CSIRO PUBLISHING

www.publish.csiro.au/journals/ajsr *Australian Journal of Soil Research*, 2003, **41**, 1509–1520

Effect of polyacrylamide additions on infiltration and erosion of disturbed lands

C. A. Vacher[A,B], *R. J. Loch*[A], *and S. R. Raine*[B]

[A]Landloch Pty Ltd, PO Box 555, Darling Heights, Qld 4350, Australia.
[B]National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, Qld 4350, Australia.

Abstract

The removal of vegetation and disturbance of the soil surface due to a range of human activities results in the potential for soil structure degradation and sediment movement. Polyacrylamides have been used to improve infiltration and reduce erosion on agricultural lands. However, they are not commonly used as part of management and rehabilitation programs on land disturbed by construction or mining activities in Australia. A study was undertaken to investigate the potential for polyacrylamides to improve infiltration and reduce erosion of soil material from 3 Australian mine sites. The polyacrylamides were found to significantly ($P < 0.05$) increase total infiltration under rainfall, reduce surface hardness, and reduce sediment entrainment and erosion by both rainfall and overland flows. The effectiveness of the polyacrylamide was found to be related to clay content of the soil as well as the molecular weight and charge density of the polyacrylamide. The implications of these results for the management and rehabilitation of disturbed lands are discussed.

Additional keywords: sediment, rehabilitation, stabilisation.

Introduction

A wide range of agricultural, forestry, mining, housing, and infrastructure construction activities involve the removal of vegetation and disturbance of the soil surface. These changes can cause accelerated erosion and lead to concerns about both the on- and off-site impacts of increased sediment movement, and associated nutrients and other pollutants. Management of disturbed lands usually involves containment/control of erosion and sediment movement during the period of disturbance, followed by rehabilitation/stabilisation to achieve long-term stability. Although guidelines for the management of construction sites (e.g. Institution of Engineers (Queensland Division) 1996) emphasise both erosion and sediment control, some site disturbance and erosion is unavoidable. Hence, the major management inputs to disturbed sites are often focused on controlling sediment movements and minimising off-site impacts. However, the suspended colloidal sediments that cause in-stream turbidity and that may carry high concentrations of nutrients (Costantini and Loch 2002) and other pollutants do not normally settle out of runoff flows. Thus, efforts to control the impacts of land disturbance by focusing on sediment settling are of questionable value in many situations (Loch 1997), and a practical method for the short-term control of erosion and the resulting generation of suspended colloidal sediment would be useful.

In rehabilitating disturbed lands, there is typically a relatively short ‘window of risk’ when the soil surface is bare and unconsolidated before vegetation establishment (Carroll *et al*. 2000). Erosion by both raindrop impact and concentrated flows can be high under these conditions and the effectiveness of different rehabilitation strategies to address these mechanisms will vary. Early establishment of a network of erosion rills and gullies during the initial stages of rehabilitation can predispose the site to increased erosion in the future

10.1071/SR02114 0004-9573/03/081509

(Moliere 2000). Hence, it is desirable to have some form of protection for the exposed material during the early stages of rehabilitation, as site damage during the initial stages commonly results in the need for additional remediation works and cost.

Soil protection measures applied during the initial stages of rehabilitation should promote plant establishment and growth rather than inhibit it, and maintain soil surface stability and infiltration capacity. Contact (usually vegetative) cover in excess of 50–60% is generally considered necessary to create sustainable soil surface conditions with low erosion potential (Carroll *et al*. 2000; Loch 2000). However, annual and seasonal variations in vegetation growth and cover suggest that higher average levels of cover may be needed (Loch *et al*. 2000).

The soil surface before plant establishment for any rehabilitation process should provide an appropriate medium for plant growth and limit further degradation from occurring. High infiltration rates will increase the amount of soil water available for plant germination and growth, and limit the amount of runoff available to cause erosion. On steep sites with little surface cover, overland flows are the major cause of erosion and of continued degradation.

Polyacrylamides (PAM) are polymers of acrylamide monomers which have been employed to enhance soil stability and plant growth. Individual PAM formulations are distinguished on the basis of molecular weight, ionic charge and charge density. The longer the polymer chain, the higher the molecular weight. The ionic charge for the polymer chain is based on the substitution of the NH_2 component of the acrylamide monomer to produce a cationic (net positive), non-ionic (neutral), or anionic (net negative) charge. The charge density of each PAM is governed by the amount of substitution applied to the length of the polymer chain. The anionic forms of PAM have a low toxicity to mammals and fish (Barvenik 1994) and are regarded as environmentally safe for use at recommended rates (Sojka and Surapaneni 2000).

