THE EFFECTIVENESS OF POLYACRYLAMIDE IN PROVIDING SHORT-TERM EROSION CONTROL ON STEEP SLOPES

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SOIL EROSION ON STEEP SLOPES

Abstract

Mark Partington Natural Resource Sciences

M. Sc.

The effectiveness of polyacrylamide in providing short-term erosion control on steep slopes

A study was conducted to determine if polyacrylamide (PAM) could be utilized as a best management practice to reduce soil erosion on forest road embankments. Experiments involving two different PAM application rates (10 and 20 kg/ha) were conducted using natural rainfall in 2001 and 2002 and indoor rainfall simulation. In 2001, PAM was combined with a broadcast application of grass seed.

The study results suggest that PAM provided no statistically significant erosion control after natural rainfall on a loam soil. In the rainfall simulation experiments PAM applied at both 10 and 20 kg/ha significantly reduced soil erosion (by 75 and 77%) and the turbidity of runoff water (by 99%). PAM application at 10 kg/ha significantly increased grass densities (by 109%) compared with the control plots. However, PAM applied at 20 kg/ha provided no significant increase in grass density compared with the control.

RESUME

Mark Partington Natural Resource Sciences

M.Sc.

Efficacité du polyacrylamide pour le contrôle à court terme de l'érosion sur de fortes pentes

Une étude a été réalisée pour déterminer si l'emploi de polyacrylamide (PAM) pouvait réduire l'érosion du sol sur des talus de routes forestières. Des expériences comportant deux taux différents d'application de polyacrylamide (10 et 20 kg/ha) ont été effectuées dans des conditions de pluie naturelle en 2001 et en 2002, et de simulation de la pluie à l'intérieur. En 2001, l'emploi de polyacrylamide était combiné à l'ensemencement en plein de graminées.

Les résultats de l'étude semblent indiquer que le polyacrylamide n'a donné aucun contrôle statistiquement significatif de l'érosion après une pluie naturelle sur un sol argileux. Cependant, son application à 10 ainsi qu'à 20 kg/ha a réduit de façon significative l'érosion du sol (de 75 et de 77 %) et la turbidité de l'eau de ruissellement (de 99 %) dans les expériences avec simulation de la pluie. L'application de polyacrylamide à raison de 10 kg/ha a augmenté significativement la densité des graminées (de 109 %) par rapport aux placettes témoins. Cependant, son application à 20 kg/ha n'a fourni aucune augmentation significative de la densité des graminées comparativement au témoin.

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1. INTRODUCTION

The protection of water quality is one of the most important environmental issues being addressed by governments, citizens, and the forest industry (Taylor 1999).

In regions where forest management activities exist, the construction and maintenance of graveled forest access roads have been identified as the single largest contributors to the sedimentation of streams (Appelboom et al. 2001; Swift 1984). Sediments, along with nutrients from agricultural runoff, are considered by the US Environmental Protection Agency (Reiter and Beschta 1999) to be some of the most damaging non-point-source pollutants.

Fine sediments (silts and clays) eroded from roads and transported into watercourses become suspended in the water and require prolonged periods before they settle out at the bottom of the body of water. These suspended sediments can be harmful to many organisms. Increased levels of suspended sediments reduce light penetration into the water, thereby reducing the photosynthetic ability of aquatic plants (Ward 1992). Moreover, suspended sediment can harm fish eggs, change fish behavior as a result of reduced visibility, and increase fish mortality when levels of suspended sediment are extremely high (Ermine and Ligon 1988).

Larger particles (primarily coarse sands) do not remain in suspension, but rather settle quickly to the streambed. These larger particles create negative impacts by filling in the small voids between rocks in spawning areas, and this either suffocates existing fish eggs or reduces reproduction by decreasing the number of suitable spawning areas (Johnson 1961).

Because of the negative impact of sediments entering a watercourse, any forest road near a watercourse must be built following Best Management Practices (BMP) to ensure that water quality is protected (Ontario Ministry of Natural Resources 1990, New Brunswick Department of Environment 1997). BMPs fall into two categories: those that prevent soil erosion from occurring in the first place, and those that prevent eroded materials from entering a watercourse.

BMPs that prevent erosion can be applied either at the road surface or on the slopes beside the road. Instituting effective maintenance procedures, such as applying coarse gravel to the road surface where a road crosses a watercourse, can protect the road surface by preventing rutting and by reducing the velocity of any runoff water that may be created (Kochenderfer and Helvey 1987). Roadside slopes are often constructed at gradients at least as steep as 2H:1V, and on these slopes, the soil must be adequately stabilized. Common road construction practices to prevent soil erosion on slopes involve the application of erosion-control blankets, hay mulch, and grass seeding, as well as the use of "armoring" practices such as the installation of rock riprap. These practices, which are applied after construction is complete, stabilize the slopes by protecting them against the impact of rainfall and runoff water and, except for rock riprap, are intended to remain effective until natural vegetation becomes established on the slope.

BMP's that act as barriers to sedimentation are usually simple structures (e.g., detention ponds, silt fences, vegetated filter strips) that divert or pond runoff water, thereby preventing it from entering a watercourse (Loch et al. 1999). These barriers are simple to construct, but are often misapplied and require frequent maintenance to remain effective. Moreover, Loch et al. (1999) stated that fine sediments are difficult to remove using barriers and that it is better to reduce sediment generation at its source. For this reason, barrier construction should be used together with practices that prevent erosion.

Despite the effectiveness and popularity of these two classes of BMP's, forestry road builders still need effective tools and prevention measures that can be applied to stabilize soil slopes during construction and until more intensive measures can be applied.

One product that may meet this need is polyacrylamide (PAM). PAM has been applied effectively in the agricultural industry to provide short-term erosion control, and has reduced soil erosion in agricultural irrigation furrows by up to 94% (Lentz and Sojka 1994). However, there has been little research on the ability of PAM to prevent soil erosion on the steeper soil slopes commonly found at road construction sites. This gap in the research led to the initiation of this project.

The main objective of this project was to determine the effectiveness of PAM in providing short-term erosion control on steep slopes. Previous agricultural research has indicated that PAM remains effective for 4 to 6 weeks, so it is this short-term application that the research project addressed. Since there has been little research done for this type of PAM application, no guidelines for recommended application rates exist. Thus, this research project also addressed this gap by testing two different PAM application rates.

The hypotheses being tested in this research project are as follows:

1. The application of PAM will reduce soil erosion over the short term.
2. Higher PAM application rates will further reduce soil erosion.
3. The application of PAM will improve the germination of sown grasses.

2. LITERATURE REVIEW

2.1. What is soil erosion?

Soil erosion has been defined by Brady (1990) as the detachment and movement of soil or rocks by water, wind, ice, or gravity. Erosion caused by rainfall and the resulting runoff water is the principal mechanism of soil erosion on disturbed soils on steep slopes, and it is this type of erosion that must be properly managed by forestry road managers and government regulators.

Three basic factors determine the extent of rainfall-induced erosion on a given soil under a given set of conditions:

1. rainfall properties
2. site characteristics
3. soil characteristics

Rainfall properties

Rainfall properties refer to: the size (large vs. small drops), velocity, intensity and duration of rainfall. The impact of raindrops causes erosion by three principal mechanisms: detachment of soil particles, destruction of soil aggregates, and transportation of soil as a result of splashing (Brady 1990). These impacts reduce the infiltration rate of water into the soil by sealing the soil surface (Agassi 1996, Shainberg and Levy 1996). Once surface sealing occurs, rain is forced to move down a slope over the soil, further detaching and transporting soil particles. Rickson (undated) emphasizes that short-duration, high-intensity rainfall events cause the majority of erosion. Long-duration, low-intensity rainfall causes erosion only after the soil has become saturated and water can no longer infiltrate; under these conditions, mass movements (mass wasting) may occur rather than, or in addition to, surface erosion.

