Advanced Permanent Erosion Control with Pyramid Structured Turf Reinforcement Mats (TRMs) using X3 Fibre Technology

Amir Shahkolahi
Technical Consultant, Global Synthetics, Brisbane, Australia
E-mail: amir@globalsynthetics.com.au

Jason Crase[1], Raymond Chow[2]
[1]QLD Manager, [2]Applications Manager, Global Synthetics, Australia
E-mail: jason@globalsynthetics.com.au

Abstract

Erosion can be controlled efficiently in many different ways such as through vegetation or by engineered structures. Selecting the best method depends on the geometry, hydrology and cost-benefit analysis. In this paper, a literature review on erosion control improvement and various systems has been presented. This includes hard-armour erosion control techniques such as concrete blocks, rock rip-rap, rock mattresses and reinforced paving systems. Rolled Erosion Control Products (RECPs) are then reviewed as the recent erosion control family for both, temporary and permanent applications for slopes and channels. Turf Reinforcement Mats (TRMs) have then been described as the most effective permanent solution for controlling erosion in channels and slopes. Furthermore, performance considerations and parameters and design procedure for designing a suitable erosion control systems with TRMs are reviewed. Finally, two case histories are presented to evaluate the efficiency of this erosion control system for slopes and channels

1. INTRODUCTION

Erosion occurs as a result of a number of interacting factors and processes such as climate, soil characteristics, vegetative cover, and topography (Alberta, 2011). High volume and velocity storm water runoff can erode soil within open channels, drainage ditches and swales and on exposed slopes, increasing the transport of sediment into receiving waters. Soil erosion can lead to high sediment loads, decreased water clarity, and increased levels of contaminants, such as nitrogen and phosphorus, in surface waters. There is also the possibility for attached pollutants to be transferred along with the sediment (Smith and Bhatia, 2013). In Australia, extensive land clearing and the introduction of agricultural practices that reduce ground cover have led to water erosion being a major and continuing issue (Ryan, 2013). Across parts of the Australian landscape, rates of soil erosion now far exceed rates of soil formation, frequently by a factor of at least several hundred, and sometimes up to several thousand (Bui et al., 2011). This process represents a major threat to the sustainability of Australia's land resources and the ecosystem services they support (Hairsine et al., 2009). The 2011 State of the Environment report identified that up to 10 million hectares of land could have less than 500 years until the soil's horizon will be lost to erosion. Much of this land is in Qld and northern Australia (Ryan, 2013).

Six generally accepted principles for effective erosion control are to reduce erosive forces and increase resisting forces, apply good erosion control for good sediment control, modify topography or grade to reduce sedimentation and increase vegetation establishment, limit soil exposure, keep runoff velocities low, and Inspect and maintain treatments. (Rivas, 2006). In this paper, various water erosion control methods are investigated and Turf Reinforcement Mats (TRMs) and their design procedure are discussed with details as the latest and most beneficial and economical permanent solution.

2. EROSION CONTROL TECHNIQUES/SYSTEMS

Erosion potential is reduced by minimising rainfall impact and by reducing the velocity and depth of surface water flow (Alberta, 2011). Erosion control techniques are activities or practices, or a combination of practices that are designed to protect an exposed soil surface, to prevent or reduce the release of sediment to environmentally sensitive areas, and to promote revegetation as soon as possible and are actually a two-step process; short-term or temporary erosion control, generally followed by the establishment of vegetation for long-term permanent erosion control (Rivas, 2006; Alberta, 2011).

Best Management Practices (BMPs) for erosion control are measures that have been proven to work on construction sites when they were properly planned and constructed. These measures reduce erosion potential by stabilising exposed soil or reducing surface runoff flow velocity. There are generally two types of erosion control BMPs that can be used in conjunction with the minimum requirements (Alberta, 2011): Source Control BMPs and Runoff Control BMPs. Source control BMPs consist of protection of exposed surfaces from the erosive energy of rain splash and surface runoff flow, and includes covering the surface with soil in conjunction with an erosion control material. This should be the primary goal when selecting appropriate control measures. Runoff control BMPs should be considered when providing surface cover for all disturbed areas however is not always possible or practical during construction. This includes the modification of slope surfaces, the reduction of slope gradients, controlling flow velocity, diverting flows around the affected area, and providing upstream storage for runoff (Alberta, 2011).

3. CLASSIFICATION OF EROSION CONTROL MATERIALS

The original classification of erosion control materials for channels and slopes was proposed by Mark Theisen, as temporary erosion and revegetation materials, and permanent erosion and revegetation materials (Koerner and Koerner, 2012). Federal Highway Administration (FHWA) defines two basic classes for erosion control systems in channels based on their type and duration of installation: rigid systems, and flexible systems. Rigid systems can be Cast-in-place concrete, asphaltic concrete, Stone masonry and interlocking modular block, Soil cement and roller compacted concrete (RCC), Fabric formwork systems for concrete or partially grouted riprap. These are non-erodible, permanent and long-duration, but are susceptible to failure from foundation instability (Kilgore and Cotton, 2005). Flexible systems can either be long-term, transitional, or temporary installations and are used where channels require protection against erosion for the service life of the channel (Kilgore and Cotton, 2005). Some long term flexible linings can be Vegetative linings (typically grass species), Cobbles, Rock Riprap, Wire-enclosed riprap (gabions and rock mattresses), Cellular confinement systems and permanent non-degradable Rolled Erosion Control Products (RECPs) such as Turf reinforcement mats (TRMs). Transitional flexible linings can be bare soil, Vegetative linings (annual grasses), Gravel mulch, Open-weave textile (degradable), Erosion control blankets (degradable) and Turf reinforcement mats (non-degradable). Temporary flexible linings can be bare soil, Vegetative (annual grasses), Gravel mulch, and temporary degradable RECPs such as Open-weave textile and Erosion control blankets (Kilgore and Cotton, 2005; Witheridge, 2010). Construction of rigid systems requires specialised equipment and costly materials. As a result, the cost of rigid systems for channel protection is typically higher than an equivalent flexible one (Kilgore and Cotton, 2005).

