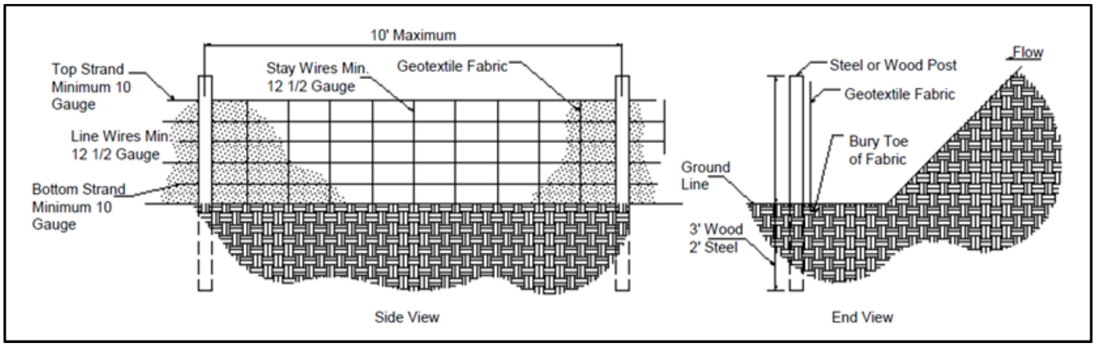

Figure 13. Example of a proper silt fence installation (from Kearley and McCallister, 2000).

Plastic-pipe wind barriers were identified as a possible dust control measure for large area land management in high elevation desert regions of Southern California (Dustbusters Research Group, 2011). Like snow fences, plastic pipe wind barriers were designed to be low-cost, low-environmental-impact mechanisms to modify wind-flow patterns and decrease the potential for wind erosion. Bilbro and Stout (1999) developed and tested an efficiency index to compare the effectiveness of several types of wind barriers based on the optical density (percent of a frontal view that would be obstructed) and density index (product of the number of rows × optical density per row). The plastic-pipe wind barriers (2.31 cm [0.91 in] diameter × 100 cm [3.3 ft] length), standing perpendicular to the soil surface, were compared to vegetation and slat-fence wind barriers. The efficiency indices for the plastic-pipe wind barriers were greater than for vegetative wind barriers and nearly equaled the efficiency of a slat-fence in reducing downwind velocities (Bilbro and Stout, 1999).

Mulching Methods

Mulching methods reduce soil erosion by the spreading or spraying of loose mulch material on the soil surface. Mulching materials include gravel and large rocks in addition to organic materials such as loose straw, pine, wood, paper/pulp, bonded-fiber matrices, organic ash, and fly ash (Rivas, 2006; Brooks, 2009). The primary benefits of mulching methods include reduced splash erosion and runoff, seed coverage, soil nutrient and structure improvement, and the moderation of soil temperature, as well as the relative low cost and ease of installation (Jennings and Jarrett, 1985; Rivas, 2006; Kearley and McCallister, 2000). A primary limitation of mulching methods is that the loose application of material results in an increased potential for wind and water to erode the mulch cover if it is not properly installed. Although gravel and rock mulches are more resistant to loss from wind erosion than organic mulches, they can be undercut by concentrated water erosion (Rivas, 2006). Other limitations of mulches include the potential for increased seedling mortality, the possible need to apply nitrogen fertilizer when using straw or wood mulch coupled with seeding, the relatively rapid decomposition rates of organic mulches, and the possible introduction of weed seeds, even if the mulch is certified weed free.

Jennings and Jarrett (1985) evaluated erosion reductions for several mulch treatments, including straw (two application rates), two sizes of bark chips (large bark had two application rates), two sizes of rocks (average diameters of 30 mm [1.2 in] and 100 mm [4 in]), and three commercial products (jute net, burlap, and the paper product Hold-Gro). Although it is doubtful that there were statistically significant results (three replicates were performed, but statistics were not presented in the paper), organic materials tended to provide improved erosion protection than the rock mulches for an unnamed location in Pennsylvania (Jennings and Jarrett, 1985; Sutherland, 1998). Results may vary for more arid locations. Improved erosion protection in this case is equated with a longer time period until runoff occurred, a decreased in total sediment yield (i.e., the amount of soil eroded from the surface), and an increase in sediment yield reduction effectiveness, as presented in Table 2.

Fly ash (a by-product of burned coal) and other organic (waste product) ash have been studied as possible mulch materials that simultaneously provide reuse and waste minimization (Oluremi *et al*., 2012). Fly ash and other ash materials generally improve soil nutrient status, as well as both soil structure and the bearing ratio, or strength. These materials typically do not improve erosion control and, in at least one case, erosion values were found to be five times greater as a result of fly ash application (Gorman *et al.*, 2000).

Hydromulches (also termed hydroseeding when seeds are present in the slurry) are typically used for simultaneous seed and fertilizer applications that are mixed with wood, cellulose, paper pulp, or recycled fibers. Generally less costly than RECS, hydromulches do reduce soil erosion and improve soil nutrients and structure. However, the effectiveness is short-lived and the material can be washed away easily in runoff from high-intensity storms (Rivas, 2006) or storms of sufficient duration to produce runoff.