Site characteristics

Site characteristics such as the type and extent of the vegetation cover, and the length and steepness of the slope, play an important role in the severity of soil erosion.

The type of vegetation cover plays an important role and the level of soil protection that is provided varies with vegetation type. Box and Bruce (1996) describe four main ways in which vegetation cover influences erosion: vegetation intercepts rainfall, thereby dissipating the impact energy of raindrops; increases infiltration because the vegetation maintains soil porosity and permeability; reduces the velocity of surface runoff by increasing surface roughness; and reduces the erodible surface area. Herbaceous vegetation and grasses are more efficient than woody vegetation at controlling surface erosion because they grow more densely and thus provide more complete coverage of the surface (Gray and Sotir 1996).

Slope length and steepness are important site characteristics that determine the levels of soil erosion (Mutchler and Greer 1980, Wu and Wang 2001). As water moves along the soil surface, it transports soil particles, and as slopes increase, the energy of the moving water increases; the increased energy can detach larger soil particles and keep them suspended longer in the surface flow (Sharma 1996). The importance of slope length increases as the slope's steepness increases. Gray and Sotir (1996) stated that an increase in slope length from 100 to 200 ft (30 to 60 m) increased erosion by 29% on a 6% slope and by 49% on a 20% slope.

Soil characteristics

Soil erosion also depends strongly on soil structure. The stability of aggregates and the infiltration capacity are the two most significant soil characteristics that affect a soil's erodibility (Glanville and Smith 1988, Brady 1990). As discussed earlier, a soil's infiltration capacity determines the level of runoff that may occur. The stability of soil aggregates represents the ability of these soil structural components to withstand the forces of rainfall and runoff (Le Bissonnais 1996). Both characteristics of soil structure are influenced by many primary physical and chemical soil characteristics such as texture, organic matter, clay mineralogy, and levels of cations and oxides, among others (Le Bissonnais 1996).

2.2. What are the principal means of controlling erosion on forest roads?

Forestry road builders control erosion on the side slopes of forest roads by containing eroded sediment and by protecting soils to prevent erosion.

Containing eroded sediment

The containment of eroded sediment can involve construction practices such as detention ponds or the application of products such as silt fences and hay bales. These methods attempt to prevent the movement of soil off-site by acting as physical barriers to its movement. These methods are commonly used, and their effectiveness has been demonstrated by many studies (e.g., Miller 2000, Appelboom et al. 2001). Unfortunately, these methods are often improperly applied or designed, and the barriers may not be adequately maintained, thereby severely diminishing their effectiveness.

The application of these methods can also create barriers to machine travel, which can interfere with construction at the work site and ongoing maintenance. The principal benefit of these methods is that they provide immediate protection against movement of soil off-site, but, despite this benefit, such methods should only be applied temporarily, until long-term soil protection can be established (Pulsifer 1999).

Protecting soils

The second class of erosion-control methods can be classified as soil protection measures. These involve, among others, construction practices and products such as hydroseeding, hay mulch, erosion-control blankets, and rock armor (riprap). These methods prevent rainfall-induced erosion by protecting against splashing and by maintaining water infiltration into the soil (Krenitsky et al. 1998). Because these methods are commonly applied, their use has been extensively researched. For example, Grace et al. (1998) found that after 6 months, the use of erosion-control blankets and grass seeding had reduced sediment yield by 85% on newly constructed roadside slopes in the forest. McCullah (2000) found that the application of various erosion-control blankets on 60% slopes reduced soil erosion by more than 80%. Because these approaches can impede machine movement and become a barrier to men and equipment, they are best applied after work has been completed at a site.

These methods of soil protection were first introduced as best management practices to control soil erosion in the highway construction industry. Their use in the forest industry is now becoming more widespread as their effectiveness in minimizing erosion becomes accepted. The methods are only intended as temporary measures until permanent vegetation can be established, therefore they should not impede the establishment of permanent vegetation on the site. Vegetation plays an important role in controlling soil erosion and Gray and Sotir (1996) listed four main beneficial effects: (i.) foliage intercepts rainfall, thereby minimizing soil detachment through splashing; (ii.) root systems act as an anchor that prevents soil movement; (iii.) foliage and stems increase the roughness of the soil surface, thereby slowing runoff velocity; and (iv.) organic matter and roots help to maintain water infiltration rates into the soil.

2.3. PAM: an alternative that does not impede work on the site

As discussed in the previous section, soil containment and soil protection can effectively control soil erosion. However, these methods are primarily temporary measures until permanent vegetation can be established, and cannot be applied while work is continuing. Because they can only be applied once all construction work has ceased, there is a need for erosion-control methods or products that can be applied during construction and that will provide cost-effective soil protection until other measures can be taken.

The forms of polyacrylamide (PAM) used in soil erosion control are water-soluble copolymers formed by the polymerization of acrylamide (AMD) and related monomers (Barvenik 1994). PAM formulations are most commonly derived from natural gas, and are produced in both liquid and flake forms. There is a wide variety of PAM formulations; those that have been studied for controlling soil erosion are similar to the formulations used as flocculants in industries such as pulp and paper processing and water treatment. The strength of PAM's adsorption to soil particles varies as a function of the polymer's molecular weight, charge, and charge density (Green et al. 2000). For PAM formulations to be effective as a soil amendment, the polymer must be anionic (negatively charged) and have a charge density of between 18 and 30%, a high molecular weight (12 to 15 Mg/mole), and 80% or higher levels of the active ingredient (Sojka and Lentz 1999, Green et al. 2000).

PAM can be manufactured as a cationic, nonionic or anionic polymer, but only anionic PAM is effective as a soil amendment. Cationic PAM is toxic because it binds to the hemoglobin in fish gills, causing mortality as a result of suffocation (Barvenik 1994). Moreover, PAM formulations used to control soil erosion must have an acrylamide monomer (AMD) content of less than 0.05%, since AMD is a known neurotoxin except at extremely low concentrations. PAM degrades at a rate of roughly 10% per year due to biological, physical, and chemical processes, and does not produce toxic AMD during its degradation (Sojka et al. 2000). PAM's low toxicity is partly attributable to the large size of PAM molecules, which prevent them from penetrating plant and animal cells (Washington State Department of Transportation 2000).

2.4. PAM's mechanism of operation

PAM has the ability to stabilize an existing soil structure, but not to remediate a poor soil structure (Lentz and Sojka 1994). PAM is attracted to the surfaces of soil particles through Coulombic and Van der Waals forces which allow PAM to increase the stability of soil aggregates (Sojka et al. 2000). The increased levels of soil cohesion increase pore space, water infiltration rates into the soil, and resistance to transport as a result of rainfall splashing and runoff (Tobiason et al. 2000).

PAM has also been extensively used as a flocculant in water treatment. In this application, PAM flocculates clay and silt particles that are in suspension by adsorbing to aggregate surfaces and by promoting inter-aggregate bonding (Ben-Hur and Keren 1997, Sojka and Lentz 1999, McLaughlin 2002). The PAM-created aggregates fall out of suspension, thereby reducing water turbidity.

The ability of PAM to control soil erosion and to flocculate suspended particles is affected by the properties of both the soil and PAM itself. It is widely believed that PAM's molecular weight, charge, and charge density are the properties that most highly affect its effectiveness (Green et al. 2000). Green et al. (2000) found that different PAM formulations were most effective for controlling soil erosion on different soils, but that a PAM formulation with a charge density of 30% and a molecular weight of 12 Mg mol^{-1} would probably be effective in most soils. PAM only enters the first 1 to 2 mm of the soil surface, and formulations with higher molecular size (chain length) may be unable to move deeper into the soil (Malik and Letey 1991, Nadler et al. 1994).