4. REVIEW OF EROSION CONTROL METHODS: ADVANTAGES AND DISADVANTAGES

The traditional way to control erosion in highly erosive areas was using hard-armour erosion control techniques such as concrete blocks, rock riprap and reinforced paving systems. Although these permanent methods can withstand great hydraulic forces, they are costly and they do not provide the pollutant removal capabilities of vegetative systems. These systems need special equipment to install and can present a hazard to people. Filters also need to be designed properly and planting between stones can be difficult (EPA, 1999; Rivas, 2006; GMA, 2009; Alberta, 2011). Cellular Confinement Systems such as Geocells are other slope erosion control systems that are occasionally used. Local available fills can be used in the cells. These systems are less common due to high cost, installation difficulties, limitation to slopes up to 1:1, and limitation in channels to low flow velocities. These systems need a good surface preparation and all major surface irregularities should be removed. The displacement of infill material in Cellular Confinement Systems can occur (especially in channels) if not suitably stabilised. The soil inside the cells is confined, but erosion and piping can occur beneath the cells on slopes and the cell system can lift from the channel surface in time if not adequately anchored. This system may be undermined on steep slopes. In addition, cell walls limit strength of root plants and waterlogging of the ground can also occur unless adequate drainage exists (CTSW, 2006;

Rivas, 2006; FDM, 2012). Prior to the late 1960's, natural materials including rock riprap, stone masonry, concrete, and vegetation were predominantly used to stabilise channels (Kilgore and Cotton, 2005). Also various mulches including loose mulches, tackifiers and hydraulic mulches have been used for many years to provide seed and soil protection from erosive forces and accelerate vegetation establishment (Lancaster and Austin, 2003). Most recently, Rolled Erosion Control Products (RECPs) have become widely accepted an engineered high-tech cost effective erosion control system for both temporary and permanent application in channels and slopes (Lancaster and Austin, 2003; Lancaster and Myrowich, 2006).

5. ROLLED EROSION CONTROL PRODUCTS (RECPS)

Rolled Erosion Control Products (RECPs) include a variety of temporary or permanently installed manufactured products designed to control erosion and enhance vegetation establishment and survivability, particularly on slopes and in channels. RECPs protect the surface from raindrop impact (NCHRP, 2012), wind and storm water erosion, and they allow vegetation to grow (EPA, 2008: NCHRP, 2012).

In the late 1960’s, faced with the limitation of conventional mulching techniques, manufacturers initiated the development of what has become a diverse group of products known as RECPs (Lancaster and Austin, 2003; NCHRP, 2012). Rolled Erosion Control Products (RECPs) represent the fastest growing and “high tech” segment within the erosion control industry. RECPs were first used in the form of jute mats imported from Asia back in the mid.1950s, but have quickly evolved to include a wide variety of temporary degradable open weave textiles and erosion control blankets, as well as permanent Turf Reinforcement Mats (TRMs). The use of RECPs began to escalate in the early 1990s with the advent of the U.S. EPA’s National Pollutant Discharge Elimination System (NPDES) and the increased awareness of the environmental impacts of soil erosion and sedimentation (Lancaster and Myrowich, 2006). This progress has been especially prevalent in the last 15 years with multiple guidelines being developed by the Erosion Control Technology Council (ECTC) and ASTM International (ASTM) in North America. Standards development has included methods to determine relevant index/physical properties and performance thresholds of RECPs (ECTC, 2006).

Many field and bench-scale laboratory studies since 1988 till now have documented the successful use of RECPs in minimising soil erosion (Smith and Bhatia, 2009; Smith and Bhatia, 2013). Recent studies by Babcock and McLaughlin (2011) and Smith and Bhatia (2013) have also verified the positive impact of RECPs on downstream surface water quality.

6. CLASSIFICATION OF RECPS

There are different classifications available for RECPs, but they are all somehow similar and are performance-oriented classification system based on their physical/performance properties, application parameters and functional longevity requirements (Lancaster and Austin, 2003; ECTC, 2006; FDM, 2012; Koerner and Koerner, 2012). The most common general classification by ECTC is: Temporary RECPs (degradable) and Permanent RECPs (non-degradable) (ECTC, 2004; ECTC, 2006; UDFCD, 2011; Smith and Bhatia, 2013). Temporary erosion control blankets and mats are two dimensional products. They are degradable and leave vegetation unprotected and unreinforced, and should only be used temporarily to establish vegetation under mild slopes and hydraulic situations (EPA, 1999). Temporary RECPs are typically made of biodegradable natural materials (e.g., straw, coconut, and jute fibre). Some temporary RECPs are mulch control nets, Erosion Control Blankets (ECBs)/jute mats, Mulch Control Nets (MCNs) and Open Wave Textiles (OWTs) (ECTC, 2004). These mats can be used in channels with maximum shear stress between 12 and 100 pa and slopes up to 5H:1V or 1H:1V, depend on the type of the RECP (ECTC, 2004, UDSCD, 2011). For applications where natural vegetation alone will not sustain expected flow conditions and/or provide sufficient long-term erosion protection, furnishing a permanent non-degradable rolled erosion control product with the necessary performance properties to effectively control erosion and reinforce vegetation under the expected long-term site conditions is necessary. Permanent RECPs are also known as Turf Reinforcement Mats (TRMs) (Lancaster and Austin, 2003; ECTC, 2004).

