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Evaluating the effectiveness of geotextiles for slope erosion control in mine restoration

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Abstract

Mining activities are associated with some of the highest sediment production rates ever recorded. Erosion rates of 100–500 t ha^{-1} y^{-1} have been recorded on unconsolidated mine spoil where rill and gully erosion takes place. Disturbed slope forming materials, over-steepened/over-lengthened slopes and lack of vegetation affect hydraulic conditions, generating runoff and accelerating the detachment and transport of slope material. Sediment delivery to watercourses affects water quality (in terms of turbidity and chemical concentrations), causing detrimental effects on aquatic ecosystems.

Establishing an effective vegetation stand may take several seasons, especially given the erodible and erosive conditions found on mine sites. Rolled erosion control products (geotextiles) can be used in particularly high risk areas, to control erosion rates significantly, so creating a stable environment for vegetation establishment, and long term reclamation of disturbed sites.

Taking a geomorphological approach, this paper sets out to examine how geotextile properties affect the mechanics of erosion processes at the sub-process scale. The aim is to present a methodology for comparing the effectiveness of different products, then linking this to geotextile properties and the underlying geomorphological processes operating. Performance data are used to identify the salient properties of erosion control geotextiles in terms of reductions in runoff and sediment production. Results show that different products (e.g. natural versus synthetic; surface versus buried installation; woven versus non-woven) perform to varying degrees, depending on the storm characteristics (intensity of rainfall) and erosion processes operating (rain splash versus runoff erosion).

Significant correlations were found between product effectiveness (sediment control) and area of geotextile (%); depth of flow (mm); geotextile induced roughness (expressed as the Manning's n roughness coefficient); water holding capacity (%); geotextile weight (g m^{-2}); and geotextile wet weight (% of dry weight both after 24 hours and after 48 hours). However, the following properties were unrelated to product performance: cost of geotextile (\$ m^{-2}); flow velocity (m s^{-1}) mean yarn diameter (mm); tensile strength (kn m^{-1}); and geotextile thickness (mm).

Understanding how geotextile properties affect erosion control performance helps end users specify cost effective products. Also, manufacturers can use this knowledge to improve the design of new erosion control products.

1 Introduction

Mining activities are associated with some of the highest sediment production rates ever recorded. Erosion rates of 100–500 t ha^{-1} y^{-1} have been recorded on unconsolidated mine spoil where rill and gully erosion takes place (Table 1). Disturbed slope forming materials, over-steepened/over-lengthened slopes and lack of vegetation affect hydraulic conditions, generating runoff and accelerating the detachment and transport of slope material (Hancock et al., 2008). Sediment delivery to watercourses affects water quality (in terms of turbidity and chemical concentrations); it is causing detrimental effects on aquatic ecosystems. These processes threaten the success of ecologically sustainable land restoration.

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To mitigate these adverse environmental impacts, the gradient, length and form (plan and profile) of artificial slopes such as mine spoils can be engineered to reduce erosion rates, but even short, gentle slopes can generate high erosion rates, given the erodibility of the slope materials (Savat and De Ploey, 1982; De Ploey, 1981). Vegetation can be used effectively to protect the slopes (Morgan, 2005), but this may be difficult to establish in such erosive conditions; in any case, there is a window of high erosion risk between slope finishing and the growth of an adequate protective vegetation cover.

Geotextiles, ‘permeable textiles used in conjunction with soil, foundation, rock, earth or any geotechnical engineering related material’ (John, 1987), have been used for erosion control in severely disturbed and degraded areas for over 30 years. By stabilising erodible sites, land managers are able to establish vegetation – seen as the first and critical step in the process of mined landscape ecological restoration (Windsor and Clements, 2001; Carroll et al., 2000; Moreno de las Heras, 2009). Geotextiles can also enhance environmental conditions for the establishment of vegetation, by increasing moisture availability and reducing diurnal temperature extremes for example (Sutherland et al., 1998; Krenitsky and Carroll, 1994). However, identifying and selecting the most cost-effective products from the wide range available on the market is a challenge for land managers, whose budgets for erosion control products may be limited.