Soil properties also play an integral role in determining PAM's effectiveness in controlling soil erosion. Lu et al. (2002) reported that soil and water properties such as texture, clay mineralogy, organic matter content, and concentration of dissolved salts affect PAM sorption. Soils with larger aggregate sizes and coarser soil texture may let PAM penetrate deeper into the soil profile, thereby creating a soil more resistant to erosive forces (Levy and Miller 1999). Lu et al. (2002) found that high soil organic matter content reduced PAM's effectiveness, possibly because organic matter reduces the available bonding sites for the PAM in the soil.

2.5. PAM research

The use of polymers as a soil amendment was first introduced in the 1950s, when polymer formulations that could improve soil structure were first introduced. At this time, the knowledge of their surface-sealing properties was not well understood (Levy 1996), and it was believed that PAM was most effective when applied in granular form and tilled into the upper levels of the soil. This approach required large quantities of PAM and this, coupled with the product's high cost, made it economically infeasible to use PAM for erosion control in agricultural fields. As a result, research was abandoned in the 1960s.

With the development of new PAM formulations and an increased awareness of PAM–soil interactions, research began again in the 1980s. The United States Department of Agriculture (USDA) began to heavily research the use of PAM to combat erosion in irrigated agricultural field furrows beginning in the early 1990s. Lentz and Sojka (1994) reported the results of 3 years of studies, conducted on silt loam soils with slopes of 0.5 to 3.5%; they found that the application of PAM reduced sediment levels in runoff water by 94%. In these studies, 10 g/L of PAM was added to furrow inflow water until that water began to run-off from the field; this application rate was equivalent to 1 to 2 kg/ha. The success of these studies and the resulting publicity in the soil science community prompted further studies to determine the effectiveness of PAM under a variety of soil and slope conditions. These further studies are now just being published in peer reviewed journals and the variety of results that are being reported illustrate the infancy in which this technology currently stands.

Mitchell et al. (1996) studied the application of PAM formulations with high and low molecular weights on silt loam soils subject to natural rainfall and with slopes of 2.5

and 3.6%. The PAM with high molecular weight was available in liquid form, and was dissolved in water to achieve an application rate of 1.1 kg/ha. The PAM with low molecular weight was provided in liquid form and was applied at a rate of 17.6 kg/ha. They found no significant difference in the sediment yield of their test plots between the PAM-treated plots and the control plots. They attributed PAM's poor performance to application rates that were too low, based on their molecular weights, and to the long period (2 months) between application and the first large natural rainfall.

Roa-Espinosa et al. (1999) studied a higher application rate (22.5 kg/ha) of a PAM mixture with high molecular weight. They studied the effects of this mixture on a silt loam soil on a 10% slope, with simulated rainfall. They found that the PAM mixture reduced soil erosion by up to 78% when PAM was applied to dry soil. Masters et al. (2000) studied the effectiveness of three application rates of PAM with high molecular weight in reducing soil erosion on a clay soil on a 5% slope. PAM mixtures applied at rates of 1.68, 3.36, and 6.73 kg/ha reduced soil runoff by 33, 40, and 28%, respectively, although the differences were not significant. When the treated soils were subjected to simulated rainfall 30 days after the initial application, the effectiveness of the PAM mixtures decreased to 22, 30, and 19%, and these differences were not significant.

Studies in agricultural field furrows have shown that PAM is highly effective in reducing soil erosion (Flanagan 1998, Sojka et al. 2000). Although the results for low-slope construction sites generally demonstrated the beneficial impacts of PAM, work remains to be done to more conclusively demonstrate PAM's effectiveness.

Research on the use of PAM to control soil erosion on steep slopes similar to those found on highway embankments has recently been brought to the forefront. Flanagan and

Chaudhari (1999) investigated the effectiveness of PAM on three sites: a clay loam soil with a slope of 3:1; a silt loam soil with a slope of 2:1; a silt loam soil with a slope of 2:1.

The third test site was subjected to simulated rainfall. On each site, PAM with a very high molecular weight was applied at a rate of 80 kg/ha as a liquid solution. Flanagan and Chaudhari (1999) found that soil erosion decreased by 54 and 40% on the first two sites and by 83% on the third site, which was subjected to simulated rainfall. The overall effectiveness of PAM differed significantly in terms of total erosion on each test site, even though there was no significant difference for some individual rainfall events.

McLaughlin (2002) studied the ability of several PAM formulations and application rates to reduce soil erosion and runoff turbidity from a variety of soils. On a 2:1 slope, PAM treatment showed no significant effects on erosion or turbidity. However, the PAM treatments reduced erosion and runoff turbidity on gentler (4:1) slopes. PAM applied at 11 kg/ha on a 4:1 slope reduced erosion and turbidity on a clay loam soil but not on a sandy soil, even when applied at a higher rate (20 kg/ha). McLaughlin's initial research suggested that soil and PAM properties both determined the treatment's effectiveness, but the precise relationships remain unclear. Understanding these relationships will help determine what PAM formulations will work under specific soil and site conditions.

Research focusing on PAM's ability to reduce turbidity in runoff water has not yet been widely reported. Research has typically focused on the total amounts of eroded soil, since this indicator is of most concern to those who are trying to protect and retain the soil for economic reasons (e.g., in agriculture). Many American states have developed regulations that limit the allowable turbidity levels in bodies of water close to active construction sites. To monitor compliance, turbidity levels have been used as an indicator of the effectiveness of erosion prevention by the implementation of best management practices on construction sites. The research conducted by McLaughlin (2002) and by Tobiason et al. (2000) are two of the few studies of turbidity levels in water from PAM-treated sites. Tobiason et al. (2000) found that treating a silt loam soil on a 3.5H:1V slope with 0.7 kg/ha of PAM reduced runoff turbidity by 82%.

2.6. Rainfall simulators

One of the largest problems in conducting soil erosion research is the need to rely on natural rainfall, which is required before erosion can begin. Natural rainfall is largely unpredictable: it is uncertain when rain will occur, in what amounts, and how long it will last. This makes it difficult to conduct controlled research because replicated treatments are required in order to test the statistical significance of the results. In addition to this variability, other factors such as wind, soil type, slope, and many others make it difficult to control a field experiment designed to obtain certain desired effects. However, many of these factors can be controlled by using simulated rainfall in a laboratory setting. This both reduces the level of experimental error and allows investigators to control the study parameters, thereby providing a better understanding of the results.

Using simulated rainfall to conduct soil erosion experiments can be a valuable tool as long as the limitations of such a tool are recognized so that the results can be properly interpreted (Meyer 1965). A rainfall simulator must be able to approximate the conditions of natural rainfall; the three most important factors are the rainfall's intensity, velocity, and drop-size distribution.

Simulated rainfall must be controlled in both space and time, and is measured as rainfall intensity (Hall 1970). The intensity of natural rain is typically measured using rainfall gauges, and combined with historical data, this approach permits the construction of rainfall intensity, duration, and frequency (IDF) charts. These charts are a valuable tool for specifying the design parameters that a rainfall simulator must meet. The intensity of simulated rainfall produced by an experimental setup can often be varied by changing spray nozzles or by adjusting spray pressures.

Raindrop fall velocity is also an important factor to emulate with a rainfall simulator. The velocity of raindrops in simulated rainfall should approximate the terminal velocity of natural rain of the same drop size (Rickson undated).

Simulated rainfall must also approximate the drop-size distribution of natural rainfall (Mech 1965). Natural rainfall at a given intensity includes a wide range of drop sizes, and that range changes as rainfall intensity increases or decreases. Any effective rainfall simulator must approximate the drop-size distribution of natural rainfall because this distribution can greatly influence the amount of erosion that occurs.

There are many different designs of rainfall simulators, but these fall into two main categories: those that use drip nozzles and those that utilize pressurized nozzles. Both categories of simulator have been used to study soil erosion, and the best choice depends on the experimental design. The use of drip nozzles requires the design of a simulator in which the simulated rain falls over a large distance, perhaps as high as 14 m. Using large heights lets the simulated raindrops fall far enough to reach their terminal velocities. The advantage of this type of simulator is that the drop sizes can be precisely controlled simply by varying the characteristics of the devices used to govern drop size. However, the large height of this type of simulator means that it is difficult to find an indoor test area that can allow for a structure of such great height. If the testing is to be conducted outdoors a 14m tall structure is difficult to transport and set up and with the greater distance that the droplets fall the impact of wind becomes important on the experimental results.