7. TURF REINFORCEMENT MATS (TRMS)

Turf Reinforcement Mats (TRMs) consist of various non-degradable UV stabilised synthetics fibres and filaments processed into permanent, high-strength, three dimensional matrices. TRMs are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation. They are designed for permanent and critical hydraulic applications where design discharges exert velocities and shear stresses that exceed the limits of mature, natural vegetation (EPA, 1999). TRMs can be used for slopes up to 0.5H:1V, shear stresses up to 576 pa and velocities up to 6.1m/s depending on the type and structure of the TRM and its tensile strength (Propex, 2006; UDFCD, 2011). TRMs with higher tensile strengths (more than 44 kN/m) and performance are called High Performance TRMs (HPTRMs) and can be used for steeper slopes and higher shear stresses and velocities (Kilgore and Cotton, 2005). Before the invention of TRMS, rip-rap and concrete were traditional “Hard Armour” solutions when vegetation alone could not provide the required permanent erosion protection for high velocities and shear stresses. TRMs are a suitable alternative to hard armour techniques and have proven ability to substantially increase the erosion resistance of vegetation, enabling its use in high velocity/shear stress areas (Kilgore and Cotton, 2005; Rivas, 2006).

8. ADVANTAGES OF TRMS

By protecting the soil from scouring forces and enhancing vegetative growth, TRMs can raise the threshold of natural vegetation to withstand higher hydraulic forces on slopes, stream banks and channels. TRMs, unlike temporary erosion control products, are designed to stay in place permanently to protect seeds and soils and to improve germination. They provide superior root entanglement and long term protection (EPA, 1999). Reinforcing vegetation with TRMs has become an acceptable, performance proven, cost effective and environmentally friendly alternative to rock riprap and other forms of non-vegetative materials (EPA, 1999; Lancaster and Austin, 2003; Rivas, 2006). Moreover, the use of TRMs is widely becoming a common replacement for hard armour alternatives such as rip rap and concrete due to effectively reducing construction times, construction costs (about 75% reduction), material costs, and equipment requirements, providing higher safety, and most importantly improving water quality and ground water recharge capabilities (GMA, 2009). Despite variation in materials, TRMs, with shear stresses up to 480 to 576 pa (similar to more than 80cm rock rip rap), have proven their performance capabilities over the past 35 years in field and laboratory tests. Allowable shear stress for High Performance TRMs (HTRMs) can even extent to as much as 718 pa (Kilgore and Cotton, 2005; Propex, 2006). A comparison between TRMs and hard armour rock riprap systems for channels by Lancaster et al, (2005) is presented in table 1. It clearly shows the advantages of TRMs over rock rip rap solution. They also found the rip rap solution to cost about 10 times more than TRM solution in the US. TRMs provide immediate erosion protection and act as a barrier to minimise soil displacement/erosion by wind and during hydraulic flows both, prior to and while vegetation is being established (EPA, 1999). The performance of the TRM increases as the vegetation becomes established. TRMs also reduce evaporation and insulates the soil, reduce soil moisture loss, moderate soil temperature, prevent crusting and sealing of the soil surface and may increase infiltration (ECSWQM, 2014).

Table 1. Summary of erosion control system features

Feature	TRM Reinforced Vegetation	Rock Riprap	Feature	TRM Reinforced Vegetation	Rock Riprap
Permissible Shear Stress	up to 718 pa	383 pa (60cm rock)	Hazard/ Safety Risk	None	Low - High
Aesthetics	Natural Green	Grey	Labor Requirements	Unskilled	Skilled
Water Filtration/Treatment	Excellent	Poor	Installation Equipment	Hand tools	Dump truck /backhoe
Noise Abatement	Yes	No	Installation Time	Fast	Slow

9. TRM PERFORMANCE AND DESIGN PROPERTIES

The performance properties of TRMs consist of Physical, Mechanical and Endurance index properties and include mass, thickness, structure, light penetration, tensile strength, elongation, resiliency (TRM's ability to retain original configuration after exposure to the stresses such as trafficking), flexibility, seedling emergence (TRM's ability to enhance the rate and quantity of germination), and UV resistance (Kilgore and Cotton, 2005; ECTC, 2006; NTPEP, 2015). These properties are important for both, short and long performance of the material and guarantee the durability of the material and long-term performance of the erosion control plan (ECTC, 2006; Sprague and Sprague 2013). TRMs with higher seedling emergence values can provide more and denser vegetation, which provides higher roughness and less shear stress on the channel bed. In fact, the US EPA and the Federal Highway Administration recommend that a high performance TRM with a tensile strength of 44 kN/m or greater be used whenever field conditions with high loading and high survivability requirements exist. Design properties for slopes include the product integrity cover factor (C factor), and design properties for channels include maximum permissible velocity, maximum permissible shear stress, and roughness (manning's coefficient) (Kilgore and Cotton, 2005; ECTC, 2006; Propex, 2006). ASTM has published standard test procedures for each of these indexed performance and design parameters. Large-scale performance tests have also been developed for slopes (ASTM D6459) and channels (ASTM D6460) to simulate expected field conditions to report performance properties of "as installed" RECPs and TRMs (Sprague and Sprague, 2013). For slopes, an appropriate soil loss ratio and associated C factor will be calculated. For channels, the permissible shear stress is defined as the shear stress necessary to cause an average of 0.5 inch of soil loss over the entire channel (Sprague and Sprague, 2013; NTPEP, 2014; NTPEP, 2015).