Table 1 Selected erosion rates from disturbed lands

Site Description	Erosion / Sediment Rates	Source
Coal mine spoil, Colorado, USA	102 t ha^{-1} y^{-1}	Renner (2002)
Gold mine tailings, South Africa	500 t ha^{-1} y^{-1}	Blight (1991)
Surface mined basin, Wyoming, USA	2.38 t ha^{-1} y^{-1} (11 × greater than undisturbed land)	Ringen et al. (1979)
Highway construction	480 t ha^{-1} y^{-1}	Diseker and Richardson (1962)
Highway construction, Virginia, USA	338 t ha^{-1} y^{-1}	Vice et al. (1969)
Urbanisation	226 t ha^{-1} y^{-1}	Yorke and Herb (1976)
Off road recreation activities	5.52 t ha^{-1} y^{-1}	Snyder et al. (1976)
Surface mine spoils, Wyoming	1.1–9.5 t ha^{-1} over 45 min, with rainfall of 38.1 mm	Lusby and Toy (1976)
Construction site	17,000 t km^{-2} yr	US EPA (1973)
Actively mined watershed	46,400 p.p.m. sediment concentrations in runoff	Curtis (1971)
Abandoned coal refuse sites	61.5 kg m^{-2}	Mandel et al. (1982)
Surface coal mine dumps	2.1–5.9 mm yr^{-1} ground loss	Haigh (1979)
Abandoned surface mines	850 t km^{-2} yr	US EPA (1973)
Active surface mines	17,000 t km^{-2} yr	US EPA (1973)

Erosion control geotextiles are classified into: geomats (three-dimensional structures, usually comprising mats of randomly distributed filaments); geocells (three dimensional, honeycomb structures); biomats (made of natural fibres, held together between two layers of lightweight mesh); and bionets (woven meshes formed from yarns spun from natural fibres). Depending on their composition, geotextiles can be biodegradable, affording only temporary slope protection, or have lifespans in excess of 25 years (Cooke and Rebenfeld, 1988). Some products are installed on the slope surface: these products control erosion by intercepting potentially erosive rainfall and reducing the velocity of any overland flow. Other products are installed by first removing the slope topsoil, laying the product down and backfilling loose topsoil into the product. The theory here is that the loose backfill will enhance infiltration of rainfall, so reducing runoff generation.

Geotextile effectiveness in controlling runoff and soil loss has been the subject of numerous studies (Bhattacharrya et al., 2010; Krenitsky et al., 1998; Reynolds, 1976; Godfrey and McFalls, 1992; Smets et al., 2011; Armstrong and Wall, 1992; Sutherland and Ziegler, 1996, 2006; Sutherland, 1998a, 1998b; Sutherland and Ziegler, 2006). Despite the wealth of data available on geotextile performance, most of the existing studies simply describe the effectiveness of various products. Explanations of product performance are very rarely given. There is little discussion of the salient properties of geotextiles that affect the erosion processes of soil detachment and transport. It is not stipulated whether geotextiles control erosion by limiting soil detachment, or whether their effectiveness is more to do with the transport of eroded soil. There appears to be a significant gap between the use of erosion control geotextiles and our understanding of how and why these products work (or in some cases, don't work).

Taking a geomorphological approach, this paper sets out to examine how geotextile properties affect the mechanics of the erosion process at the sub-process scale: do these products work by controlling rainsplash erosion or by reducing erosion due to runoff processes? The aim is to present a methodology for comparing the effectiveness of different materials, then linking this to geotextile properties and the underlying geomorphological processes operating. This level of understanding will assist land managers evaluate existing products more effectively and efficiently, and assist manufacturers to develop more reliable, cost-effective products that the market can trust.

2 Methodology

2.1 Simulating soil erosion sub-processes

Soil erosion is a four phase process, comprising detachment, entrainment, transport and deposition of individual soil particles or small aggregates (Meyer and Wischmeier, 1969; Morgan, 2005). The two primary agents of erosion are rainsplash (individual raindrops impacting on the soil surface) and overland flow (surface runoff generated where rainfall rate exceeds infiltration rate). Both agents are capable of detaching and transporting slope forming materials. When there is insufficient rainfall or runoff energy to transport the detached material, then deposition takes place. The process is very dynamic, with deposited material being re-detached and transported by the erosion agents during the course of an erosive storm. Very few studies have observed geotextile effectiveness for rainsplash and runoff erosion separately, so an experimental programme was set up to generate the necessary data.

2.2 Experimental variables

Six different types of erosion control geotextile were used in this study, representing all the main generic types of erosion control geotextile (Table 2). The experiments were conducted on an erodible, sandy loam soil (16% clay, 39% silt and 45% sand). This is classified as an Eutric Cambisol (FAO, 1990).

2.3 Role of geotextiles on rainsplash erosion

The initial (and therefore arguably the most important) soil erosion sub-process is the detachment and transport of soil particles or aggregates by raindrop impact. As raindrops are the most efficient and effective means of soil detachment (Morgan, 2005), control of their erosive energy dramatically reduces total soil losses. Reductions in detachment rates also have implications for processes such as surface sealing and crusting, which rely on a source of detached material to be deposited on the soil surface (Farres, 1977). Sealing can be detrimental in terms of infiltration and runoff generation, thereby increasing erosion risk.