About 400 000 ha of agricultural land is treated each year with PAM in the USA (Sojka and Surapaneni 2000). Because PAM stabilises soil aggregates, it has been widely shown to prevent surface seal formation and increase infiltration of both irrigation and rainfall (Fox and Bryan 1992; Norton 1992). Similarly, many studies have shown reductions in erosion on agricultural soils due to PAM applications (Levin *et al*. 1991; Agassi and Ben-Hur 1992; Fox and Bryan 1992; Lentz and Sojka 1994; Levy and Agassi 1995; Flanagan *et al*. 1997). Other benefits include reductions in surface hardness and crust strength (Rubio *et al*. 1984) and increased seedling establishment (Rubio *et al*. 1984; Cook and Nelson 1986; Wallace and Wallace 1986; Helalia and Letey 1988). However, the effectiveness of PAM reduced in a matter of weeks (Lentz *et al*. 1992).

Because of the properties outlined above, PAM applications have been suggested as a short-term method for stabilising disturbed soils either during periods of disturbance or during initial periods of rehabilitation when the soil is normally most vulnerable. However, the use of PAMs in minesite and construction situations in Australia is virtually non-existent (Sojka and Surapaneni 2000). In part, this may be due to the lack of suitable systems and equipment for delivery/application of PAM at those sites. As well, the potential benefits of PAM applications for disturbed land rehabilitation under Australian conditions are poorly documented, and there is little if any information on whether the benefits of PAM addition are sufficient to provide economic or practical advantages. The aim of this paper is to quantify the effect of various PAM formulations on infiltration, surface hardness, and erosion for a range of Australian minesite soil materials. Further work is being carried out to assess, using runoff and erosion models, whether the measured responses to PAM additions are sufficient to make its use cost-effective.

Table 1. Characteristics of soil materials studied

Soil material origin	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/cm^3)	CEC (cmol(+)/kg)	pH
Goonyella/Riverside Coal Mine (Qld) topsoil	50	11	39	1.62–1.80	9.7	7.4
Capel Mine (WA) topsoil	<1	<1	99	1.50–1.65	4	5.2
Alcan Gove Mine (NT) Retention pond 5 soil[A]	16	8	77	1.40–1.60	5	8.2
Alcan Gove Mine (NT) Retention pond 7 soil[A]	3	3	94	1.40–1.60	4	6.5

[A] Samples from the Residue Disposal Area.

Materials and methods

Soil material used for rehabilitation (Table 1) was collected from 3 Australian mine sites and transported to the University of Southern Queensland for subsequent study. The materials were air-dried and gravel > 50 mm in diameter was removed before being stored in air-tight drums. Soil physical and chemical properties (Table 1) were measured in the laboratory. Particle size analysis was conducted using the pipette method. The pH was measured using a 1:5 soil–water extract, and cation exchange capacity measured by summing the extractable cations with 1 M ammonium chloride at pH 7.

One rainfall simulation and 2 overland flow simulation studies (Table 2) were conducted to evaluate the effect of PAM addition on infiltration, surface hardness, and erosion. The rainfall simulations were conducted using rainfall water (~0.03 dS/m) and the overland flow simulations were conducted using townwater (~0.4 dS/m). A barley straw mulch (2.75 t/ha) and combined barley straw mulch and PAM treatment were included in the rainfall simulation study for comparison. Gypsum (5–6 t/ha) was also applied by hand to the soil surface in each of the overland flow studies, as previous work (e.g. Theng 1982; Agassi and Ben Hur 1992; Norton 1992) suggested that the divalent calcium ions improve the cation bridging between the PAM molecules and the clay surfaces. The effect on PAM efficacy of clay (kaolinite-dominant, CEC ~3 cmol(+)/kg) additions (0–20% of the total soil mass) to the Capel topsoil was also investigated.

In each study, a deep layer (up to 125 mm) of the soil material was packed above a porous foam matting in square plot trays with a surface area of 0.16 m^2. The matting allowed air and water movement below the soil and the trays were allowed to drain freely. The top surface of the soil was raked level with the top of the tray edge to reduce ponding.

Both low molecular weight (LMW, <10^5 g/mol) anionic PAMs (A86 and Aerotil) and high molecular weight (HMW, >10^6 g/mol) anionic PAMs (A311, X-135, and LT25) were evaluated (Table 2). The A86 and A311 PAMs (Cytec Industries Inc., New Jersey) were low charge density formulations (<10% hydrolysis),

Table 2. Treatments used to evaluate the effectiveness of polyacrylamide to stabilise disturbed soils

Evaluation method	Soil material	Parameter	PAM formulation	PAM application rate[A]
Rainfall simulation	Goonyella /Riverside	Infiltration, surface hardness & sediment conc.	A86, A311	5, 10, 20, 40 kg/ha
			Aerotil	28, 56 kg/ha
			Aerotil	112 kg/ha
Overland flow study 1	Capel	Sediment conc. & critical shear stress	A86, A311	5, 10 kg/ha
			Aerotil	112, 225 L/ha
Overland flow study 2	Alcan Gove Retention Ponds 5 & 7	Sediment conc.	A86, A311	5, 10 kg/ha
			Aerotil	112, 225 L/ha
	Alcan Gove Retention Pond 5	Sediment conc.	LT25	5, 10 kg/ha
			X-135	30, 60 L/ha