10. TRM FIBRES AND STRUCTURE

The fibre used in the manufacturing process of TRMs can be extruded into various cross sectional shapes but are predominating round in section. Then one advanced fibre technology designed to capture more seed, soil and water for the fastest seedling emergence of all TRMs is X3 fibre technology. In this technology, the cross section of the fibres is not circular, but triangular sectional shape (figure 1). X3 fibres are extruded through a process that provides 40% more surface area over a more common round fibre. Constructing interlocking crimped fibres in a three dimensional pattern creates a thick matrix of voids. This design allows X3 fibres to trap and contain more soil and water required for rapid growth in steep slopes and moderate to high flow channels (Propex, 2006).

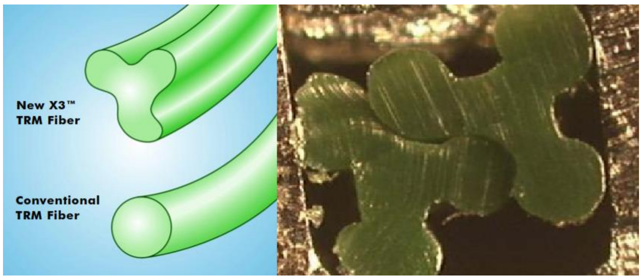

Figure 1. X3 fibres vs. round fibres

X3 fibre technology and interlocking of crimped fibres used in TRMs provide extra advantages over conventional TRMs with circular fibres. Some of these advantages are: 40% increase in seed germination and plant growth during the first 21 days, 60% greater tensile strength to ensure structural integrity during and after installation (the tensile strength of TRMs made of these type of fibres can exceed 58.4kN/m), 10% greater resiliency that provides a crush-proof environment during the germination period when seedlings are most vulnerable, 30% Reduction in soil loss, and 50% Improvement in vegetation growth (Propex, 2006).

TRMs, as three dimensional products, can have different structures. Their structure can be open weaved, flat, pyramid, etc. The efficient geometry of pyramid structured erosion matrix improves soil stabilisation soils. Upward and downward protruding "pyra-cells" capture and contain soil while the multiple layers of grid-like "pyra-ribs" interlock with surrounding soils. In addition, close inspection of the lofty matrix will reveal "hidden chambers" which literally entomb soils, even under high flow conditions (SI Geosolutions, 2000). Figure 2 shows the pyramid structure and its contribution with soil and vegetation in large scale hydraulic flume and field tests (Thornton and Beasley, 2013).

Figure 2. Pyramid structure in TRMs (left), and the contribution with soil and vegetation in large scale hydraulic flume and field test (middle and right)

Open weave TRMs are typically installed as soil filled. Although their voids contain the soil and allow grass to germinate, this openness can create a tendency for some initial soil loss to occur which interferes with the establishment of vegetation. To prevent this, either the application of an approved soil stabiliser, an ECB, or a dense TRM over the open wave TRM is required on slopes and in channels, after installation is complete (FDM, 2012).

11. DESIGNING WITH TRMS

Apart from the geotechnical analysis and other considerations, a TRM design procedure considers hydraulic design, vegetation type, product specification/properties, and installation guideline. Hydraulic design is based on the shear stress and velocity. Water flow over a surface causes tractive force or shear stress between the water and the soil surface. When this shear stress exceeds the permissible shear stress of the surface material, the movement or loss of these materials will occur which may lead to significant damage to the channel or slope. Shear stress predicts the performance or when erosion will occur and is the governing design parameter, superior to velocity, in predicting potential failure. The magnitude of the shear stress generated by a flow and thus the hydraulic design depends on the discharge, depth of flow, flow duration, slope or energy gradient, surface geometry, channel geometry, hydraulic roughness of the TRM, and underlying soil type (Kilgore and Cotton, 2005).