Table 2 Geotextile products tested

Product Name	Material Characteristics	Weight ($g\ m^{-2}$)	Area of Geotextile (%)	Type	Buried/ Surface Installation
Geojute	100% jute woven mesh	500	54	Bionet	S
Fine geojute	100% jute woven mesh (fine)	292	80	Bionet	S
Bachbettgewebe	100% coir woven mesh	700	58	Bionet	S
Enviromat	Wood chips in a photodegradable synthetic mesh	450	94	Biomat	S
Tensarmat	3D Polypropylene mat	450	38	Geomat	B
Enkamat (surface)	3D nylon mesh	265	60	Geomat	S
Enkamat (buried)	3D nylon mesh	265	30	Geomat	B

The hypothesis to be tested is that different geotextiles will have different effects on the detachment of soil particles by rainsplash as a function of the properties of the products, so that the salient characteristics of erosion control geotextiles can be identified. To isolate the process of soil erosion by raindrop impact, Ellison splash cups (diameter = 7.7 cm, depth 4.7 cm; Figure 1) were used in these experiments. The small surface area (186 cm^2) of the cups restricts the generation of runoff and hence the soil loss observed is assumed to be due to splash erosion alone.

Figure 1 Ellison splash cups with geotextile treatments prior to rainsplash erosion tests using simulated rainfall. Top row (left to right: Enkamat (surface); Enkamat (buried); Geojute; Bachbettgewebe. Bottom row: Control (bare soil; no geotextile); Tensarmat; Enviromat; Fine geojute

Two rainfall intensities of 35 mm hr^{-1} and 115 mm hr^{-1} of 15 minutes and 10 minutes duration respectively were simulated using a pressurised, nozzle rainfall simulator in the soil erosion laboratory at Cranfield University. These storms represent the 1-in-1 year and 1-in-85 year event respectively in central UK (NERC, 1975), so representing both moderate and extreme rainfall events. Each test was replicated five times.

2.4 Role of geotextiles on overland flow erosion

Tests using runoff only are normally conducted in flumes or on specially designed runoff rigs, where an even flow of water can be applied just above the test bed and overland flow is simulated. The overland flow simulator used in the present tests comprises a sheet metal water tank (0.3 length × 1 width × 0.5 m deep), a sand/bitumen approach slope (0.5 m length × 1 m width), soil tray (2 length x 1 m width x 0.15 m depth) and collecting troughs. At the top of the simulator, a flow-regulating device (gap meter) is used to control water flow from the mains water supply to the water tank. Once the tank is full, water overtops the level tank weir, and discharges onto the sand/bitumen approach slope. This section has a rough texture (similar to coarse sandpaper), which spreads out the flow into a uniform sheet. The water then discharges onto the soil tray section. The soil tray was inclined at a slope of 10° (17.6%), chosen to be representative of a moderately sloping engineered slopes, on which erosion control geotextiles are likely to be specified by a contractor. The slope length is sufficiently long to allow micro-rills and rills to form, if flow concentrates and critical shear stress thresholds are exceeded (Kamalu, 1993).

For these experiments the flow discharge into the water tank and thus onto the soil tray was set at 2.4 l min^{-1} (40 ml sec^{-1}). Assuming all the discharge contributes to overland flow, then this corresponds to a rainfall intensity of 72 mm hr^{-1} for the 10 minute experimental period. Runoff (ml) and sediment (g) were measured at the bottom of the slope.

3 Results

3.1 Rainsplash erosion tests

3.1.1 Low intensity rainfall

As shown in Figure 2, the buried geotextiles yielded higher rates of splash erosion compared with the bare soil control. The buried Enkamat and Tensarmat treatments gave 133% and 141% of the soil loss observed for the control respectively. The surface laid Enkamat performed better, although it reduced soil losses to only 83% of those reported for the bare soil control. The best protection from splash was given by the natural fibre (wood wool) Enviromat, which reduced soil loss significantly ($p<0.05$) to 38% of that from the control. The woven jute products also performed well, compared with the bare soil. Geojute reduced splash losses to 59% of those observed for the control, but this is not significantly different. The fine Geojute reduced splash losses to only 44% of those from the control, which is significantly lower ($p<0.05$).

3.1.2 High intensity rainfall

Not all geotextiles reduced erosion compared to the bare soil control. The buried Enkamat and Tensarmat increased erosion to 130% and 125% of that from the control respectively. Again, these results are not significantly different to those from the control, partly because of the high variability between the replicates for the buried products. The surface laid Enkamat was effective by reducing soil loss significantly to only 35% of that coming from the unprotected control ($p<0.01$). All the natural products performed well, with significant reductions in splash losses compared with the control ($p<0.01$). Best protection came from the Geojute – reducing soil loss to only 14% of that from the control. Fine mesh Geojute was also effective at reducing soil loss to 18% of the control.