[A] PAM application rates based on product quantities.

whereas the Aerotil (Cytec Industries Inc., New Jersey), and X-135 and LT25 (Ciba Pty Ltd, Sydney) had comparatively higher charge densities (>15% hydrolysis). The powdered PAM formulations (A86, A311) were dissolved in water and the liquid forms of PAM (Aerotil, X-135, LT25) were diluted with water to enable application onto the soil surface using a hand sprayer. Water containing PAM treatments was applied at standard rates of 5.7 L/m^2 for rainfall simulation studies and 2.5 L/m^2 for overland flow studies. The HMW PAM solutions were found to be more viscous than the LMW PAM solutions and needed to be diluted by up to 5 times the standard rate to achieve similar viscosities for hand spraying. However, no significant reduction in viscosity was observed for the X-135 solution when diluted by 5 times the standard rate, and application in this case was in the form of a jet rather than a mist spray. Following PAM application to air-dry soil, all plots were left for a minimum of 12 h to dry before rainfall and overland flow tests.

Infiltration

The effect on infiltration of PAM addition was investigated using a laboratory rainfall simulator of the type described by Loch *et al*. (2001). The simulator applied a nominal rainfall rate of 100 mm/h for a 30-min period to the soil plots, which were placed on a 10% slope (3 replicates per treatment). Total infiltration and infiltration rate were measured as the change in plot mass through time measured using load cells. Corrections were applied to the mass data to account for soil loss through runoff during rainfall.

Surface hardness

Surface hardness and gravimetric moisture content were measured immediately following the rainfall simulation and at 4–5, 8, and 11 days of glasshouse drying after the rainfall application. A Geotester penetrometer was used to assess surface hardness with the tip (diameter 6.5 mm) inserted to a depth of 10 mm or until the surface crust broke. Six penetrometer readings were taken on each plot and an average hardness calculated for each treatment. Gravimetric moisture content (3 replicates) of the crust (max. 10 mm) was measured to compare against surface hardness for each PAM treatment.

Erosion

The effect of PAM addition on erosion was assessed in both rainfall and overland flow simulation studies. Runoff and sediment were collected using a tray attached to the bottom edge of the soil plots. For the first overland flow study (Table 2), simulated rainfall was applied for 10 min at an intensity of 50 mm/h prior to the application of the overland flow, to generate a uniform initial sample wetness and soil surface consolidation.

Overland flow was supplied by a constant flow regulated with a rotameter and applied via a reservoir attached to the upper end of each soil plot to maintain a uniform flow depth over the entire soil surface. Flow rates were selected to create flow shear stresses consistent with the range of critical shear values previously reported as necessary for rill initiation on sandy and sandy loam soils (Flanagan and Livingston 1995). For the Capel mine topsoil, flow rates of 0.34 L/s (estimated flow shear stress of 1.9 Pa) and 0.65 L/s (estimated flow shear stress of 3.7 Pa) were applied to the treatment plots, which were placed on a 10% gradient (2 replicates per treatment). Flow rates of 0.14 and 0.29 L/s were used with a 12.5% plot gradient for the Alcan Gove retention pond soil treatments (3 replicates per treatment). Sediment concentration in the runoff was measured throughout the experiments and was recorded as an average for each flow rate.

Data analysis

Analyses of variance (ANOVA) were conducted for each experiment and used to calculate the least significance difference for each treatment during rainfall simulations and unbalanced paired *t*-tests on the surface hardness, moisture content, and overland flow data to a significance level of $P = 0.05$. Unless otherwise stated, 3 replicates of all treatments were used in all tests.

Results

Infiltration

The application of PAM significantly ($P < 0.05$) improved infiltration of rainfall into the Goonyella Riverside topsoil (Fig. 1). Increasing the rate of PAM addition significantly increased total infiltration. Low application rates (5–10 kg/ha) of both the LMW and HMW PAMs increased total infiltration from 6 mm (control) to 8–15 mm, whereas higher application rates (i.e. 40 kg/ha) increased infiltration to 14–18 mm. There was no