Rock mulches involve simply covering the soil surface with rock material. Rock pavements (e.g., desert pavement) are natural features in desert environments (Whitford, 2002; Dixon, 2009), but typically rock mulches are installed as part of xeriscaping (low-water-use landscaping) in dry environments. In addition to physically covering the soil surface, in a natural setting, rock mulches still allow for water movement into the soil and vegetation growth, which provides sites for biological activity. In a study of the stabilization of gold mining activities in the Mojave Desert, Walker and Powell (2001) found background soil moisture contents were higher under an abandoned, bulldozed (compacted) dirt road than overburden piles or heap leach (processed rock). When subjected to simulated rainfall, rock mulches increased the soil moisture retention on the unconsolidated material piles, even though there was no effect on the road (Walker and Powell, 2001). In a study on gravelly loam soils from Plutonium Valley on the NNSS, Winkel *et al*. (1995) examined the effect of gravel mulch depth on seed emergence. Four treatments were applied to greenhouse flats using seeds from nine native plants with one control treatment and three cover treatments. Seeds were broadcast on all treatments and no covering was applied to the control. A 1.0 cm (0.39 in) layer of soil covered the seeds on the second treatment, a 2-3 cm (0.79-1.18 in) layer of gravel was applied to the third treatment, and a 4-5 cm (1.57 to 1.97 in) layer of gravel was applied to the fourth treatment. Gravel size ranged from 3-25 cm (1.2-9.8 in). Only one plant (a grass, galleta [*Hilaria jamesii*]) germinated successfully. Winkel *et al*. (1995) concluded that even though a 2-3 cm (0.79-1.18 in) layer of gravel mulch may aid galleta grass emergence, a deeper layer (4-5 cm; 1.57-1.9 in) prevented emergence and acted as a barrier to plant growth. Therefore, the long-term effectiveness of rock mulches requires further examination.

Table 2. Selected runoff (RO) and sediment yield (SY) data from a laboratory investigation (from Sutherland [1998] with data modified from Jennings and Jarrett [1985]).

Surface Cover	Time to RO (s)	ROC* (%)	RO reduction effectiveness (%)	Time to Peak SY (s)	Total SY (kg m^{-1} hr^{-1} [lb ft^{-1} hr^{-1}])	SY reduction effectiveness (%)
Bare	70	75.11	0.00	125	2.07 (1.39)	0.00
Small rocks (212 Mg ha^{-1}) (95 ton $acre^{-1}$)	110	63.11	15.98	200	0.76 (0.51)	63.19
Oat straw (2.24 Mg ha^{-1}) (1 ton $acre^{-1}$)	130	52.89	29.58	250	0.56 (0.38)	73.04
Large rocks (506 Mg ha^{-1}) (225 ton $acre^{-1}$)	100	55.56	26.03	270	0.44 (0.30)	78.55
Hold-Gro†	100	54.22	27.81	345	0.40 (0.27)	80.87
Burlap	150	46.22	38.46	295	0.23 (0.15)	88.70
Jute	250	28.00	62.72	450	0.10 (0.07)	95.36
Oat straw (8.96 Mg‡ ha^{-1}) (4 ton $acre^{-1}$)	260	23.11	69.23	445	0.04 (0.03)	97.97

* ROC = runoff coefficient, in percent

† Hold-Gro: a heavy porous paper product reinforced with nylon string and often prepared with embedded seeds.

‡ Mg ha^{-1} = Megagram per hectare (ha)

Revegetation and Shrub Facilitation

One of the goals of soil restoration and stabilization is to increase the vegetation density and species richness to pre-disturbance levels. This commonly requires a mix of erosion control methods to stabilize the soil for seed germination and plant growth. In arid climates, this process is exacerbated by long dry periods and short, intense rain events that produce runoff. Therefore, revegetation treatments may require irrigation until vegetation becomes established.

Although it is typically desirable to revegetate with native species, conditions may dictate the use of artificial materials that simulate plant structure and form. The presence of vegetation reduces water erosion by intercepting water before it strikes the soil, increasing infiltration of water into the soil, and reducing runoff velocity, which subsequently decreases water erosion (Sotir and Gray, 1989; Goldsmith and Bestmann, 1992). Vegetation and artificial materials simulating vegetation also increase surface roughness, which reduces wind velocities near the soil surface, and thus reduces wind erosion.

Revegetation is performed either by applying seeds or planting shrubs. To perform successful seeding of an area, it is recommended that the slope not exceed 50 percent and that mulch or RECS be applied to hold the seeds in place long enough for germination and seedling establishment (Kearley and McCallister, 2000). Hydromulch containing native seeds is often an effective combination treatment that enhances soil stability at the same time that seeds and nutrients are applied to the soil surface (Rivas, 2006). Anderson and Ostler (2002) reported that seeding before winter with plastic mulch performed better than straw mulch and successfully revegetated areas within the Great Basin portion of the NNSS. This treatment method also worked well in the Mojave Desert with the addition of irrigation to help germinating seeds survive long, dry periods. A revegetation study in the Tengger Desert of northern China used a straw checkerboard treatment (the placement of straw in a grid pattern within open interspaces) to stabilize sand dunes for revegetation, which provided the added benefits of accelerating conditions for the formation of a biological soil crust and enhancing the species diversity of the crust (Li *et al.*, 2003).