Even the worst performance by a natural product (30% with Bachbettgewebe) still represents a significant reduction ($p<0.01$) in soil loss compared with where no geotextile has been used. The natural products reduced splash losses significantly compared with the buried synthetics ($p<0.01$). However, their performance was not significantly different to that of the surface laid synthetic, Enkamat.

3.2 Runoff erosion tests

3.2.1 Runoff

Variability between treatments is very low for the total runoff results. All treatments yielded similar total volumes of runoff (Figure 3), but with the buried products yielding slightly lower quantities. Best performance in terms of controlling runoff was given by the Tensarmat (15,056 ml), which yielded significantly less runoff than all the other treatments. The other buried product, Enkamat also performed well at reducing runoff (19,933 ml), but the difference between this and all other treatments (except the Tensarmat) is not statistically significant. The bare soil control with no geotextile was ranked 3rd, with 20,832 ml. The three woven natural fibred products (Geojute, Fine Geojute and Bachbettgewebe) yielded more runoff than the control (21,378 ml, 21,618 ml and 22,107 ml, respectively). The greatest runoff of all treatments was generated by the woven coir Bachbettgewebe product (22,107 ml). These are surprising results as it was expected that the natural fibred products, with significantly higher water holding capacities (see Section 4) would absorb the most water and thus yield the least runoff.

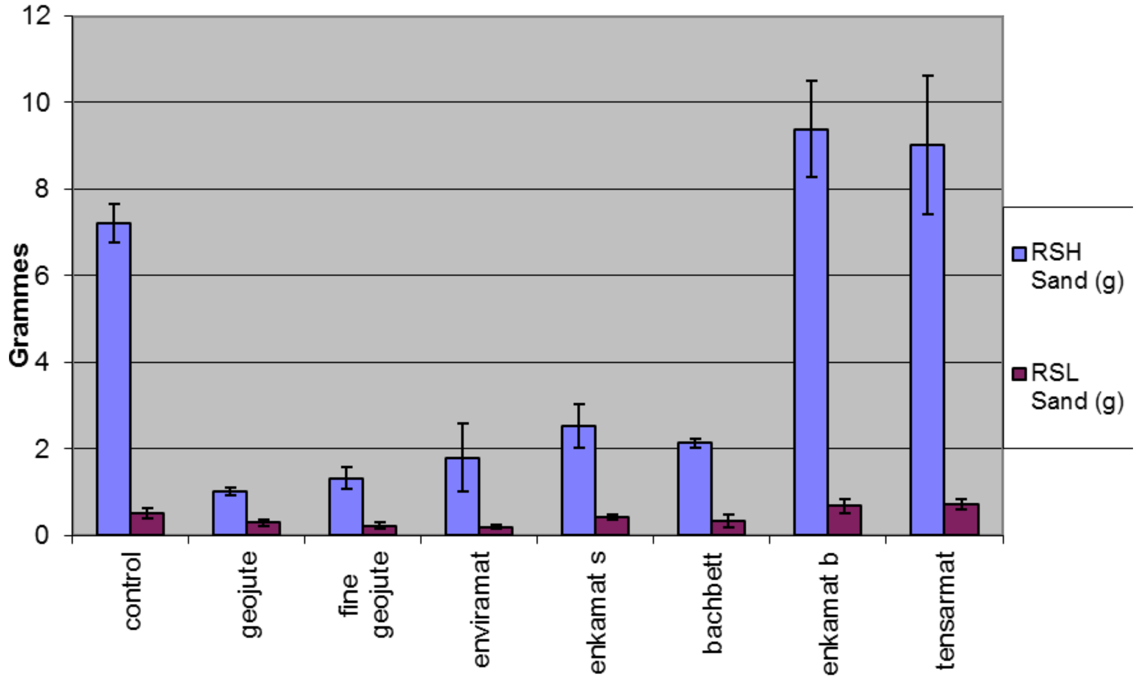

Figure 2 **Mean rainsplash erosion (g) for high (RSH) and low (RSL) intensity rainfall. Error bars represent one standard error of the mean**