The second category of rainfall simulator uses pressurized nozzles so that the water sprayed out of the nozzles already has an initial velocity; this lets water droplets reach their terminal velocity in less distance. This type of rainfall simulator can thus be smaller (with a lower height), making it more conducive to outdoor experiments where portability and ease of setup are vital. However, higher spray pressures create higher fall velocities—perhaps even greater than the rain's natural terminal velocity, thereby increasing soil erosion beyond the level to be expected from natural rainfall. As well, most rainfall simulators that use pressurized nozzles produce a decreased drop-size distribution and uniformity as spray pressure decreases. Therefore, spray pressures must be recorded to let investigators calculate the intensity and uniformity.

Rainfall simulators are valuable tools in soil erosion research, but the abovementioned limitations must be acknowledged. The inherent variability in natural rain makes it difficult to simulate rainfall well enough to satisfy all researchers. However, continuing development and use of rainfall simulators, and combining them with natural rainfall, makes them an increasingly valuable tool for soil erosion research.

3. METHODS AND MATERIALS

The performance of polyacrylamide was evaluated in two separate testing phases. The first phase involved outdoor tests subject to natural rainfall; the second involved indoor tests under controlled conditions using a rainfall simulator.

3.1. Outdoor testing

The outdoor tests formed a completely randomized design with three treatments in nine test plots. The test plots were wooden test beds constructed to simulate actual soil–slope conditions. The test beds (Figure 1) faced southwest and were installed on the grounds of the Forest Engineering Research Institute of Canada, in Pointe-Claire, Québec. These test beds offered many advantages over natural slopes, including the ability to control many factors that would otherwise have significantly influenced the test results. Factors such as aspect, slope, soil conditions, and soil depth were kept constant across all the test beds. As well, the fabricated test beds allowed for quick and efficient collection of data.

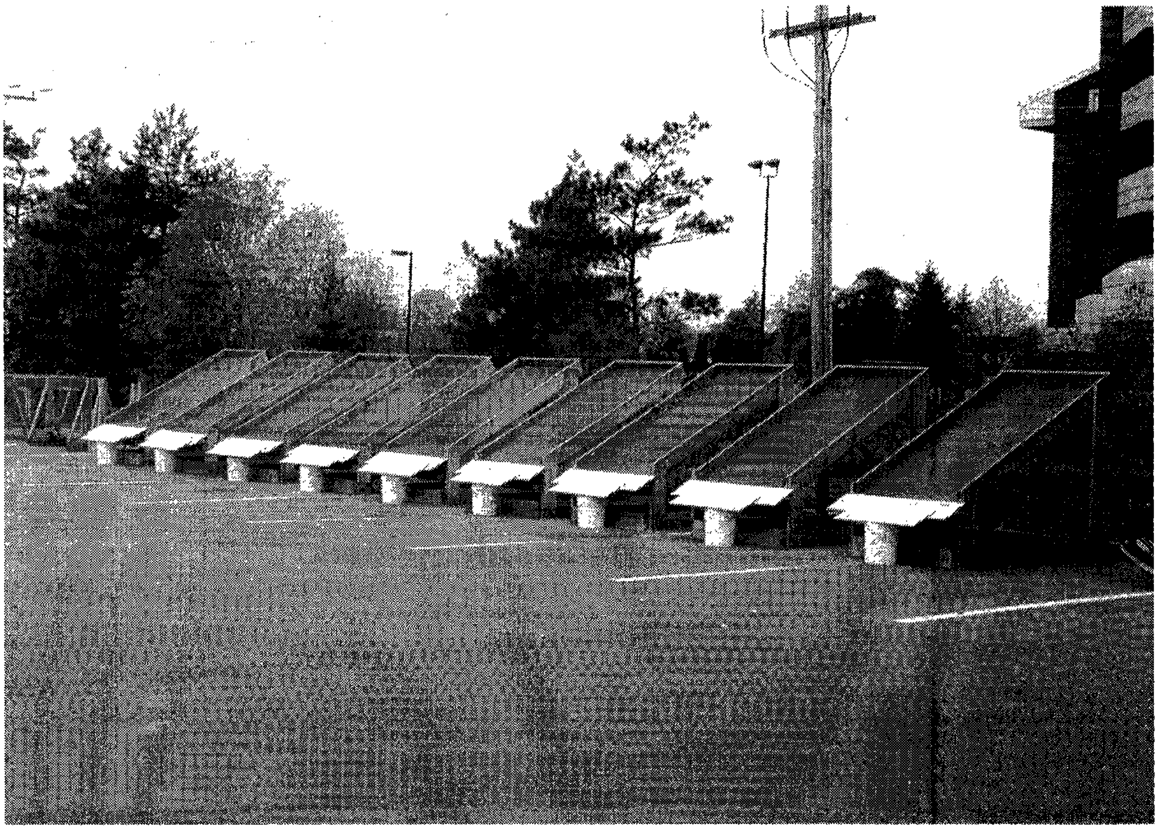

Figure 1. The fabricated test beds and experimental setup used for the outdoor trials conducted in 2001 and 2002.

The test beds were 1.4 m wide and 2.1 m long. The sides of the beds were 25 cm tall and allowed soil to be placed at a consistent depth of 15 cm throughout each test bed. The beds were constructed with a slope of 2H:1V (30%) to represent the typical design of roadside slopes on the embankments of forest access roads. Holes were drilled into the floor of the test beds to let excess soil moisture escape. The floors of the test beds were then covered with a geotextile that allowed the passage of water but prevented loss of soil particles through the drainage holes. A wooden lattice was then placed over the geotextile to provide a rough surface that would help the soil adhere.

In 2001, an on-site rain gauge was not available, but weather data were obtained from an Environment Canada weather station located less than 5 km from the test site. To ensure accurate recording of rainfall in the 2002 tests, a Davis Instruments tipping bucket rain gauge was installed adjacent to test bed 1 at a height of 1.7 m above the ground. The rain gauge was connected to a Hobo Event datalogger that recorded each tip of the rain gauge. The datalogger information was downloaded after each significant rainfall and tabulated using Microsoft Excel.

Eroded soil and runoff water were collected in 18-L buckets below the test beds. A V-shaped metal diversion channel ensured that all soil runoff was carried into the collection buckets. A wooden cover was then placed over the buckets and diversion channel to prevent contamination of the collected material by outside sources.

Each of the soil beds was filled with soil purchased from a landscape contractor. The properties of the soils used in 2001 and 2002 are shown in Table 1. Textural analysis was done using the sieve and hydrometer analysis specified by ASTM standards 422 (ASTM 1998) and 1140 (ASTM 2000). The organic matter content was determined using the method of Schulte et al. (1991), and the wet aggregate sizes were determined using the method of Angers and Mehuys (1993).

Table 1. Properties of the soils used in the 2001 and 2002 outdoor tests.

Year	Sand %	Silt %	Clay %	Texture classification	Organic matter %	Mean weight diameter (mm)[a]
2001	33	57	10	Silt loam	2.8	0.44
2002	46	46	8	Loam	3.2	0.32

[a] Mean weight diameter of soil particles smaller than 4.00mm

The amount of soil required to maintain a depth of 0.15 m was calculated and then this amount of soil was measured out before being placed in the test beds. The soil was then raked smooth and lightly compacted using a hard-toothed rake.

The outdoor tests conducted in 2001 and 2002 were similar in design, but in 2001, each test bed also received an application of grass seed. This was done to determine the effect of PAM on grass establishment. The seed mixture applied to the slopes was the Lab2009 product supplied by LABON Inc. (Boucherville, Québec) Details of the species in this mixture appear in Table 2.

