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Low-Logistic Erosion Control Methodologies

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PURPOSE: This paper provides an in-depth review of certain slope stability practices discussed in ERDC/GSL TR-19-44, a technical report titled *Erosion Control of Earth Covered Magazines to Maintain Minimum Cover Requirements*. At the request of the sponsor, US Army Engineering and Support Center, this document specifically focuses on cost-efficient, low-logistic methods of erosion control such as shotcrete and spray-applied stabilizers.

INTRODUCTION: As described in ERDC/GSL TR-19-44, earth-covered magazines (ECMs) must maintain a minimum soil cover to meet specified safety regulations. Even when adequately constructed, soil movement over time can be of concern and may lead to lack of appropriate cover. ERDC/GSL TR-19-44 gives broad descriptions of multiple techniques of interest to alleviate these issues, while this document serves to focus on methods that are perceived to be of highest interest. These techniques are therefore described in a narrower but deeper scope. In order to ascertain whether these techniques are appropriate for the project requirements, focus will be on soil and erosion movement control rather than traditional slope-stability structural needs.

SPRAY-ON CONCRETE PRODUCTS: Spray-on concrete, commonly referred to as shotcrete or "gunite," utilizes air pressure to spray concrete through a nozzle and compact on the targeted surface. "Gunite" actually refers to a proprietary product, so while the two words are often used interchangeably, this document will focus on the wider category of shotcrete. Wet-mixed shotcrete describes the process in which a pre-mixed concrete, typically directly from a batch plant in a concrete mixing truck, is pumped into the shotcrete pump and nozzle equipment. In dry-mixed shotcrete, materials are not mixed with water until they are combined at the nozzle of the sprayer. Dry-mixed shotcrete requires the storage of materials on site, usually in bags, until required. Due to these differences, wet-mixed shotcrete can have advantages in availability and logistics, while dry-mixed is more common for proprietary products.

Shotcrete composition and mixture designs are similar to typical cast-in-place concrete in that a Type I/II cement with or without supplementary materials will provide the cementing component of the mixture. Coarse and fine aggregate are also utilized, although the coarse aggregate is typically prescribed a nominal maximum aggregate size of 3/8 in.[1], and the sand must meet the requirements for corresponding local state shotcrete mixtures. Admixtures for air entrainment and high-range water reduction are also common. Specifically, a polycarboxylate admixture may be necessary to ensure adequate pumpability and workability on the surface.

[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *U.S. Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Soil type and properties can be indicative as to the success rate of a shotcrete surface. Water movement behind a shotcrete face can be problematic as the density of shotcrete will prevent moisture movement through the surface. In areas in which freeze/thaw cycles are common, care should be taken to ensure there is no water build up behind the surface as expansion due to freezing can fail the shotcrete surface. Shotcrete is typically tested for freeze/thaw resistance utilizing ASTM C666 (2015); but, according to the Federal Highway Administration, weep holes or wick drains are required in all shotcrete applications to prevent water build-up that can lead to cracking or instabilities (FHWA 2020).

Adhesion or shotcrete bond strength is an important indicator of the likelihood of success of a shotcrete rehabilitation or prevention project. Adhesion to hard, dry granite materials are often quite high, but can be low in softer materials, damp ground, or areas that are frequently exposed to water and moisture (Kumar et al. 2002). For this reason, an initial bonding study may be required to evaluate the applicability of shotcrete for each specific project location and soil type. In the case of low bond strengths, additives or accelerants may be used to increase bonds to an acceptable level.

Application of shotcrete can be conducted at a large range of slopes and heights. Figure 1 illustrates high-slope, high-elevation shotcrete for an earth-retaining structure applied with a mechanical sprayer. For this reason, the specific ECM application slope angles are not perceived to be an issue as they will be fewer than common application slopes. For the slope in Figure 1, a wire mesh system with nails into the slope was required for sufficient adhesion.

Figure 1. Shotcrete for high-slope, high-height applications (Putzmeister 2019).

The appropriate curing of shotcrete will be crucial in the long-term effectiveness of the application. Typically, shotcrete is cured according to ACI 308R (2016). Shotcrete surfaces must be kept moist for a minimum of seven days after placement usually by misting or covering with a wet fabric. After the initial cure, cellulose or membrane curing can be used to ensure the shotcrete meets sufficient strength to reduce shrinkage.