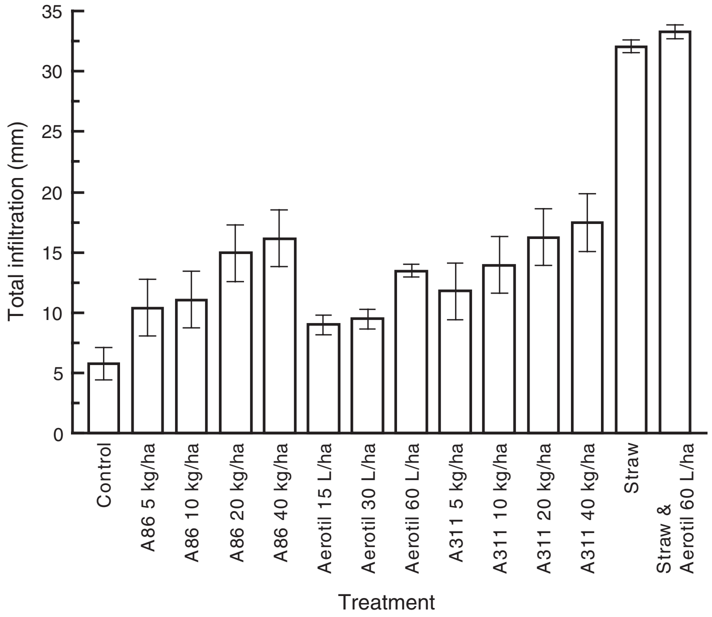

Fig. 1. Effect of polyacrylamides and straw mulch on infiltration of a nominal 50 mm of simulated rain into Goonyella/Riverside mine topsoil. Capped lines are ±s.e.

significant difference in the effect of the LMW and HMW PAMs. Straw mulch produced greater infiltration increases for Goonyella Riverside topsoil than did PAM treatments. However, the application of a high rate of PAM in addition to the straw produced a further small but significant increase in total infiltration.

The PAM additions were found to delay the onset of infiltration rate decline and to significantly ($P < 0.05$) increase the final infiltration rate of the soil (Fig. 2). For example, the average infiltration rate measured over the last 10 min of the rainfall simulation was 4.3 mm/h (s.d. = 0.86) for the control, and 7.7, 8.7, and 5.9 mm/h (s.d. = 1.51, 1.41, and 1.12, respectively) for low, medium, and high levels of Aerotil application. Over the last 10 min the straw mulch treatments had an infiltration rate of 48.0 mm/h compared to infiltration rates of 49.8 mm/h measured for straw mulch and straw mulch plus high Aerotil application. Neither straw treatment reached steady-state infiltration rate during the rainfall simulation period.

Surface hardness

PAM treatments decreased soil surface hardness at all measurements ($P < 0.05$) compared with controls. This effect was at least partly due to PAM's tendency to increase soil water content which, in turn, decreased soil hardness.

Measurements of gravimetric moisture content taken at the same time as surface hardness confirm a strong non-linear inverse relationship between surface hardness and water content (Fig. 3). The molecular weight of PAM had no significant ($P > 0.05$) effect on the surface hardness observed when the soil was either wet or dry. Similarly, there was no difference in surface hardness due to the rate of PAM application when the soil was moist. However, for samples where the soil water content was <7.5%, surface hardness

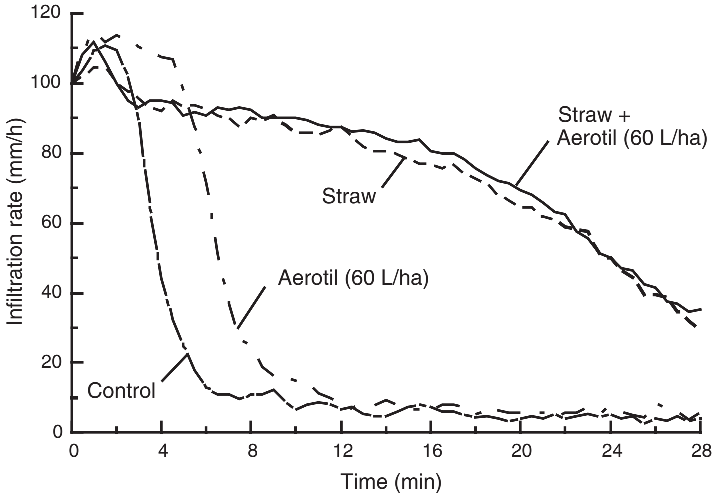

Fig. 2. Effect of polyacrylamide and straw mulch on infiltration into Goonyella/Riverside mine topsoil under a nominal 100 mm/h simulated rainfall event.

tended to increase ($P < 0.1$) with PAM addition from an average of 24.2 (± 4.6) kg/cm^2 for the untreated soil through to 32.7 (± 6.7) kg/cm^2 for the PAM additions of 40 kg/ha.

Erosion

The application of PAMs reduced sediment concentration in rainfall runoff by 22–54%. The reduction in total runoff for the PAM treatments due to increased infiltration rates (Fig. 1), combined with lower sediment concentrations in rainfall runoff (Fig. 4), resulted in a reduction in soil lost by rainfall and runoff.