RELEVANCE TO NNSS AND SUMMARY

Lee *et al*. (1987) showed that the distribution of radionuclides at NNSS test locations were deeper and more widespread than expected due to post-test redistribution by wind and water erosion and infiltration into the mostly porous and sandy soil. Turner *et al*. (2003) documented Cs and Pu levels in soils downwind of the NNSS in excess of levels found at upwind locations, even though these elements were confined to the upper few centimeters of the soil profile.

Published reviews indicate several methods of soil stabilization have been implemented at and near the NNSS, including vacuuming, capping, burying of surface soil, re-contouring the surface, adding PAM, and adding mulches. In addition, and most of these methods (except for vacuuming) were used in combination with revegetation efforts (Anderson and Ostler, 2002; Hansen *et al.*, 2012). The reported revegetation efforts were successful in terms of achieving vegetation densities comparable to surrounding vegetation densities within three years. Although subsequent data reported in Hansen *et al.* (2012) show that plant densities and species diversity are being maintained, no data assessing revegetation effectiveness in terms of soil loss and movement were presented. The effect of a proprietary emulsion applied to soils at the NNSS Smoky Site location to abate soil erosion from wind and water was inconclusive as above-normal precipitation during the test period precluded long-term evaluation, even though depositional dust from treated plots increased after treatment (Etyemezian *et al*., 2006). The test of the chelating ability of the emulsion on desert soils near Yuma, Arizona, showed that the emulsion pH likely changed the ambient soil pH, mobilizing depleted U while the hydraulic conductivity of the treated soil decreased (Young *et al*., 2007). However, no long-term impacts on the perennial vegetation structure were evident. Field testing of the emulsion at the Smoky Site showed that existing vegetation was unaffected by the treatment, but runoff and sediment movement increased (Desotell *et al*., 2008). The effect of the emulsion was observed to have degraded significantly 20 months after application.

No single stabilization treatment exists that can decrease the sustained susceptibility of contaminated soils to wind and water erosion throughout the NNSS. *Ex situ* treatments can be damaging to vegetation and produce contaminated by-products, but they may be necessary in some instances. Some *in situ* chemical soil stabilization methods have been shown to increase soil cohesion, and thereby decrease soil erosion by wind, but chemical treatments can decrease soil infiltration and increase runoff. Some chemical treatments increase soil aggregation, which can potentially maintain soil infiltration and increase the size of particles exposed to wind, but they require periodic re-treatment. The treatments themselves can also change the physiochemical characteristics of the soil and alter the nature and mobility of the contaminants in the soil. Long-term stability of soils may be achieved by revegetation, but establishment of vegetation in the dry Mojave Desert portion of the NNSS requires multiple irrigations (Anderson and Ostler, 2002).

Mechanical stabilization methods involve some level of soil disturbance, from grading or compaction to movement over the soil surface during mulch application. In areas where rill or gully erosion has occurred, grading and backfilling, terracing, or other soil reinforcement methods will have to be considered to prevent further water erosion and soil movement down slope. In areas where rills or gullies have not formed, mulching and revegetation may be sufficient to reduce soil erosion, but RECS should be considered for areas where erosion control is more critical. As noted by Anderson and Ostler (2002), plastic mulches provided a higher germination and plant establishment rate than straw mulches. In areas where wind erosion is of concern, it is important to add vertical structure above the soil surface to provide wind breaks. The most natural addition of a vertical structure is revegetation, but until plants grow to a sufficient size to reduce the impact of wind, artificial structures may need to be placed at the site. Artificial structures include fencing with geotextiles, artificial plants or PVC/wood stakes. Gravel mulches have been proscribed for a portion of the Owens Valley Lake by the Great Basin Unified Air Pollution Control District in Bishop, California (Jack Gillies, DRI, personal communication). A gravel mulch/cover was designed to provide 95 percent control efficiency.

Maintenance of soil stabilization activities is important and necessary for continuing soil erosion control. An inventory and comparison of treatments and treatment location characteristics can be useful to assess the long-term efficacy of soil stabilization activity on the NNSS. A form, like the one presented in Figure 4, can be used with the addition of soil parameters such as pH, cation exchange capacity, sodium absorption ratio, calcium carbonate content, particle size distribution, structure, and surface soil cohesion. Documentation of soil parameters is helpful in selecting an appropriate soil stabilization treatment method (Rivas, 2006). Any new soil stabilization activity should be monitored and documented to help develop a list of successful treatments. Stabilization will be site specific and, depending on the type and degree of contamination, may require a unique combination of physiochemical stabilizers and mechanical stabilization methods to address both wind and water erosion on the NNSS.

The keys to successful erosion control are a thorough assessment of the site, careful consideration of soil stabilization methods best suited to the site, proper installation of the treatment by trained individuals, and long-term monitoring and maintenance of the site after installation. Maintenance of the erosion control treatment will be important for radiological-contaminated soils to constrain the movement of contaminants as much as possible.

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