Table 2. The grass species mixture used in the studies conducted in 2001.

Species	% of total mixture
REBEL 3-D tall fescue	20
SALVO timothy	20
PRELUDE-II perennial ryegrass	20
Mountain bromegrass	10
Crested wheatgrass	6
Tall wheatgrass	6
Slender wheatgrass	6
Altal wildrye	5
Russian wildrye	5
Galega orientalis	2

The grass seed was broadcast by hand. A measured amount of grass seed (1 kg/50 m^2) was weighed before sowing to ensure that the same amount of seed was applied to each test bed. Once the seed had been applied, the test bed was lightly raked to cover the seed adequately with soil.

To measure the effects of PAM on grass establishment, seedling densities were measured at the end of the trial. Fourteen 10 cm × 10 cm plots were randomly located inside each test bed. The number of established grass stems was counted in each plot.

The PAM formulation used in this testing (Soilfix Polybead) was supplied by CIBA Specialty Chemicals (Suffolk, Virginia). This product is an anionic polymer with 90% active ingredient, a charge density of 15%, and a molecular weight of 17 Mg/mole. This product is available in granular form and has properties similar to PAM mixes produced by other companies to control soil erosion. The application of PAM to control steep-slope erosion control is a recent idea, thus there were few guidelines on the recommended application rate for this product. Based on a review of previous research, an application rate of 20 kg/ha was initially chosen. An application rate of 10 kg/ha was also chosen to provide results that would guide future testing.

To ensure that the same amount of water and PAM was applied to each test bed, only the amount of PAM mix needed for each test bed was prepared before application. The manufacturer of the product suggests a maximum mix rate of 1 g/1.7 L of water when using high-pressure professional spraying equipment. This rate was found to be too high for the spray equipment used in this study, so a rate of 1 g /3.4 L of water was chosen.

The PAM formulations were mixed in 20-L plastic buckets using a paint mixer attached to an electric drill. To ensure proper mixing, the required amount of PAM was added slowly to the water. If PAM is added too quickly, the granules can clump together and won't mix properly into the water, resulting in inadequate coverage of the soil plots. The PAM formulations were mixed vigorously for approximately 10 minutes before being transferred to the sprayer. The sprayer used was an 11-L, steel-canister pressurized garden sprayer with a full-fan jet spray nozzle.

To ensure that each test plot began the test at approximately the same moisture content, all test plots were sprayed uniformly with three canisters of water. The control plots did not receive any treatments but received 29.4L of water; the 10kg/ha test plots received 9.8L of PAM-water mixture and 18.6L of water; while the 20kg/ha test plots received 18.6L of PAM-water mixture and 9.8L of water.

After the PAM application, 20-L plastic collection buckets were installed beneath the test beds, the tipping-bucket rain gauge was installed beside test bed 1, and the datalogger was calibrated to the correct date and time.

The collection buckets were replaced after each significant rainfall. The eroded soil was obtained by drying each bucket's contents in an oven at 105°C.

3.2. Indoor testing

The indoor testing was conducted using the laboratory facilities of the Forest Engineering Research Institute of Canada, in Pointe-Claire, Québec. The indoor testing utilized the single-nozzle, downward-spraying rainfall simulator shown in Figure 2. This rainfall simulator was patterned on the GRS II device developed at the University of Guelph (Tossell et al. 1987, 1990a, 1990b).

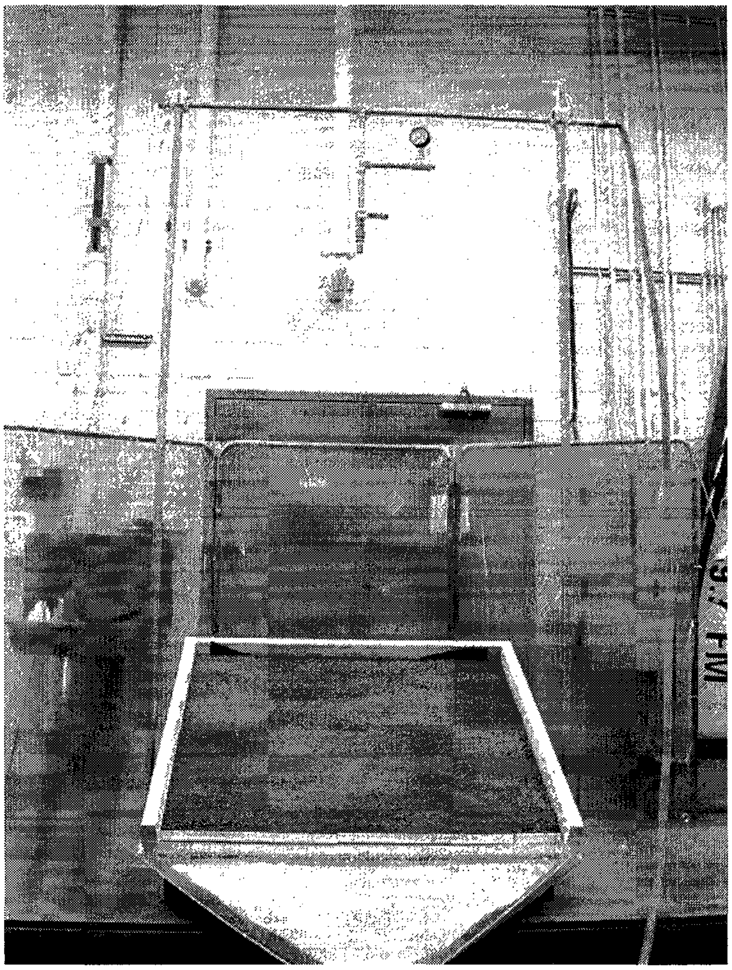

Figure 2. The rainfall simulator used in the indoor phase of the study.

This rainfall simulator consisted of a downward-spraying nozzle that can be adjusted in height and spray pressure in order to produce different rainfall intensities. Three different full-jet spray nozzles were evaluated in terms of their spray intensity and uniformity to provide a range of rainfall patterns. The spray nozzles were the same as those recommended by Tossell et al. (1987) and were supplied by Spraying Systems Company (Wheaton, Illinois). The models used were the high-intensity ½" 30W nozzle, the medium-intensity $^{3}/_{8}$" 20W, and the low intensity $^{1}/_{8}$" 4.3W spray nozzle. In the present study, the nozzle remained at 1.43 m above the soil; Tossell et al. (1987)

recommended heights of between 1.0 and 2.0 m to closely emulate natural rainfall velocities.

Rainfall intensity and uniformity were determined for each of the spray nozzles operating at two different spray pressures. To evaluate rainfall intensity, nine 1.5-L plastic buckets (150 mm wide by 14 mm tall) were placed on a 1×1 m test bed raised to a slope of 2H:1V. The buckets were placed in three rows of three buckets distributed evenly across the top, bottom, and middle of the test bed. Rainfall simulations using each of the three spray nozzles were then conducted for 10 minutes using the two recommended spray pressures (48 and 96 kPa). The volume of water was then measured in each of the buckets and mean rainfall intensity was calculated as described by Pall et al. (1983) and Tossell et al. (1987) using:

$$I_p = 10\ ((\sum V_i / A_g) / n) \times 60/t$$

where: I_p is the plot-average intensity (mm/h)

V_i is the volume of water collected in the i^th^ gauge (cm^3)

A_g is the gauge's collection area (cm^2)

t is the time of each run (min)

n is the number of gauges

the coefficient 10 converts measurements from cm/h to mm/h.