11.1. Slope Erosion and TRMs: Slope Erosion Potential

A great concern for designers is to correctly assess the erosion potential resulting from the construction activities. The site erosion potential is an estimate of the quantity of soil that could be removed from the construction site due to erosion and transportation by un-concentrated surface water flow. With certain modifications, established soil loss evaluation methods used in agricultural practice can be reasonably applied to other practices. The estimates produced using these methods should be supplemented with judgement and experience so that the site erosion potential assessment is appropriate for the construction site. The main method to assess the erosion potential is the Revised Universal Soil Loss Equation (RUSLE) which is an update of the Universal Soil Loss Equation (USLE). RUSLE calculates the annual soil loss based on Rainfall, Soil erodibility, slope length and steepness, and vegetation (C factor) as below (Alberta, 2011):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where: A = Annual soil loss (tonnes ha-1 year-1), R = Rainfall factor (MJ mm ha-1 hour-1 year-1), K = Soil erodibility factor (tonne hour MJ-1 mm-1), LS = L and S are the slope length and steepness factors, respectively (dimensionless), C = Vegetation and Management Factor (dimensionless), and P = Support Practice Factor (dimensionless). The C-factor is used to determine the relative effectiveness of soil management systems in terms of vegetation, crop cover and/or artificial protection cover (such as mulch, TRMs and other RECPs) to effect prevention or reduction of soil loss. For bare soil, C=1 can be used. For soil surface protected with mulch C=0.1 to 0.2 is common. Typical C factor for RECPs is less than 0.25 (Kilgore and Cotton, 20056, UDFCD, 2001). By providing a very low C factor (typically less than 0.01), TRMs will permanently control the erosion and reduce the annual soil loss on a slope compared to an exposed soil.

11.2. Channel Erosion and TRMs

The existence of the TRM affects the roughness and the Manning's factor (n). Of course there is no single "n" value for RECPs. The roughness of these materials must be determined by full-scale testing in laboratory flumes using defined testing protocols such as ASTM D 6460 (Kilgore and Cotton, 2005). Manning's coefficient for bare soil is between 0.016 and 0.025, for Erosion Control Blankets (ECBs) is between 0.028 and 0.045 and for Turf Reinforcement Mats (TRMs) is between 0.024 and 0.036) (Kilgore and Cotton 2005). When vegetated, the "n" value varies significantly with the applied shear. Manning's roughness coefficient varies also depending on grass properties (grass stem height and density/stiffness) (Kilgore and Cotton, 2005).

11.3. Designing Channels with TRMs

For channels, the Hydraulic Engineering Circular No. 15 (HEC-15) design approach by Federal Highway Administration (FHWA) can be used (Kilgore and Cotton, 2005). The erosion protection required can be determined by computing the shear stress on the channel lining (and underlying soil, if applicable) at the design discharge and comparing that stress to the permissible value for the type of lining/soil that makes up the channel boundary (Kilgore and Cotton, 2005). For designing channels with TRMs, the first step is to check if the channel is stable without any vegetation. If not, the next step is to check if the channel is stable with unreinforced vegetation (without TRM). If not, TRM is required to control the erosion. To check if the maximum shear stress of the non-vegetated channel is less than the permissible shear for the soil surface, the maximum shear stress on the channel bottom is calculated as:

$$\tau_d = \gamma d S_0 \quad (2)$$

where τ_d is the shear stress in channel at maximum depth (N/m^2), γ is the unit weight of water (N/m^3), d is the depth of flow in channel (m), and S_0 is the channel bottom slope (m/m). The permissible shear stress for fine-grained, non-cohesive non-vegetated soils (D_{75} < 1.3 mm) is relatively constant and is conservatively estimated at 1.0 N/m^2. For coarse grained, non-cohesive non-vegetated soils (1.3 mm < D_{75} < 50 mm) the following equation applies:

$$\tau_{p,\,soil} = \alpha D_{75} \quad (3)$$

where $\tau_{p,\,soil}$ is the permissible soil shear (N/m^2), D_{75} is the soil size where 75% of the material is finer (mm), and α is the unit conversion constant (0.75). For cohesive soils, the basic equation for permissible shear on the soil (without vegetation) is:

$$\tau_{p,\,soil} = (c_1 PI^2 + c_2 PI + c_3)\,(c4 + c_5 e)^2\, c_6 \quad (4)$$

where $\tau_{p,\,soil}$ is the permissible soil shear (N/m^2), PI is the plasticity index, e is the void ratio, and c_1 to c_5 are coefficients depending on the soil type and PI (Kilgore and Cotton, 2005). When the permissible shear stress is less than the allowable shear for the soil surface and equation is satisfied, erosion of the soil surface will be controlled:

$$\tau_p \geq SF\ \tau_d \quad (5)$$

where τ_p is the permeassible shear stress for the channel lining (N/m^2), τ_d is the shears tress in channel at maximum depth (N/m^2). If equation 5 was not satisfied for unvegetated soil, then the soil will be eroded and we should check the vegetated scenario. When vegetated, the permissible shear stress of the vegetated soil can be determined by:

$$\tau_p = \tau_{p,\,soil}\,(1 - C_f)^{-1}\,(n/n_s)^2 \quad (6)$$

where τ_p is the permissible shear stress on the vegetative lining (N/m^2), $\tau_{p,\,soil}$ is the permissible soil shear stress (N/m^2), C_f is the grass cover factor, n_s is the soil grain roughness, and n is the overall lining roughness. Soil grain roughness (n_s) is taken as 0.016 when D_{75} < 1.3 mm. For larger grain soils, the soil grain roughness is given by:

$$n_s = \alpha (D_{75})^{1/6} \quad (7)$$

where α is the unit conversion constant (0.015). If equation 5 is still not satisfied, the vegetation alone (without reinforcement) cannot control the erosion in the channel, and a Turf Reinforcement Mat (TRM) is required. A TRM modifies the cover factor for vegetated linings, which affects the permissible vegetation/soil shear stress (Equation 6). The adjusted cover factor is determined by the following equation.