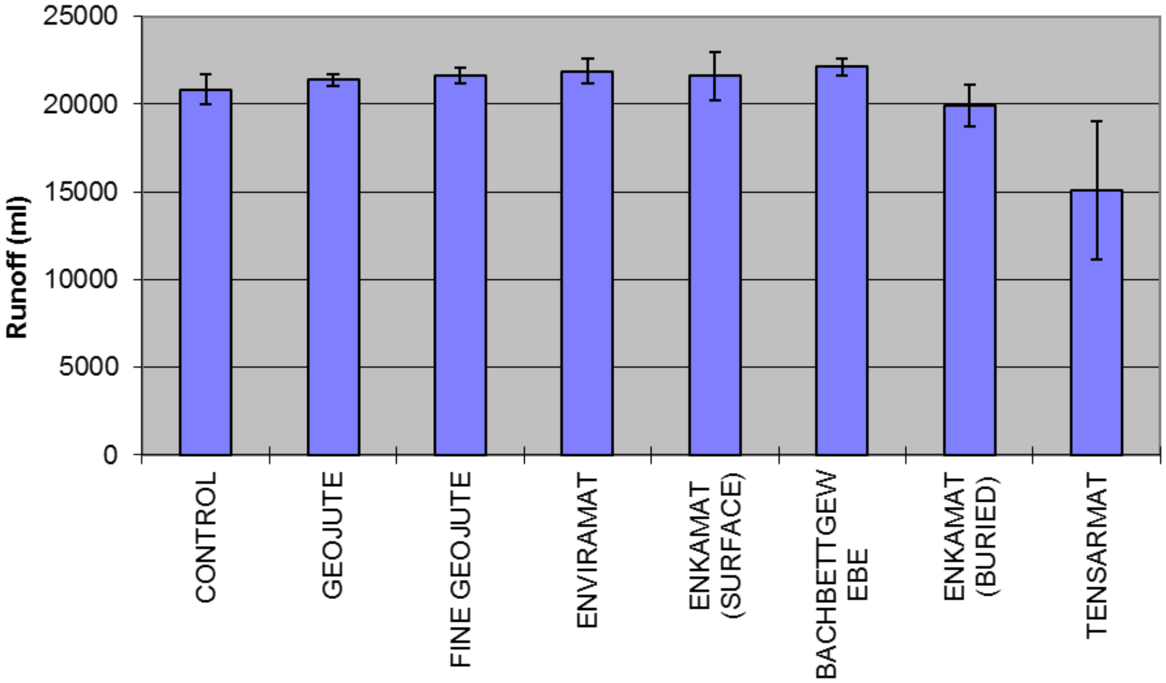

Figure 3 **Mean total runoff volume (ml) for the different geotextile treatments and bare soil control**

3.2.2 Soil losses from the runoff erosion tests

As shown in Figure 4, highest soil loss came from the bare soil control (197 g), followed by the buried Enkamat (166 g = 84% of the control). The other buried product, Tensarmat performed better in reducing soil losses to 35% of the control plot. When the Enkamat was surface laid, it gave less soil loss than the control (68%), but not significantly so. Best erosion control effectiveness came from the woven jute products (both 15% of the control plot), although the coir woven was not as effective (51% of the control).

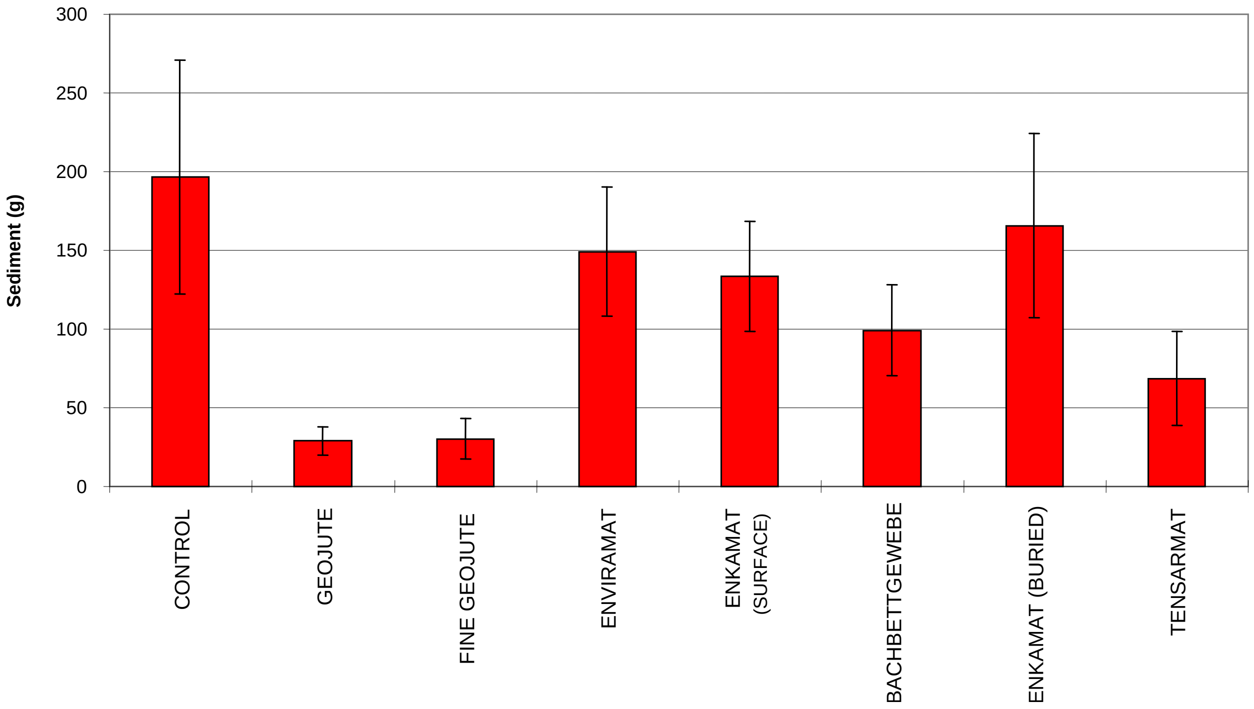

Figure 4 **Mean total soil loss (g) from simulated runoff. Error bars represent one standard error of the mean**