Uniformity coefficients were also calculated for each of the three spray nozzles using the data collected for the rainfall intensity calculations. The uniformity coefficient is important because it indicates the relative uniformity of the rainfall pattern across the test plot. A poor uniformity coefficient indicates that modifications (height or pressure) must be made to the rainfall simulator or the placement of the test bed. Rainfall uniformity was represented by the Christiansen uniformity coefficient (ASTM 1999) and was calculated using:

$$C_u = 100\left\{1 - \frac{\Sigma|d|}{n\,\bar{X}}\right\}$$

Where: C_u = Christiansen uniformity coefficient (%)

$d = X_i - \bar{X}$

n = number of rain gauges

$\bar{X}$ = average volume captured in all rain gauges

X_i = volume captured in rain gauge i

The calculated rainfall intensities and uniformity coefficients for the nozzles calibrated for this rainfall simulator are presented in Table 3.

Table 3. Calculated rainfall intensities and uniformity for the rainfall simulator used in the indoor tests.

	Nozzle type				
	1/8" 4.3W		3/8" 20W		½" 30W
Spray pressure (kPa)	48	96	48	96	48
Rainfall intensity (mm/h)	26	29	51	72	209
Uniformity coefficient (%)	85	84	87	89	84

The indoor rainfall simulations were arranged in a completely randomized test design using three treatments in nine test plots. The test beds used in the indoor testing were similar to those used in the outdoor tests, but smaller (1 m ×1 m). Soil and runoff water were again collected in 20-L plastic buckets using V-shaped metal diversion channels. Unlike the outdoor test beds, which had an average soil depth of 0.15 m, the indoor test beds had a soil depth of 0.10 m.

The same soil was used in each indoor test bed during the rainfall simulations, and the soil properties (Table 4) were similar to those of the soils used in the outdoor tests. The soil was pre-sifted using a #4 (4.75-mm) sieve to remove any large aggregates, and was then added to the test beds at a uniform depth of 0.10 m. The soil was then lightly raked and compacted in preparation for testing.

Table 4. Properties of the soil used in the indoor rainfall simulator tests.

Sand %	Silt %	Clay %	Texture classification	Organic matter %	Mean weight diameter (mm)[a]
31	55	14	Silt loam	3.1	0.35

[a] Mean weight diameter of soil particles smaller than 4.00mm

The indoor tests differed from the outdoor tests in that the soil was pre-wetted more thoroughly before product application. This was done to test the effectiveness of PAM on soils with high moisture contents representative of field conditions in which work crews apply the product as rain begins to fall and erosion-control measures must be quickly implemented. The soil in the 10 kg/ha PAM treatment was pre-wetted by exposure to a 52 mm/h rainfall for 25 minutes. A shorter wetting period (15 minutes) was used for soils in the 20 kg/ha PAM treatment to compensate for the greater volume of water added to the soil in this treatment. After pre-wetting, the test bed was inclined to a 2H:1V slope and left for 3 hours before running the test simulation. Immediately prior to that simulation, soil samples were taken to determine the moisture content.

The PAM application rates (10 and 20 kg/ha) were the same as those used in outdoor testing. The 20 kg/ha treatment had to be adjusted in order to compensate for the increased amount of water being applied to the soil; the mixture rate of 1 g PAM per 3.4 L of water required 6.8 L of water added to the soil. As a result, small amounts of runoff would have occurred; thus, the PAM application had to be conducted in stages, with half the PAM applied during the first stage, a 10-minute delay to let the water enter the soil, then the remaining amount of PAM applied.

Once PAM had been applied to the test beds, the rainfall simulation was conducted with a rainfall intensity of 72 mm/h for 1 hour. This intensity was similar to levels used in other research on the use of PAM (Flanagan and Chaudhari 1999, Roa-Espinosa et al. 1999, Teo et al. 2001) and was required in order to produce enough erosion to permit meaningful comparisons between the two treatments.

The amounts of water and soil runoff were determined following the same method that was used in the outdoor testing. The total material collected from each rainfall simulation was weighed and then dried in a 105°C oven to determine the oven-dry weight.

Samples for the water turbidity analysis was collected from the 20-L buckets that had received the eroded sediment and water following each of the simulations. Before water samples were taken each of the buckets was stirred for 15 seconds using an electric drill operating at 1050 rpm. A 50-mL sample was then taken 60 seconds after stirring was complete. These samples were then placed into a turbidity-measurement device that provided nephlelometric turbidity unit (NTU) readings.

3.3. Statistical analysis

The data from the outdoor natural rainfall tests were treated as a completely randomized design (CRD) with repeated measures. Statistical analysis of this data was done using the PROC MIXED GLM Repeated Measures ANOVA model in SAS version 8.0. (SAS Institute Inc., Cary, N.C.). Multiple comparisons were made of the treatment differences using adjusted t-values, and the associated probabilities produced by SAS.

The data collected for grass establishment were analyzed similarly, but differences between treatments were calculated as multiple comparisons using adjusted t-values.

Statistical analysis of the indoor rainfall simulation experiments used a CRD with two covariates (soil moisture and bulk density before testing). These two measurements were taken to confirm that the soils in the test beds used for the simulations were as similar as possible and that any differences in their preparation would not affect the results. Adjusted t-values ($p = 0.05$) were used to identify significant differences based on the PROC GLM model in SAS.

A CRD was also used to make multiple comparisons of the turbidity readings. Analysis was conducted using the PROC MIXED model in SAS.

4. RESULTS AND DISCUSSION

4.1. Outdoor testing 2001

The outdoor testing conducted in 2001 occurred over a 34-day period from August 23rd through September 26th. During this time, eroded sediment was collected on four dates (Table 5). The precipitation amounts were provided by Environment Canada from the Dorval weather station located less than 5 km from the test site.

Table 5. Rainfall events and sediment collection dates in 2001.

Sediment collection date	Measurement period	Rainfall dates and amounts (mm)	Total recorded rainfall per period (mm)
August 26	August 23–26	August 26 – 10.0 [a]	10.0
September 10	August 27–September 10	August 31 – 12.5 [a] September 4 – 7.0 [a] September 8 – 3.0 [a]	22.5
September 24	September 11–24	September 13 – 1.5 September 20 – 7.5 September 22 – 5.0 September 24 – 22.0	36.0
September 26	September 24–26	September 25 – 21.0	21.0

[a] Rainfall was in the form of thundershowers.

The collected sediment from each of the rainfall collection periods appear in Table 6.

Table 6. Mean sediment yields of treatments subject to natural rainfall in 2001.

Collection date	Total rainfall (mm)	Time since product application (days)	Soil treatment (PAM, kg/ha)	Mean sediment yield (g)	95% confidence interval	Statistical significance of differences [a]	Reduction of sediment yield relative to control (%)
August 26	10.0	–	Control	56.4	40.2 ; 72.6	A	-
		3	10	41.9	25.7 ; 58.1	A	26
		3	20	27.6	11.4 ; 43.8	A	51
September 10	22.5	–	Control	17.5	1.3 ; 33.7	A	-
		18	10	11.6	0 ; 27.8	A	34
		18	20	12.0	0 ; 28.2	A	31
September 24	36.0	–	Control	44.5	28.3 ; 60.7	A	-
		32	10	30.9	14.7 ; 47.1	A	31
		32	20	29.8	13.6 ; 46.0	A	33
September 26	21.0	–	Control	174.1	157.9 ; 190.3	A	-
		34	10	97.2	81.0 ; 113.4	B	44
		34	20	81.2	65.0 ; 97.4	B	53

[a] Mean sediment yields on a given collection date followed by the same letter did not differ significantly (t-test, $p<0.05$).

The mean sediment yields from the treated and control plots differed significantly ($p<0.05$) only on the final collection date, 34 days after initial application of the product. The 10 and 20 kg/ha PAM treatment reduced soil erosion by 44 and 53%, respectively, compared with the control. The sediment yields of the two PAM treatments did not differ significantly ($p<0.05$) on that date.