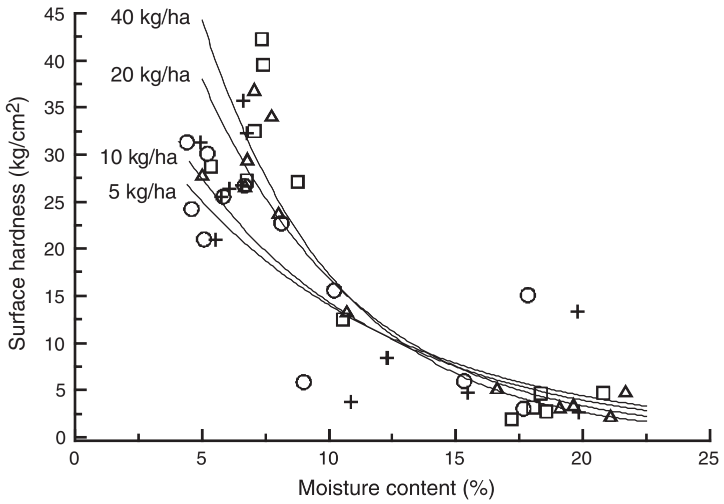

Fig. 3. Relationship between surface hardness and soil moisture content measured at 4–5, 8, and 11 days after rainfall simulation for PAM (A311 and A86) application rates of 5 (○), 10 (+), 20 (△), 40 (□) kg/ha.

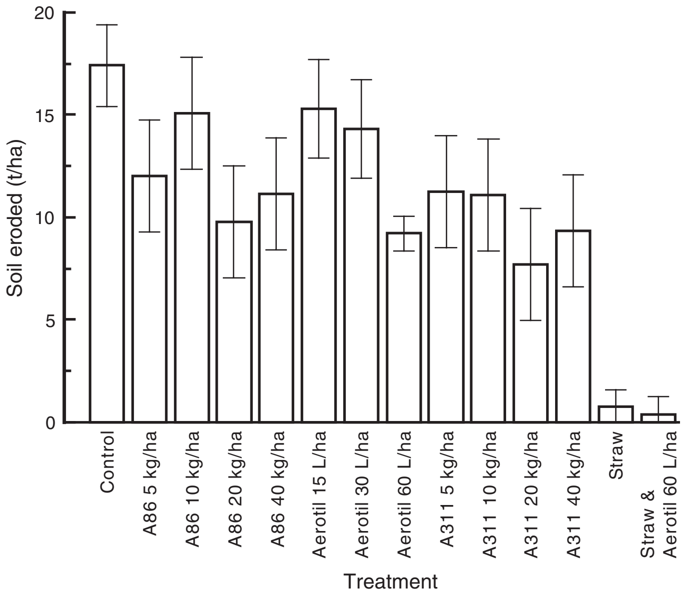

Fig. 4. Effect of polyacrylamide on soil eroded by a nominal 100 mm/h simulated rainfall event applied for 30 min to Goonyella/Riverside mine topsoil. Capped lines are ±s.e.

The application of PAM also significantly ($P < 0.05$) reduced sediment concentration in applied overland flows (Tables 3 and 4). The proportion of clay in the soil material was found to influence both sediment concentrations in overland flow and the effectiveness of the various PAMs in reducing sediment concentrations. The HMW PAMs were more effective than the LMW PAMs on low clay, low pH retention pond soil (Table 4). However, there was less difference between the effectiveness of the LMW and HMW PAMs on soils with higher clay contents (Tables 3 and 4). Similarly, low charge density (A86) and high charge density (Aerotil) LMW PAMs were equally effective on low clay, low pH soil (Table 4). However, where the clay content of the soil material was higher, the higher charge density PAMs were more effective in reducing sediment concentrations in overland flow (Table 4).

PAM additions to the Capel topsoil produced a significant ($P < 0.05$) increase in the critical flow shear stress to be exceeded for rilling to occur. Rills formed on untreated plots at the low flow rate, indicating a critical flow shear stress for rill initiation of <1.9 Pa. Applying PAM to the Capel topsoil typically increased the critical flow shear stress for rilling to 1.9–3.7 Pa. However, the HMW PAM (A311) applied at the higher rate (10 kg/ha) increased critical shear for rilling to >3.7 Pa without clay addition. Where any of the PAMs were applied to clay-amended soil, critical shear for rill development was >3.7 Pa. Overland flows on clay- and PAM-treated soils produced very low levels of sediment losses (Table 3) and no noticeable disturbance to the surface layer, indicating that these treatments had a critical shear for rill initiation that was much higher than the 3.7 Pa applied.

Discussion

PAM formulation and clay content

The addition of PAM improved infiltration and reduced surface hardness and erosion from disturbed soils under both simulated rainfall and overland flows. However, the effectiveness

Table 3. Effects of PAM and clay addition on sediment loss by overland flows for Capel topsoil on 10% slope

Within PAM treatment and flow rate, means followed by the same letter are not significantly different at $P = 0.05$