4 Discussion

4.1 Rainsplash erosion results

The natural fibre geotextiles performed well in controlling rainsplash erosion. One reason for this appears to be the high percentage area cover afforded by these products. It would appear that the interception function (percentage ground cover) is important, in line with what is known about vegetation and mulches (Morgan and Rickson, 1995). Indeed the correlation between splash loss and percentage area of the geotextile is extremely strong (Table 3). The interception of raindrops has a profound effect on the erosivity of rainfall, as demonstrated by the classic mosquito gauze experiment (Hudson, 1957). The plot of percentage cover against splashed soil loss (Figure 5) resembles the negative exponential relationship between ground cover and soil detachment found by Laflen and Colvin (1981).

Table 3 **Correlation coefficients between variables studied**

Experimental Conditions	**Soil Loss and % Area of Geotextile**	
	r^2 Value	**Significance**
High intensity rainfall, sandy loam	-0.874	p<0.01
Low intensity rainfall, sandy loam	-0.917	p<0.01

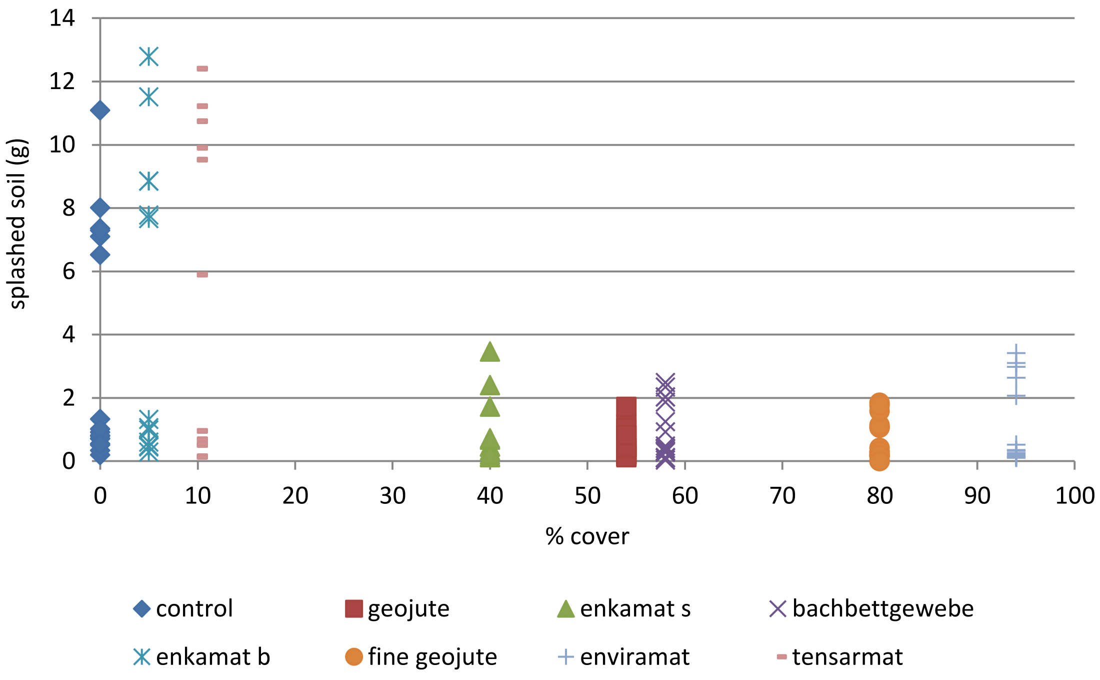

Figure 5 Relationship between geotextile % cover and total rainsplash loss (g)

Natural fibres also have thicker and rougher fibres, which intercept any splashed material before it leaves the Ellison splash cup. There seems to be a link with intensity on this point. The thinner, fine woven jute product (300 g m^{-2}) was very effective at the low intensity rainfall, as splashed material could be intercepted by the yarns of this product. However under more erosive conditions, the product was not thick enough to intercept so much material. This explains the relatively better performance of this product at the lower intensity. The standard Geojute with thicker yarns (500 g m^{-2}) was able to intercept the splashed materials generated under both high and low intensity storms.