In most shotcrete applications, soil nails or a nailed reinforcement system is used to ensure adequate structural reinforcement. Figure 2 shows soil nails being driven into a slope prior to shotcrete application. The type and level of reinforcement necessary is soil and slope dependent. This technology has been successfully used on bluffs in southern California including Dana Point and San Clemente (Leighton et al. 2014). These projects utilized shotcrete up to 6 in. in depth for stabilization of structurally unsound slopes.

Figure 2. Soil nailing (Chinchiolo and Barret 2011).

Few cases were found in which shotcrete was used without soil nailing, as generally shotcrete for erosion control is utilized in areas with structurally deficient slopes. In the absence of soil nails, thin rebar sections or mats are typically required to provide a bonding surface. An example of a thin wiring section is shown on a partially finished shotcrete retaining wall in Figure 3. Shotcrete with steel-fiber reinforcement can reduce or eliminate the need for a reinforcement layer. Steel fiber shotcrete will add materials' costs, but may reduce costs for the project if it eliminates the need for thin wire sections.

Unreinforced shotcrete products provide little structural support but can be effective in mitigation of erosion and soil movement (Andrew et al. 2011). A project by the Missouri Department of Transportation (DOT) utilized shotcrete in this manner to provide stability and prevent soil sloughing on a hillside cutback necessary to increase roadway width (Helitech 2020). This contractor has successfully completed projects of this nature in Midwestern and Southeastern environments.

Costs for shotcrete vary widely with application type and location. For nonstructural general use shotcrete, a rough estimate between $125 and $195 per yd of material in place is likely. Use of specialty materials, such as the steel fiber-reinforced concrete, may increase costs.

Figure 3. Shotcrete retaining wall (Soil Engineering Construction 2020).

Current ongoing work at the Engineer Research and Development Center (ERDC) is investigating shotcrete and other spray-on concrete products and techniques for applicability in blast and ballistic protection, as well as force projection for infrastructure repair. This research effort is novel and is likely of high interest for this specific application. The methodology also includes some extremely high fiber loading for protection against blast and ballistic effects. However, results of this research effort were not envisioned being complete until 2022 or later. Specifically concerning the ECM application, almost no cases of spray-on concrete products were found to be constructed without soil nailing, rebar matting, or, in most cases, both. While it is perceived that the lower slopes and lack of a true soil-stabilization requirement present in ECMs would not require these additions, there is a lack of data and in-service case studies to support this assumption.

SPRAY-ON ADDITIVE PRODUCTS: Spray-on noncementitious-based products have the capability of preventing soil erosion while providing a rapid and low logistics alternative to full-scale soil-stabilization practices. Spray-on products are typically applied with a standard pump truck and do not usually require skilled operators. While some products do require surface-level mixing of soil and product, many compositions are topical only and require no disturbance of the soil surface. Depending on chemical composition, these material's effects and working performance properties will differ in determining optimal products for a specific site and application requirement. A list of potential stabilizers was developed by the US Army Corps of Engineers (under the name Waterways Experiment Station) that included acids, asphalts, cements, lime, resins, salts, silicates, and other products (Oldham et al. 1977). This list has become somewhat outdated but can still be useful in identifying potential treatments.

Application rates for polymer stabilizers likewise depend on soil properties, but in general application rates of 4%-5% polymer typically achieve the highest level of stabilization. While increasing polymer content further can continue to increase compressive strength, it does not necessarily provide any additional soil erosion control (Naeini et al. 2012). Evaluations by scanning electron microscope (SEM) have suggested that the erosion control is a factor of the mechanical property changes, specifically the interconnections between particles, and not typical structural soil stabilization (e.g., compressive and shear strength) factors (Al-Khanbashi and Abdalla 2006).

A newly developed material, polyacrylamide polymers (PAM), was originally created for soil-erosion controls during farming and irrigation activities (Lentz et al. 1992; Lentz and Sojka 1994) and has now become a common spray-on additive. PAM has since been modified for use in roadways and construction projects (Roa-Espinosa et al. 2000) and for use as a dust control product to prevent dust storms or “brown-outs” on helicopter landing pads. PAM works by stabilizing the soil surface structure and pore continuity (Malik and Letey 1991). Compared to typical starch copolymers, PAM has shown to be significantly more reliable at providing a greater level of erosion control (Lentz et al. 1992).