Treatment	PAM application rate	Clay addition (%)	Low flow sed. conc. (g/L)	High flow sed. conc. (g/L)
Control	0	0	16.81a	16.62ab
A86	5 kg/ha	0	15.12 ab	13.88abc
		5	14.39 abc	19.66a
		10	10.79 bc	14.52bc
		20	1.63e	8.23de
	10 kg/ha	0	11.64abc	10.16cde
		5	4.36de	10.28cde
		10	3.36e	13.73bc
		20	0.83e	2.83fg
Aerotil	112 L/ha	0	12.26ab	8.31de
		5	9.30cd	15.46ab
		10	5.01de	12.97bcd
		20	1.67e	3.18fgh
	224 L/ha	0	16.50a	11.36bcde
		5	2.51e	3.17fgh
		10	0.89e	0.81gh
		20	1.17e	0.33gh
A311	5 kg/ha	0	5.50de	6.83ef
		5	2.57e	6.16efg
		10	2.03e	5.87ef
		20	0.83e	0.84gh
	10 kg/ha	0	1.62e	0.56h
		5	0.70e	0.30h
		10	0.59e	0.32h
		20	0.62e	0.47h

of PAM addition was influenced by both the molecular weight and charge density of the PAM used as well as by the clay content of the soil. This is consistent with earlier findings, which suggest that the effectiveness of PAM in improving aggregate stability and flocculation is influenced by the length of the polymer chain and the number of charged sites available for bonding (Levy and Agassi 1995).

The clay particles are the primary soil constituent on which the polymer is adsorbed (Schamp *et al.* 1975). Increasing the clay content of the Capel topsoil from 0 to 20% improved the effectiveness of each PAM treatment evaluated (Table 3) because the number of charged sites for bonding increased. The effectiveness of LMW PAM, in particular, is improved with higher clay content in the soil, consistent with data of Green *et al.* (2000).

For soils with low clay contents (≤10%) the HMW PAM (e.g. A311) was more effective than the LMW PAM (e.g. A86, Aerotil) at reducing sediment concentration (Tables 3 and 4). This reflects the direct relationship between polymer length and molecular weight. In soils with low clay contents, the distance between potential clay bonding sites is larger and long chain polymers appear more effective at bridging these distances (Levy and Agassi 1995). However, where the clay content of the soil was 15–20% (Tables 3 and 4), the high charge density LMW PAM (Aerotil) performed much better than either the LMW or HMW low charge density PAMs (A86 and A311). For soil with a clay content of 50% (Figs 1

Table 4. Effect of PAM on sediment loss by overland flows across retention pond 5 (16% clay) and retention pond 7 (3% clay) material from the Alcan Gove Mine Residue Disposal Area on 12.5% slope

Within material and flow rate, means followed by the same letter are not significantly different at $P = 0.05$

Treatment	PAM application Rate	Low flow sed. conc. (g/L)	High flow sed. conc. (g/L)
	Retention Pond 5		
Control	0	27.62a	Not tested[A]
A86	5 kg/ha	27.78a	Not tested[A]
	10 kg/ha	13.44b	14.99a
Aerotil	112 L/ha	0.33d	0.85b
	224 L/ha	0.31d	1.89b
A311	5 kg/ha	1.99c	17.34a
	10 kg/ha	6.23bc	5.26b
	Retention Pond 7		
Control	0	4.10ab	6.86a
A86	5 kg/ha	5.10a	5.83ab
	10 kg/ha	2.87bc	3.36c
Aerotil	112 L/ha	3.21bc	4.04bc
	224 L/ha	3.89abc	3.82c
A311	5 kg/ha	0.42d	1.49d
	10 kg/ha	2.34c	2.97c

[A] Materials not tested under high flow rate due to failure under low flow conditions.

and 4), there was no significant difference between PAMs with different molecular weights and charge densities, but their effectiveness improved with rate of PAM application. This suggests that as the clay content of the soil increases, the distance between potential clay bonding sites decreases and the length of the polymer chain becomes less important relative to the charge density. However, where the clay content of the soil is high, the number of charged clay sites available for bridging is large and the main factor influencing PAM performance is the amount of product used, as that will control the number of bonds formed between soil particles.

As maximum responses to PAM addition were not observed, it seems likely that the effectiveness of the PAMs could also have been increased if higher rates had been used. However, it is unlikely that higher rates of PAM would have been as effective as the straw mulch treatment in maintaining infiltration (Fig. 1), as the mulch both protects surface aggregates from breakdown associated with rapid wetting and protects the soil surface from compaction by raindrop impacts. The addition of PAM only increases the strength of the aggregates and so assists in reducing aggregate breakdown. However, PAM addition provides no protection against the compactive effects of raindrop impacts.

Using existing relationships between steady infiltration rate and aggregate size for bare and covered surfaces (Loch and Foley 1994), a steady infiltration rate of ~4.5 mm/h is consistent with a bare soil surface having 65% of particles with a size <0.125 mm. A 10–20% reduction in particles (aggregated and non-aggregated) <0.125 mm in size could be expected to increase steady infiltration rates to 6.7–10 mm/h, consistent with the changes in infiltration rate noted with PAM addition (Fig. 2). However, surface cover of this soil would be expected to increase the steady infiltration rates to ~12 mm/h, with those steady rates being much slower to be reached (c.f. Fig. 2), and therefore giving increases in total infiltration over 30 min rain of much more than 6 mm.