The poor performance of the buried geotextiles was due to the mode of installation used. Removing the top soil layer, placing the geotextile on the subsoil and then backfilling the geotextiles with the top soil effectively sieves the soil, breaking up any soil structure or aggregation, so that the loose, unconsolidated backfill is highly erodible, and preferentially detached by the impacting raindrops. Indeed for the Tensarmat samples at the low intensity rainfall, splash erosion was far greater than that observed for the control (141%).

Also, the surface laid Enkamat always performed better at controlling splash losses than when the same product was buried. This product is able to hold some water within its filaments (in a way similar to coniferous pine needles), and on the surface the product does provide some (if very low) surface cover. At higher intensities the poor water holding capacity of the product is evident as incoming raindrops were intercepted but then splashed back rather than being absorbed by the product as occurred with the natural products.

These experiments show that each geotextile tested provided a different degree of protection to rainsplash. This degree of protection varied with rainfall intensity in some cases. The results presented enable us to identify a number of geotextile properties that explain the observed rates of soil detachment. These include:

- high percentage cover
- high water holding capacity
- thick fibres and/or filaments

- uninvasive mode of installation.

Conversely, the results demonstrate that undesirable characteristics of geotextiles with respect to the control of splash erosion appear to be:

- buried products
- thin, synthetic fibres
- loose mulch components
- tightly spun fibres and weaves
- low areal coverage.

4.2 Runoff erosion results

The fact that the different products did not yield significantly different volumes of runoff was surprising. It was expected that because the products (especially the natural fibred products) have variable water holding capacities (Table 4), so overland flow would be intercepted and held before surface overland flow was generated. This mechanism was not operating. Indeed, some of the woven natural products enhanced runoff generation – presumably by preferential flow along the warp (up/downslope) fibres. This was more marked than any possible interception of overland flow by the weft (across slope) fibres.

Table 4 Water holding capacity of selected geotextiles

Treatment	Mean Saturated Weight (as % of dry weight) (n = 4)	Weight After 24 Hours (as % of dry weight) (n = 4)	Weight After 48 Hours (as % of dry weight) (n = 4)
Woven jute 500 g m^{-2}	641	268	116
Woven jute 300 g m^{-2}	472	203	101
Wood shavings in light degradable mesh	389	129	103
Nylon 3D mat	232	100	100
Polypropylene 3D mat	183	100	100
Coir woven product 750 g m^{-2}	314	187	104

It is notable that the mean total soil losses cannot be explained by the mean total runoff volumes for the different treatments. The correlation between mean total runoff and mean total sediment for all treatments is very weak ($r^2 = +0.1768$, which is not significant). This contradicts the findings of Fifield and Malnor (1990), who found sediment yield to be closely related to runoff volume ($r^2 = 0.64$) for various natural geotextile treatments.

Despite the insignificant control of runoff volume by the jute products, they reduced sediment effectively. The across-slope, weft yarns provide high ‘drapability’ (an ability to conform to the microtopography of the slope form and profile), and thus good contact with the soil, especially when the yarns were wet, thus creating obstacles to flow and trapping any detached sediment. The results show that woven products transmit overland flow very well, but at the same time, are able to restrict sediment detachment and transport. Whilst the overland flow could be transmitted via the warp fibres and yarns, sediment cannot be transmitted in this way.

Also, by intercepting and holding water, the geotextile becomes wet and heavier, improving contact with the soil surface beneath. This retards any flow at the soil/geotextile interface, so interrupting surface flow, limiting detachment and transport of soil by the overland flow, and avoiding subsequent undermining of the geotextile, which can lead to geotextile failure. Reynolds (1976) argues that the erosion control is primarily afforded by the area of contact between the soil and the geotextiles, and good attachment to the soil.

The similarity of runoff volumes from the different products, yet high variability of sediment yields, suggest that geotextiles do not control erosion by reducing runoff volume, but by other mechanisms. Variations in observed soil losses for the different treatments can be explained by measured overland flow velocities (Table 5). For the runoff erosion tests, a positive relationship exists between soil loss and overland flow velocity, as expected ($r^2 = +0.4475$, significant at the $p<0.05$ level).