Despite the differences between the PAM treatments and the control following the final collection date it is difficult to clearly state that this difference is fully attributable to the effects of PAM as grasses had become established on the test plots at this time (Table7). Grass density measurements were not taken after each of the three previous collection dates so it is not possible to state that the established grasses are responsible for this effect found following the final collection period. Although, on the collection date of September 24, just two days previous to the final collection, ocular assessments indicated that grasses had been established. Despite the likely establishment of grasses during this earlier collection date no significant differences in PAM treated plots were found.

4.2. Grass establishment in 2001

Grass establishment measurements were taken after the last sediment collection period, 34 days after the initial application of PAM (Table 7). The grass density measurements are an indicator of the level of germination of the initial grass seed applied to each treatment bed and not necessarily the overall health or vigor of the grass.

Table 7. Mean grass densities 34 days after the beginning of the trial in 2001.

Treatment	Mean grass density (stems per 100-cm^2 plot)	95% confidence interval	Statistical significance of differences [a]	Change in grass density relative to control (%)
Control	52.0	31.2 ; 72.8	a	-
PAM – 10 kg/ha	108.0	87.2 ; 128.8	b	+ 107
PAM – 20 kg/ha	61.0	40.2 ; 81.8	a	+ 17

[a] Means followed by the same letter are not significantly different (t-test, $p<0.05$).

Grass density was significantly different ($p<0.05$) in the 10 kg/ha PAM treatment, which had a density increase of 107%. Surprisingly, grass density in the 20 kg/ha treatment was not significantly different from that in the control.

This result is unexpected and it is unclear why the lower PAM application rate caused such a large increase in the mean grass density. Study design and preparation were made carefully to ensure that all treatments and test plots were exposed to the same conditions, thereby reducing the possibilities of experimental errors.

The experimental design used to determine the effect of PAM on grass establishment utilized fourteen 10×10 cm measurement plots that were randomly assigned to each test bed which allowed for a sampling of 5% of the total test bed area.

All plots received the same type and amount of soil and as well all test beds received the same amount of grass seed (60 g), which was broadcast by hand and lightly raked into the soil. It is unlikely that initial soil moisture levels in the test plots contributed to differences in the mean grass densities found in the plots. To ensure that initial soil moisture levels were kept as close as possible, water was applied to each of the treatment plots ensuring that 18L was applied to each. The 18L of water was the amount that was required to apply the PAM at a rate of 20kg/ha, therefore additional water was applied to the 10kg/ha plots and the control plots to reach this level.

Grass density measurements were only taken during the final sediment collection date, which occurred 34 days after the initial application of PAM. As previously mentioned, the measurements taken at the conclusion of this study only indicate seedling density. If measurements had been taken throughout the 34 days of the test, seedling emergence could also have been determined and further data would have been obtained that may have helped to explain the unexpected results found in this study.

4.3. Outdoor testing in 2002

For the outdoor testing conducted in 2002, we recorded rainfall using a tipping-bucket rain gauge installed at the test site (Table 8).

Table 8. Rainfall events and sediment collection dates in 2002.

Sediment collection date	Measurement period	Rainfall dates and amounts (mm)	Total recorded rainfall per period (mm)
October 15	October 11–15	October 13 – 2.0	2.0
October 17	October 16–17	October 16 – 26.5 October 17 – 4.5	31.0
October 22	October 18–22	October 19 – 19.0	19.0
October 27	October 22–27	October 26 – 9.0	9.0

The eroded sediment collected following each rainfall period is shown in Table 9.

Table 9. Mean sediment yields of treatments subjected to natural rainfall in 2002.

Collection date	Total rainfall (mm)	Time since product application (days)	Soil treatment (PAM, kg/ha)	Mean sediment yield (g)	95% confidence interval	Statistical significance of differences [a]	Reduction of sediment yield relative to control (%)
October 15	2.0	–	Control	510.9	462.3 ; 559.5	A	
		4	10	500.5	451.9 ; 549.1	A	2
		4	20	486.0	437.4 ; 534.6	A	3
October 17	31.0	–	Control	132.3	83.7 ; 180.9	A	
		6	10	120.6	72.0 ; 169.2	A	9
		6	20	136.9	88.3 ; 185.5	A	(+) 14
October 22	19.0	–	Control	47.6	0 ; 96.2	A	
		11	10	37.3	0 ; 86.2	A	22
		11	20	47.8	0 ; 96.4	A	(+) 28
October 27	9.0	–	Control	32.6	0 ; 81.2	A	
		16	10	50.1	1.5 ; 98.7	A	(+) 54
		16	20	91.1	42.5 ; 139.7	A	(+) 81

[a] Differences in mean sediment yields for a given collection date were not significantly different (t-test, $p<0.05$).

In the 2002 study, the PAM treatments provided no significant ($p<0.05$) improvement in erosion control compared with the control treatment. Unlike the testing that occurred in 2001, the 2002 testing did not involve the use of stabilizing grass seed, so the results illustrate solely the results of the PAM applications.

Despite the differences in the establishment of grass seed in 2001, neither PAM treatment provided a significant reduction in soil erosion in 2001 and 2002 compared with the control.

McLaughlin (2002) also found that PAM did not prevent soil erosion on steep slopes subjected to natural rainfall events. McLaughlin had tested PAM at 11.2 kg/ha on a loam soil on a 2H:1V slope in which no effects of PAM in reducing soil erosion were found. This combined with some of his other studies left McLaughlin to conclude that PAM effectiveness may be limited to soils on low slopes. However, Mitchell (1996) found that even on low 3.5% slopes that a low molecular weight PAM applied at 17.6 kg/ha did not reduce soil erosion.

4.4. Rainfall simulation experiment

The effect of initial soil moisture and soil bulk density were analyzed as co-variates and the statistical model showed no significant effect of either (Table 10).

Table 10. Statistical tests of the fixed effects used in the rainfall simulation model.

Effect	Calculated F value	Probability > F
Treatment	34.19	0.003
Soil moisture	2.92	0.1628
Soil bulk density	2.03	0.2272

The values of the initial soil moisture levels and bulk densities taken before each of the rainfall simulation is presented in Table 11.

Table 11. Mean initial soil moisture levels and bulk densities for each treatment level

Treatment	Initial soil moisture		Bulk density	
	Mean %	95% confidence interval	Mean	95% confidence interval
Control	27.0	23.05 ; 30.95	1.7	1.59; 1.81
PAM – 10kg/ha	22.9	21.31 ; 24.49	1.6	1.54 ; 1.66
PAM – 20kg/ha	27.3	26.33 ; 28.27	1.8	1.74 ; 1.86

Both PAM applications significantly ($p<0.05$) reduced the amount of eroded sediment in the rainfall simulations (Table 12). The 10 kg/ha treatment reduced the amount of eroded sediment by 84%, versus 76% for the 20 kg/ha treatment. The two treatments did not differ significantly with each other in sediment yield.

Flanagan and Chaudhari (1999) also found PAM to be effective in reducing soil erosion during simulated rainfall testing on steep slopes. They found that PAM applied at 80 kg/ha reduced soil erosion on a 3H:1V slope by up to 83%. PAM performance was also found to be significant under simulated rainfall by Roa-Espinosa et al. (1999). In their studies, PAM was applied at a rate of 22.5 kg/ha on a silt loam soil on a 10% slope where PAM was found to reduce soil erosion by up to 78%.

Table 12. Mean sediment yields of treatments during the rainfall simulation tests.

Soil treatment	Mean sediment yield (g)	95% confidence interval	Statistical significance of differences of means [a]	Reduction of sediment yield relative to control (%)
Control	1216.0	1022 ; 1409	a	–
PAM – 10 kg/ha	193.8	0 ; 533.4	b	84
PAM – 20 kg/ha	288.4	6.2 ; 570.6	b	76

[a] Mean sediment yields followed by the same letter did not differ significantly (t-test, $p<0.05$).

The results of the rainfall simulation studies showed PAM to be effective in controlling soil erosion in contrast with the results of the outdoor testing conducted with natural rainfall. However, one major difference in the test methodology used in the rainfall simulation experiments must be discussed.