Pre- and postapplication testing has been conducted at Marine Corps Air Ground Combat Center in California, as this site has soil similar to Middle Eastern areas of interest. An array of spray-on products was tested, and it was found that anionic PAM/acrylic acid copolymer called Tri-PAM was the most capable of significantly reducing airborne dust by preventing soil erosion due to wind of the top surface (Orts et al. 2007). The average product price was \$400-\$500 per 50 m^2 treated. Some cheaper alternatives for PAM products with other additives were also tested and are shown in Figure 4. The figure illustrates the percent of reduction in sediment after product applications.

While PAM and PAM-based products provide a useful metric, a variety of other products are also available. Polymer-based stabilization techniques have expanded in the recent decades to include buildings, roads, embankments, slopes, and structural capabilities. Specific stabilizer-type to soil-type studies have been conducted for the most common soil types and are readily available in literature. For example, polymer resin materials have been shown to perform well with sandy soils, and urea-formaldehyde has shown success for dune sands (Gopal et al. 1983). For clayey soils, a combination of epoxy resin and polyamide hardeners have been shown to increase strength of soil at a reduced set time after application (Ajayi-Majebi et al. 1995). Polymer emulsions, while useable on all soil types, can be more beneficial on some types than others, as the polymers’ emulsions increase soil strength by bonding the particles to each other. These may be especially beneficial in soil erosion control. Synthetic versions of polymer emulsions are widely available and can be used in similar methods without the added environmental concerns (Kestler 2009). The synthetic emulsions can be bound using water, which dissipates upon reaction with the soil, to replace the usual petroleum-based binding.

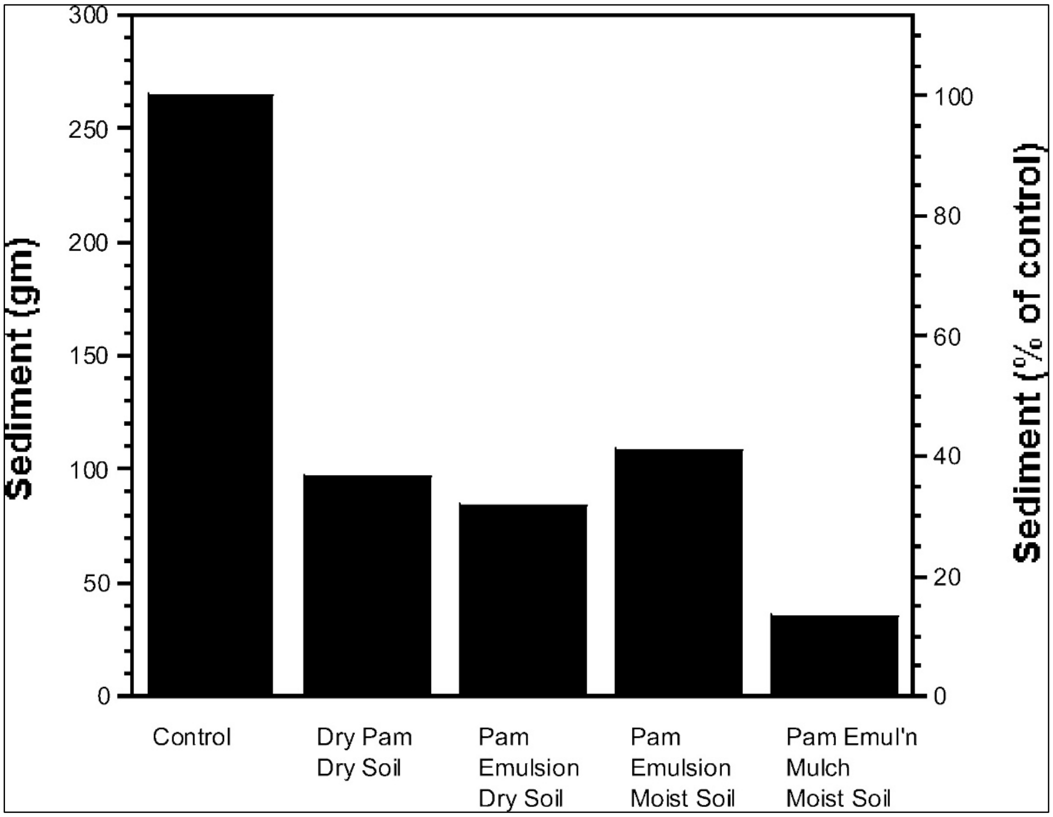

Figure 4. PAM product combinations' effect on sediment (Orts et al. 2007).