$$C_{f,TRM} = 1 - (\tau_{p,\ VEG\text{-}test}/\tau_{p,\ TRM\text{-}test})\ (1 - C_{f,VEG}) \quad (8)$$

where $\tau_{p,\ VEG\text{-}test}$ is the permissible shear stress on the vegetative lining as reported by the manufacturer (N/m^2), $\tau_{p,\ TRM\text{-}test}$ is the permissible shear stress on the turf-reinforced vegetative lining as reported by the manufacturer (N/m^2), $C_{f,VEG}$ is the grass cover factor, and $C_{f,TRM}$ is the TRM cover factor. The grass cover factor ($C_{f,VEG}$) is between 0.41 and 0.98 depending of the vegetation type and growth form (Kilgore and Cotton, 2005). The permissible vegetation/soil shear stress is then calculated using the same equation for unreinforced vegetation, but with a modified cover factor, $C_{f,TRM}$:

$$\tau_p = \tau_{p,\ soil}\ (1 - C_{f,TRM})^{-1}\ (n/n_s)^2 \quad (9)$$

The permissible shear stress of a TRM can also be determined and provided by the manufacturer through large scale tests. If equation 5 is satisfied, the erosion will be controlled by using the TRM. If not, other solutions such as rock mattresses should be checked.

When designing with soil filled TRMs, the design condition before vegetation can be similar to an unreinforced unvegetated bare soil depending on the TRM type. In this case, the soil stability under flow conditions in the period before vegetation should be checked using the unreinforced unvegetated soil state (bare soil). If flow velocity and shear stress is critical before vegetation, a soil filled installation is not recommended and a surface applied installation is a better solution. For a surface applied condition, checks should also be undertaken for the unvegetated TRM with flow conditions for the period before vegetation. For this unvegetated period, the unvegetated roughness value of the TRM should be used in the design.

The design of the erosion control measures should be viewed as a flexible process that responds to new information that is obtained throughout the construction phase. As such, the design of temporary and permanent erosion and sediment control measures should be expected to evolve throughout construction to varying degrees based on site conditions and field performance of implemented measures (Alberta, 2011).

12. CASE HISTORIES

Two case histories are presented with one being a slope and one being a channel to be protected from erosion.

12.1. Channel: Masters Home Improvement Development, Richlands, QLD

The development of the Masters Home Improvement Centre consisted of a retail, garden and timber centre with an associated office and receiving area with a gross floor area of 13,404 square metres. The proposed development was approximately 4.25 hectares in area and was located at the corner of Garden Road and Pine Road, Richlands. The primary constraint facing the development was the relocation of the ephemeral waterway that traverses the site. The waterway had to be designed to accommodate the 1 in 100 year ARI peak flow. The design of the waterway included a fully vegetated channel bed (Manning's factor n=0.15); comprised of a low flow channel design to be predominately wet; and berms/terraces along the batters to enhance a natural channel appearance. Due to the sharp change in flow direction entering the site, the use of gabion mattress protection was proposed by the consultant in the initial design to cover the entire extent of flow entering the development. The gabion mattress protection was considered to ensure that the flow passing over the 1:3 slope drop chute would not result in channel scour. A Manning's factor of 0.3 was adopted for the gabion mattress.

The head contractor started considering ways to reduce the construction costs and increase the performance by using a Turf Reinforcement Mat (TRM). As soil loss was important even before vegetation, the open weave TRMs which should be installed as "soil filled" were not considered. A comparison between different solutions including three TRMs, the original gabion mattress solution and some other traditional hard-armour techniques is provided in table 2. Some of the input values are the base width=5m, channel slope=2%, batter slope=1V:4H, channel length=300m, flow depth=1.2m, discharge=9.08m3/s. The properties of TRMs are as provided by manufacturers or reported by Kilgore and Cotton (2005), Propex (2006), and Hsieh and Chen (2014). TRM1 is a flat TRM with round fibres, TRM2 is a semi-dense flat TRM with x3 fibres, TRM3 is a pyramid structured TRM with X3 fibres, TRM4 is an open weave TRM, and TRM5 consist of a matrix stitch bonded to a nettings on each side. As the results show, TRMs provide an acceptable allowable shear stress and safety factor. It also verifies that the Turf Reinforcement Mat with X3 fibres (TRM2 and TRM 3) could provide a highest safety factor compared to the TRMs without the X3 fibres. The results also show that the TRM with x3 fibre and pyramyd structure (TRM3) could provide even a higher safety factor compared to the TRM with X3 fibre and non-pyramid structure. The results also show that the Rock Mattress solution provides a very higher allowable shear stress, much higher than required for this project. This emphasises that the client can easily use the TRM3 solution in this project and still achieve an acceptable safety factor.