Higher rates of PAM addition increased surface hardness when the soil dried and could be expected to affect crust development and seedling establishment. Visual observations suggest that increasing PAM addition reduced crust breaking at low water contents. At higher water contents, there is little direct effect of PAM on soil crust strength of breaking. However, it also seems that PAM addition affects the drying of the soil surface, and we suggest that the following mechanisms are operating. Where PAM is not applied, the less-permeable surface loses water more slowly than PAM-treated surfaces, so that the untreated soil remains wetter for longer under conditions of high evaporative demand (Callebaut *et al.* 1979). Where evaporative demand is lower, surfaces receiving PAM may stay wetter for longer because of the greater quantity of water initially infiltrated.

Implications for site management and rehabilitation

The data show that PAM addition can achieve practically significant increases in infiltration and reductions in erosion. A particular benefit of this approach is that erosion is prevented at source, rather than 'controlled' at some downstream location. As Costantini and Loch (2002) show, high-erosion, high-deposition situations are not effective in controlling fine sediment, and can lead to considerable enrichment of nutrients in the fraction of sediment that is not 'trapped'. Therefore, the use of PAM appears to be a worthwhile option for short-term stabilisation requirements.

There is obvious potential to use PAM to stabilise short, steep slopes where flows are likely to generate maximum flow shear stresses in the order of 3–4 Pa (up to 10 m long at 50% gradient, longer for lower gradients). Such slopes will often be subject to predominantly interrill detachment and transport, and will generate fine sediment that will not be effectively controlled by silt fences. In those situations, PAM would be more effective.

As yet, it is not clear whether PAM increases critical shear values for rilling sufficiently to enable protection of longer slopes, and research using larger flow rates to generate flow shear values more consistent with the long slopes occurring in the field is required. If relatively large increases in critical shear can be achieved, the use of PAM could influence site preparation for rehabilitation and could enable cost savings by allowing reductions in the intensity of other erosion control measures.

The interactions between PAM type and soil clay content mean that there may, in some situations, be potential for soils used in site rehabilitation to be selected on the basis of the effectiveness with which they can be stabilised using PAM. For other situations, PAM formulations that are most effective for the soils present at a site may be selected. HMW PAM formulations (e.g. A311) consistently reduced erosion across all soils tested, whereas the LMW formulations were less consistent. Nonetheless, the LMW formulations offer great advantages in terms of convenience, as they are less viscous, easier to spray, and would require smaller water application volumes, and for that reason, would be preferred wherever possible.

At this stage, solution viscosity is one of the main barriers to the use of PAM in general land management practice. To apply the relatively low rates of chemical required evenly across a relatively large area, spraying is an ideal delivery method. However, the dilutions used in these studies equate to relatively large volumes, and at such dilutions, broad-acre spraying would still be quite difficult. For example, solutions of A311 and Aerotil of similar viscosity equate to spray volumes of 300 and 62.5 m^3/ha, respectively. It is for this reason that the less viscous LMW formulations such as Aerotil and A86 are extremely attractive options. Any treatments that could further reduce solution viscosity would be particularly useful in aiding adoption of PAM as a soil amendment. One alternative that has been considered is to apply the PAM as a dry powder. This might require (or achieve) somewhat higher rates of application, but raises issues of spatial uniformity of application and the need for some wetting to achieve adequate coverage.

As PAM can be expected to break down in a matter of weeks under field conditions, its use is also likely to be limited to situations where either (*a*) wetting (some form of irrigation) to germinate vegetation can be reliably expected soon after application, or (*b*) there is a clearly defined wet season and the probability of rain soon after application is high, so that a vegetative cover can establish and increase soil surface stability before all benefits of PAM addition are lost.

Acknowledgments

This work was conducted with the support of Iluka Resources Pty Ltd (Capel Mine), BHP Coal Pty Ltd (Goonyella/Riverside Mine) and Alcan Gove Pty Ltd (Alcan Gove) and that support is gratefully acknowledged. The assistance of Mr S. DeJersey, Mr R. Allen, and Ms E. Knopf in undertaking some of the trial work in partial fulfilment of their undergraduate studies at the University of Southern Queensland is also acknowledged.

References

Agassi M, Ben-Hur M (1992) Stabilizing steep slopes with soil conditioners and plants. *Soil Technology* **5**, 249–256. doi:10.1016/0933-3630(92)90025-V.

Barvenik FW (1994) Polyacrylamide characteristics related to soil applications. *Soil Science Society of America* **158**, 235–243.

Callebaut F, Gabriels D, De Boodt M (1979) Effect of polymer structure on soil physio-chemical properties and soil and water evaporation. *Journal of Chemical Technology and Biotechnology* **29**, 723–729.

Carroll C, Merton L, Burger P (2000) Impact of vegetative cover on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. *Australian Journal of Soil Research* **38**, 313–328. doi:10.1071/SR99052.

Costantini A, Loch RJ (2002) Effects of site preparation on runoff, erosion, and nutrient losses from *Pinus* plantations established on the coastal lowlands of south-east Queensland, Australia. *Australian Journal of Soil Research* **40**, 1287–1302. doi:10.1071/SR02032.