Table 5 Hydraulic variables associated with different geotextiles

Treatment	Slope (°)	Mean Velocity ($m\ s^{-1}$)	Mean Depth of Flow (mm)	Manning's n
Control	10	0.061	0.68	0.0566
Geojute	10	0.047	3	0.2091
Fine Geojute	10	0.034	2	0.2167
Enviromat	10	0.05	2	0.1474
Enkamat (surface)	10	0.042	1	0.1077
Bachbettgewebe	10	0.082	2	0.0899
Enkamat (buried)	10	0.059	0.68	0.0586
Tensarmat	10	0.034	0.68	0.1016

However, despite the statistically significant correlation between soil loss and flow velocity, there is still too much unexplained variation in the soil loss results. Therefore, it was decided to calculate other hydraulic parameters such as Manning's n values for the different treatments, in an attempt to increase the explanation of the variations in soil loss. Foster et al. (1982) report on predicting a parameter to describe roughness imparted to flow by different types of agricultural mulch. The required input parameters needed for these calculations are: flow depth (m), slope (°) and flow velocity ($m\ sec^{-1}$). These can be substituted into the following equation to calculate Manning's n:

$$\text{Manning's n} = \frac{r^{0.67} \cdot s^{0.5}}{v} \tag{1}$$

where v = overland flow velocity ($m\ sec^{-1}$)

r = Hydraulic radius (m – assumed to be equal to flow depth)

s = Slope ($m\ m^{-1}$)

There is a very good correlation between the Manning's n values and soil loss ($r^2 = -0.8043$, significant at $p<0.02$), reflecting how an increase in roughness imparted to the flow by the geotextiles leads to a reduction in soil loss. This represents a better explanation of soil loss variations for the different treatments than when using overland flow velocity alone ($r^2 = +0.4475$). Clearly, velocity is one factor affecting soil loss control. It appears that depth of flow also affects how geotextiles perform in controlling erosion losses by runoff. The correlation of flow depth to soil loss was stronger ($r^2 = -0.6357$) than that between soil loss and velocity. From these observations, the desirable characteristics of erosion control geotextiles, which reduce erosion by runoff, appear to be:

- high geotextile induced roughness
- high water holding capacity (and associated increased weight and soil contact when wet)
- ability to increase flow depth

- ability to reduce flow velocity
- high drapability.

5 Validation of findings from rainsplash and runoff tests

Having identified the salient properties of geotextiles for controlling rainsplash and runoff erosion, these relationships were validated with an independent set of experiments where a more realistic simulation of erosion processes was run, i.e. where overland flow was combined with rainsplash impact. The same experimental set was used as for the runoff tests, but with simulated rainfall (95 mm hr^{-1} for 10 minutes) generated above the slope. (It was not possible to repeat the exact rainfall intensity simulated for the rainsplash erosion experiments, because of the spatial variability of rainfall applied over the larger target area in the validation tests). Soil loss and runoff were measured and results correlated with geotextile properties (Table 6).

Table 6 Correlation coefficients between geotextile properties and erosion control effectiveness (rainfall and runoff combined)

Geotextile Property	Correlation With Erosion Control Effectiveness	Significance of Correlation
Area of geotextile (%)	-0.8723	$p<0.05$
Cost ($ m^{-2})	0.2970	NS
Depth of flow (mm)	-0.8302	$p<0.05$
Flow velocity (m s^{-1})	-0.0681	NS
Manning's roughness coefficient (n) / geotextile induced roughness	-0.7095	$p<0.05$
Mean yarn diameter (mm)	-0.4667	NS
Tensile strength (kN m^{-1})	0.2939	NS
Thickness (mm)	0.3730	NS
Water holding capacity (%)	-0.8369	$p<0.05$
Weight (g m^{-2})	-0.7189	$p<0.05$
Wet weight as % after 24 hours	-0.8419	$p<0.05$
Wet weight as % after 48 hours	-0.5990	$p<0.10$

Correlations between geotextile properties and effectiveness in controlling erosion (Table 6) under these independent tests confirmed the relationships found at the sub-process scale (rainsplash and runoff). Erosion control geotextiles with the following properties are likely to be most effective:

- high area of geotextile (%)
- ability to pond water and increase surface depth of flow
- high Manning's roughness coefficient (n) / geotextile induced roughness
- high water holding capacity (%), including wet weight after 24 and 48 hours
- high weight per unit area (g m^{-2}).

For the geotextiles tested, the following properties are not well-correlated with product performance in controlling erosion:

- cost (\$ m^{-2})
- flow velocity ($m\ s^{-1}$)
- mean yarn diameter (mm)
- tensile strength ($kN\ m^{-1}$)
- thickness (mm).

6 Conclusions

A methodology for evaluating erosion control geotextiles is presented, where the interactions between geotextile physical properties and erosion processes operating are investigated. By understanding these interactions, salient properties of geotextile products have been identified. This understanding will assist land managers to specify the most effective products and manufacturers to develop reliable products that the rapidly increasing erosion control markets can trust. Interestingly, there appears to be no relationship between the cost of erosion control geotextiles and their effectiveness in controlling sediment production, which has implications for land managers searching for cost-effective solutions to mitigate erosion risks. Although the findings are based on small scale, laboratory experiments, Smets et al. (2011) found that runoff and soil loss results at this scale are similar to those observed in the field.

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