Table 2. Calculations and shear safety factor for different solutions

Erosion Control Method	**Manning's Factor(1)**	**Calculated Shear (pa)**	**Permissible Shear (pa)**	**Shear Safety Factor**
Bare Soil	0.02	80.43	20(1)	0.25
Unreinforced Vegetation	0.15	230	48(1)	0.21
Gabion Mattress	0.03	95	1675	17.63
Rock Riprap 15 cm	0.05	136	96	0.70
Rock Riprap 30 cm	0.06	145	191.5	1.32
Rock Riprap 45 cm	0.064	150	283	1.89
Rock Riprap 60 cm	0.067	154	383	2.49
TRM1, Flat structure, Vegetated	0.034(1)	107	138(1)	1.29
TRM2 with X3 fibres, Non-Pyramid structure, Vegetated	0.049	130	479	3.68
TRM2, with X3 fibres, Non-Pyramid structure, Unvegetated	0.025	91	239	2.62
TRM3 with X3 fibres, Pyramid structure, Vegetated	0.047	130	766	5.9
TRM3 with X3 fibres, Pyramid structure, Unvegetated	0.028	97	335	3.45
TRM4, Open weave structure, Vegetated	0.04	130	240	1.84
TRM5, Stich bonded Matrix, Unvegetated	0.02(1)	93	156(1)	1.67

(1) From Kilgore and Cotton (2005), Alberta (2011), product data sheet, or provided by manufacturers

TRM3 with X3 fibre and Pyramid structure was selected to be used in this project due to higher hydraulic performance (both vegetated and unvegetated) and high test results on index properties such as high durability and UV resistance of greater than 85% tested up to 10,000 hours, high resiliency of greater than 80%, which was important for future maintenance works, high light penetration of 10%, high seedling emergence, and high tensile strength of 58 kN/m. The high tensile strength was an important parameter for the TRM to resist turbulent flows. It was also in acceptance with the recommendation by the US EPA and the Federal Highway Administration to use a high performance TRM with a tensile strength of 44 kN/m or greater for high loading and high survivability requirements. Through this method, the client ended up with a permanent vegetated solution and achieved some 50% saving and faster and safer installation compared to the original rock mattress option. Figure 3 shows the TRM3 installation before and after vegetation.

Figure 3. Installed TRM3 (left) and vegetated TRM3 after few months (right), Masters Home Improvement Development, Richlands, QLD

12.2. Slope: King Solomon, WA

Solomon Project is located in the Pilbara Region of Western Australia, 200km south of Port Hedland, and approximately 60km north of Tom Price. The steep 60% wing walls of the Primary Ore Crushing Hub needed protecting from cyclonic rain & wind events which are increasingly prevalent in the Pilbara region. As permanent erosion control was required, a TRM solution was considered. TRM3, TRM5 and TRM6 which is a flat dense TRM with round fibres were used to model the soil loss. Results are presented in table 3.

Table 3. Soil loss saving for different TRMs

Erosion Control Method	Cover Management Factor(1)	Annual Soil Loss (kg/m^2/year)	Soil Loss Saving (kg/m^2/year)	Soil Loss Saving (%)
Unprotected Soil	1.0	4.3885		
TRM3 with X3 fibres, Pyramid structure,	0.01	0.0395	4.349	99.1%
TRM5 Stich bonded Matrix	0.057	0.2502	4.1383	94.3%
TRM6 flat dense	0.015	0.0658	4.3227	98.5%

(1) Provided by manufacturers' data sheets.

Results show that all TRMs provide an acceptable saving in regards to soil loss. According to the steep and long slope, TRM3 with a high tensile strength of 58 kN/m and advantages of X3 fibre to capture sediment, high resiliency and high UV resistance was selected and installed (figure 4).

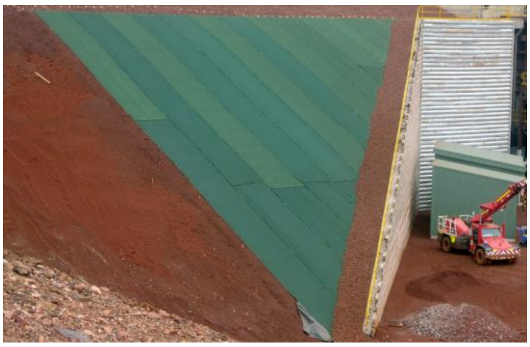

Figure 4. Installed TRM3 on the slope, King Solomon, WA

13. CONCLUSION

A review and history of erosion control techniques has been provided and various techniques have been compared to each other in this paper, and design considerations and performance parameters have been introduced. Then the design procedure for channels and slopes with TRMs has been reviewed and a case history for each application has been presented.

Reinforced vegetation linings/erosion control systems using Turf Reinforcement Mats (TRMs) has become an acceptable, performance proven, cost effective and environmentally friendly permanent erosion control alternative to rock riprap, rock mattresses and other forms of non-vegetative "hard" lining. Benefits include huge cost savings, high performance, higher safety, lower maintenance, being less hazardous, more aesthetically pleasing and environmentally friendly. By protecting the soil from applied shear stresses and enhancing vegetative growth, TRMs can improve the shear resistance of natural vegetation to withstand higher hydraulic forces in channels and reduce the amount of soil loss on slopes.

Performance and design parameters of TRMs such as allowable shear stress, roughness, resiliency, tensile strength, light penetration, seeding emergence, and UV resistance along with the soil and vegetation properties such as soil type, geometry, slopes, and vegetation type should be considered in the design. The structure of the TRM can also affect the performance of the whole system. For example a pyramid shaped TRM made of tri-lobar fibres (X3 fibres) instead of round fibres can increase the hydraulic performance of the TRM up to 776 pa allowable shears tress and provides an improvement in tensile strength and vegetation properties of the TRM, through trapping of additional sediments and providing greater surface area of the fibre within the TRM.

The correct installation in accordance with related installation guidelines should be considered for each project to guarantee the designed performance of the erosion control system.

14. ACKNOWLEDGMENT

The authors acknowledge the assistant and information provided by Geoinventions Pty Ltd.