Cook DF, Nelson SD (1986) Effect of polyacrylamide on seedling emergence in crust-forming soils. *Soil Science* **141**, 328–333.

Flanagan DC, Livingston SJ (1995) Effect of water chemistry and soil amendments on a silt loam soil—Part 2: soil erosion. *American Society of Agricultural Engineers* **40**, 1555–1561.

Flanagan DC, Norton LD, Shainberg I (1997) Effect of water chemistry and soil amendments on a silt loam soil—Part 2: soil erosion. *American Society of Agricultural Engineers* **40**, 1555–1561.

Fox D, Bryan RB (1992) Influence of a polyacrylamide soil conditioner on runoff generation and soil erosion: field tests in Baringo District, Kenya. *Soil Technology* **5**, 101–119. doi:10.1016/0933-3630(92)90012-P.

Green SV, Stott DE, Norton LD, Graveel JG (2000) Polyacrylamide molecular weight and charge effects on infiltration under simulated rainfall. *Soil Science Society of America Journal* **64**, 1786–1791.

Helalia AM, Letey J (1988) Polymer type and water quality effects on soil dispersion. *Soil Science Society of America Journal* **52**, 243–246.

Institution of Engineers (Queensland Division) (1996) Soil erosion and sediment control. Engineering guidelines for Queensland Construction Sites. (The Institution of Engineers Australia: Brisbane, Qld)

Lentz RD, Shainberg I, Sojka RE, Carter DL (1992) Preventing irrigation furrow erosion with small application of polymers. *Soil Science Society of America Journal* **56**, 1926–1932.

Lentz RD, Sojka RE (1994) Field results using polyacrylamide to manage furrow erosion and infiltration. *Soil Science* **158**, 274–282.

Levin J, Ben-Hur M, Gal M, Levy G (1991) Rain energy and soil amendments effects on Infiltration and erosion of three different soil types. *Australian Journal of Soil Research* **29**, 455–465.

Levy GJ, Agassi M (1995) Polymer molecular weight and degree of drying effects on infiltration and erosion of three different soils. *Australian Journal of Soil Research* **33**, 1007–1018.

Loch RJ (1997) Sediment properties: importance for erosion control and relationship to nutrient and pesticide movements. In ‘Proceedings, Day 3, Stormwater and Soil Erosion 97, Future Directions for Australian Soil and Water Management’. International Erosion Control Association. pp. 453–459. (International Erosion Control Association : Brisbane)

Loch RJ (2000) Using rainfall simulation to guide planning and management of rehabilitated areas: I. experimental methods and results from a study at the North Parkes mine. *Land Degradation and Development* **11**, 221–240. doi:10.1002/1099-145X(200005/06)11:33.3.CO;2-U.

Loch RJ, Foley JL (1994) Measurement of aggregate breakdown under rain: comparison with tests of water stability and relationships with field measurements of infiltration. *Australian Journal of Soil Research* **32**, 701–720.

Loch RJ, Connolly RD, Littleboy M (2000) Using rainfall simulation to guide planning and management of rehabilitated areas: II. Computer simulations using parameters from rainfall simulation. *Land Degradation and Development* **11**, 241–255. doi:10.1002/1099-145X(200005/06)11:33.0.CO;2-Y.

Loch RJ, Robotham BG, Zeller L, Masterman N, Orange DN, Bridge BJ, Sheridan G, Bourke JJ (2001) A multi-purpose rainfall simulator for field infiltration and erosion studies. *Australian Journal of Soil Research* **39**, 599–610. doi:10.1071/SR00039.

Moliere DR (2000) Temporal trends in erosion and hydrology characteristics for a post-mining rehabilitated landform at Energy Resources of Australia Ranger Mine, Northern Territory. ME thesis, The University of Newcastle, NSW.

Norton LD (1992) Chemical amendments for erosion control. 1992 International Winter Conference, The American Society of Agricultural Engineers, Nashville, Tennessee, pp. 2–9.

Rubio HO, Wood MK, Cardenas M, Buchanan BA (1984) Effect of polyacrylamide on seedling emergence of three grass species. *Soil Science* **148**, 355–360.

Schamp N, Huylebroeck J, Sadones M (1975) Adhesion and adsorption phenomena in soil conditions. In ‘Proceedings of Symposium on Experimental Methods and Uses of Soil Conditioners’. pp. 13–23. (Soil Science Society of America: Madison, WI)

Sojka RE, Surapaneni A (2000) Potential use of polyacrylamide (PAM) in Australian agriculture to improve off and on-site environmental impacts and infiltration management. Final Report Project No. UNE39. Land and Water Resources Research and Development Corporation, Canberra.

Theng BKJ (1982) Clay-polymer interactions: summary and perspectives. *Clays and Clay Mineralogy* **30**, 1–10.

Wallace A, Wallace GA (1986) Effect of polymeric soil conditioners on emergence of tomato seedlings. *Soil Science* **141**, 321–323.

Manuscript received 13 September 2002, accepted 28 July 2003