Polyvinyl acetate-based polymer emulsions have shown high resistance to wind-based erosion on multiple soil types including wind-blown sand, silty loam, and silty clayey loam. In a 2012 experiment, wind tunnel tests successfully proved erosion control in up to 26 m/s winds (Movahedan et al. 2012). In this study, treatment amounts were held constant at 25 g/m^2 of soil treated. In other studies focusing on particularly sandy soils, polyvinyl acetate and acrylic polymers were found to be too water sensitive in arid environments and were not the product of choice (Siddiqi and Moore 1981). This study concluded that in sandy arid environments, a copolymer material of butadiene-styrene was the ideal method of erosion control without affecting soil permeability.

As with any industry, proprietary blends and names for these polymers and compounds are abundant and individual contractors may be able to dial in exact chemical compositions based on soil profiles. One of the proprietary products, Soiltac, is primarily utilized for dust control, erosion control, or road surface hardening. Figure 5 illustrates the application process for a proprietary material under the name Soiltac. Typically, application is by spreader truck or directly sprayed on the surface from personnel. Soiltac is a copolymer that has previously been used by the Marine Wing Support Squadron 271 for helicopter landing zones. Dust suppression and erosion control are achieved by creating a crust or cap surface for the spoil that is resistant to wind and water.

The material is synthetic and therefore carries little to no negative environmental effects or exposure effects to human, animals, or vegetation. Application rates vary depending on length of required treatment, but reapplication is usually necessary after 2–3 yr. Figure 6 shows an example of hardened crust formation after Soiltac application. This product, like many others having been previously utilized by government agencies, is available through the US General Services Administration.

Figure 5. Soiltac application (Soilworks 2020).

Figure 6. Hardened crust (Soilworks 2020).

A proprietary material developed by Global Road Technology (GRT), under the name "Enviro-binder," is a film-forming polymer emulsion that provides erosion control on surfaces. This material has been previously used successfully in multiple projects for dust and erosion prevention. The product is synthetic, does not pose added environmental concerns, and is described as completely waterproof and unaffected by storm seasons or runoff (GRT 2019). Figures 7 and 8 illustrate the product being applied to hillside projects for erosion control on a slope.

Figure 7. Light rail embankment (GRT 2019).

Figure 8. Interchanged embankment (GRT 2019).

While the two products mentioned above, Soiltac and Enviro-binder, illustrate excellent examples of successful dust- and erosion-control materials, there are a multitude of products available that will likely meet specifications for the slopes of ECMs. The specifics of each material will determine reapplication rates; however, little to none of these materials should be described as “permanent” solutions, as over the course of time reapplications will likely become necessary. Due to the cost effectiveness and ease of application, further treatments every 2 or 3 yr may not be of highest concern.

Final costs of spray-on additive products will depend on the soil samples at each location to determine which product would be most beneficial and at what dosage rate. At normal application rates, chemical compounds such as PAM or PAM composites may be as low as $265–$550 per hectare, less than mulch covering (Green and Stott 2001). Dust-control-specific proprietary chemicals will be higher, but still significantly less than shotcrete products.

CONCLUSIONS: Past research efforts and in-service projects have shown high ability of both shotcrete and spray-on polymer products to control erosion. Shotcrete applications typically involve creating a structurally sound slope, usually for construction purposes. Because of this, rebar matting and soil nailing are commonly associated with shotcrete operations. For ECM erosion control purposes, the slopes in question are lesser than those typically seen with shotcrete reinforcing, and the ECM cover is not necessarily required to be structurally sound. This would seem to indicate that soil nailing and rebar matting may not be required, but there is little evidence available to support this as it is atypical for a shotcrete project. If soil nailing and rebar matting is required, the increased time and cost of constructing could be prohibitive.

Spray-on additives, such as polymers and synthetic polymers, have had a large amount of successful use in projects very similar to the ECM requirements. These materials are typically used for "dust control" or small slope erosion prevention. Proprietary products already exist and are utilized by the DoD for multiple sediment control purposes, and the ease of applicability is a critical factor in keeping costs and logistics to a minimum. The vast majority of spray-on additives are not permanent and will need to be reapplied usually every 2–3 yr; however, considering the cost savings of each application compared to longer-lasting techniques, this erosion-control methodology may remain the most advantageous and economical. Additionally, the ability to purchase proprietary products that have already proven acceptable in DoD dust-control projects may be worth marginally higher costs compared to common typical chemical additives.

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