15. REFERENCES

ASTM D6459 (2011). *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion,* ASTM International, West Conshohocken, PA, 2011

ASTM D6460 (2012). *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion,* ASTM International, West Conshohocken, PA, 2012.

Alberta Transportation, (2011). *Erosion and Sediment Control Manual*, Alberta Transportation, Alberta.

Babcock, D.L., and McLaughlin, R.A (2011). *Runoff water quality and vegetative establishment for groundcovers on steep slopes*, Journal of Soil and Water Conservation, 66(2): 132-141.

Bui, E. N., Hancock, G. J. and Wilkinson, S. N. (2011). *Tolerable hillslope soil erosion rates in Australia: Linking science and policy.* Agriculture Ecosystems & Environment 144 (1), 136-149.

CTSW (2006). *Cellular Confinement System Research*, State of California Department of Transportation, Division of Environmental Analysis, Stormwater Program, CTSW-RT-06-137.20.1, January 2006.

ECSWQM (2014). *Erosion Control and Storm Water Quality Manual*. BOWEN, COLLINS & ASSOCIATES, Provo Public Works, Revision March 2014.

ECTC (2004). Standard Specification for Rolled Erosion Controlled Products. Erosion Control Technology Council, Version 2, Rev. 4904.

ECTC (2006). *A Technical Guidance Manual: Terminology, Index, & Performance Testing Procedures for Rolled Erosion Control Products*, Erosion Control Technology Council.

EPA (1999). *Storm Water Technology Fact Sheet: Turf Reinforcement Mats.* United States Environmental Protection Agency, EPA 832-F-99-002.

EPA (2008). *National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices*, Stormwater Best Management Practices, EPA, Washington.

FDM (2012). *Facilities Development Manual*, Wisconsin Department of Transportation, Wisconsin.

GMA (2009). *Handbook of Geosynthetics*. Geosynthetics Martials Association.

Hairsine, P. B., Barson, M., Randall, L. and Wilkinson, S. (2009). *Identification of areas in Australia where soil loss from hillslope erosion could be reduced.* CSIRO Land and Water Report 45/09.

Kilgore, R. T. and Cotton, G. K. (2005). *Design of Roadside Channels with Flexible Linings*. Hydraulic Engineering Circular No. 15 (HEC-15). Third Edition, Federal Highway Administration, FHWA-NHI-05-114.

Koerner, R. and Koerner, G. (2012). *The need for erosion control material specifications. Geosynthetics*, February 2012.

Lancaster, T. and Austin, D. N. (2003). *Classifying Rolled Erosion Control Products: A Current Perspective*. Erosion Control Technology Council (ECTC).

Lancaster, T. and Myrowich, M. (2006). *ECTC: 14 Years of Guiding and Growing the Rolled Erosion Control Products Industry*. Land and Water, Vol. 50 (6), PP 39.

Lancaster, T., Lutyens, D., and Austin, D. (2005), *Flexible Channel Lining Systems: The Benefits of Geosynthetically Reinforced Vegetation over Rock Riprap*, Erosion Control Technology Council, St. Paul, Minn.

NCHRP (2012). *Cost-Effective and Sustainable Road Slope Stabilization and Erosion Control*, *A Synthesis of Highway Practice*, National Cooperative Highway Research Program, NCHRP Synthesis 430, National Academy of Sciences, Transportation Research Board, Washington.

NTPEP (2014). *Standard Practice for NTPEP Evaluation of Erosion Control Products (ECP) and Sediment Retention Devices (SRD)*, American Association of State Highway and Transportation Officials (AASHTO), AASHTO Designation: ECP 14-01, Washington.

NTPEP (2015). *AASHTO/NTPEP Erosion Control Products: User Guide, National Transportation Product Evaluation Program*, February 2015.

Propex (2006). *Erosion Control Solutions*. Propex Inc., LL-501.

Rivas, T. (2006). Erosion Control Treatment Selection Guide, United States Department of Agriculture, Forest Service, National Technology & Development Program

Ryan, A. (2013). *Water erosion in Australia. Caring for our Country Sustainable Agriculture Fact Sheet*, Department of Agriculture, Fisheries and Forestry.

SI Solutions (2000). *Pyramat Earth Stopping Solutions*, SI Corporation, GPD-PM-100.

Smith and Bhatia (2009). *Evaluation of Vegetated RECPs using ECTC's Bench-Scale Test*, Geosynthetics 2009, February 25-February 27, 2009, Salt Lake City, Utah.

Smith, J.L., Bhatia, S.K. (2013). *Time-dependent Impact of RECPs on Surface Water Quality*, Geosynthetics 2013, California, April 1- April 4, 2013, pp. 1015-1023.

Sprague, C. J., Sprague J. E. (2013). *Testing and Specifying Rolled Erosion Control Products*, Geosynthetics 2013, California, April 1- April 4, 2013, pp. 503-512.

Thornton, C., Beasley, J. (2013). *Vegetative Cover and Turf Reinforcement Mats*, 2013 NDSP Dam Safety, Technical Seminar No. 20: Overtopping of Dams, February 20, 2013.

UDFCD (2011). *Urban Storm Drainage Criteria Manual Volumes 3: Best Management Practices,* Urban Drainage and Flood Control District, Denver, CO.

Witheridge, G. (2010). *Erosion and Sediment Control – A field Guide for Construction Site Managers,* Catchments and Creeks Pty Ltd, Version 2, February 2010.