In the rainfall simulations, PAM was applied to soil that had been pre-wetted and left to dry for 3 hours before running the simulation. Before the testing had begun, the soil had been stored indoors for a 5-month period and had reached a soil moisture content of approximately 5%. Rainfall simulation tests run at such a low soil moisture level would not be representative of what would be found naturally, so the soil was subjected to 15 or 25 minutes of rainfall to provide a moisture level near field capacity.

This initial soil moisture in the simulated rainfall experiments was much higher than that in the outdoor soil beds. The mean initial soil moisture levels for the outdoor tests conducted in 2001 and 2002 was 12.4% while the mean initial soil moisture levels for the rainfall simulations tests was 25.7% (table 11). This difference in initial soil moisture levels must be considered. Soil moisture levels are an important factor in determining soil erosion levels given that as soil moisture levels increase the amount of erosion caused by water will also increase even though two comparable soils may have similar erosivity.

The period between product application and events that could lead to erosion also provided more time for other natural forces (wind, UV radiation, etc.) to begin natural breakdown of the PAM, possibly further reducing the product's effectiveness.

4.5. Turbidity analysis from rainfall simulations

Table 13. Mean turbidity values of runoff water after rainfall simulations.

Soil treatment	Mean turbidity reading (NTU)	95% confidence interval	Statistical significance of differences of means [a]	Reduction of turbidity relative to control (%)
Control	542.0	432 ; 651	a	-
PAM – 10 kg/ha	6.67	5.87 ; 7.47	b	99
PAM – 20 kg/ha	4.91	3.51; 6.31	b	99

[a] Differences followed by the same letter did not differ significantly (t-test, $p<0.05$).

The PAM treatments produced significantly lower turbidity (Table 13) than in the control treatment. However, the difference between the two PAM treatments was not significant.

A reduction in turbidity in the rainfall simulation experiments was expected given that PAM significantly reduced the amounts of eroded sediment from the test plots. However, the degree to which PAM reduced turbidity was surprising. Turbidity readings were not taken during the outdoor tests with natural rainfall, so it is not possible to draw comparisons between the two experiments, but the test methodology used for the simulation experiments probably played a large role in the observed reductions in turbidity.

The relative quickness of rainfall and the soil moisture levels prior to application of the PAM played key roles in reducing turbidity levels. Two main processes probably combined to cause this dramatic drop in turbidity. First, the PAM would have increased aggregate size through the bonding of clay particles before being eroded; these larger particles would then settle quickly out of suspension when eroded. Second, any PAM eroded from the soil and transported into the collection bucket would have a further opportunity to flocculate dispersed, suspended particles.

The significant effect of PAM in reducing water runoff turbidity reflects the study results presented by Tobiason (2000). Tobiason found that PAM applied at a rate of just 0.7 kg/ha on a silt loam soil reduced runoff turbidity by 82% on a 3.5H:1V slope. McLaughlin also found reduced turbidity levels on silt loam soils on a slope of 4H:1V with PAM applications of 11kg/ha. However, McLaughlin did not find PAM to be effective in reducing runoff turbidity on steeper 2H:1V slopes as was found in this study.

5. SUMMARY AND CONCLUSIONS

Experiments involving two PAM application rates were conducted using natural rainfall in 2001 and 2002 and indoor rainfall simulation in 2003. Application rates of 10 and 20 kg/ha were used to determine the effectiveness of polyacrylamide in providing short-term erosion control on steep slopes. In 2001, the PAM applications were combined with a broadcast application of grass seed.

Following the occurrence of rainfall, the eroded soil was collected, dried, and weighed to determine the total amount of eroded sediment. For the study that involved treatment with both PAM and grass seed, the densities of grass stems were measured upon completion of the study.

A rainfall simulator was built so that further PAM treatment studies could be conducted indoors. To create erosion-causing events, the rainfall simulator was run for 1 hour at an intensity of 72 mm/h. Throughout the simulation, the eroded sediment was collected. Upon completion of the simulation, the eroded sediment was dried and then weighed to determine the total sediment yield. Samples (50 mL) were also taken after completion of each of the simulations to determine the turbidity level of the runoff.

The first objective of this study was to determine whether PAM could provide short-term erosion control on steep slopes. The study results suggest that:

1. PAM did not provide statistically significant erosion control following natural rainfall events on a loam soil. PAM significantly reduced soil erosion following one natural rainfall event but due to the effect of the established grasses it is not clear that PAM was the sole contributor to this erosion reduction.
2. PAM at both 10 and 20 kg/ha significantly reduced soil erosion (by 75 and 77%, respectively) in simulated rainfall studies on a silt loam soil.

3. Both PAM applications combined with sown grasses provided statistically significant erosion control on the silt loam soil 32 days after application of PAM. However, this is believed to be a result of the grasses becoming established on the plot rather than the result of PAM application.
4. PAM application at 10 kg/ha significantly increased grass seed densities (by 109%) compared with densities in the control plots. However, PAM applied at 20 kg/ha provided no significant increase compared with the control.
5. PAM applications of 10 and 20 kg/ha significantly reduced the turbidity of runoff water (by 99%) in the rainfall simulation experiments.

The second objective of this study was to determine what PAM application rates would be most effective in controlling soil erosion. Although the results were inconclusive, future work could use lower application rates than in the present study, since the results of the 10 and 20 kg/ha PAM applications were never significantly different in terms of mean sediment yields or mean turbidity levels in runoff water.

5.1. Application of research results to forest road management

The research that was conducted in this study was designed to address ongoing concerns of erosion control on forest roads. The forest industry has identified a need for products or methods that could provide effective short-term erosion control on steep slopes until more intensive long-term methods can be applied.

Previous research on the use of PAM on steep slopes has been limited and this study set out to investigate, using basic characteristics of forest road sideslopes, if PAM could be recommended as a best management practice to control soil erosion. There is a wide variety of forest road sideslope conditions, including soil type, slope steepness and surface conditions, that are found along forest roads. In this study the soil types of loam and silt loam and slope steepness of 2H:1V (30%) were chosen to represent the most frequently occurring, basic characteristics of forest road sidelopes. By choosing these conditions the performance of PAM could be evaluated under the conditions that are most applicable.

However, the conflicting results that were found from the simulated and natural rainfall tests in this study make it difficult to develop any firm recommendations on the use of PAM for forest roads. The results of this study indicate that PAM does have the potential ability to reduce soil erosion in the short-term but further studies are required to confirm this. Further studies could not only confirm the effectiveness of various PAM application rates on different soils and slopes but could be used to develop a field application guide for forest road managers.

5.2. Recommendations for future research

The conflicting results from the rainfall simulation and the natural rainfall study make it difficult to draw firm conclusions from the results of this study. Nonetheless, this study is one of the few to address the use of PAM on steep slopes, and the experience gained can be a valuable tool for guiding future research. Future research on the use of PAM to control erosion on steep slopes must consider the following important issues identified during this study:

1. Each treatment should be replicated more than three times in order that the likelihood of finding significantly different results may be increased.

2. Overall levels of eroded sediment should be measured in combination with turbidity to provide a more complete picture of the effectiveness of PAM. Turbidity levels are the factors of most concern to government regulators attempting to quantify the industry's compliance with soil erosion regulations.
3. This study investigated erosion on loam and silt loam soils, which are the type most often used as the surface layer on roadside slopes. Future studies could examine the ability of PAM to control soil erosion on other types of soils, thereby possibly influencing the choice of soil type for the surface layer on roadside slopes. For example, because the turbidity levels in runoff water were significantly lower in the PAM treatments than in the control, this suggests that fine-textured soils such as clays and silts will benefit more from PAM treatments; given the number of forest roads built from low-quality, fine-textured *in situ* materials in many parts of Canada, it would be important to extend the present study to these types of soils.
4. If rainfall simulation experiments are to be conducted using simulated soil beds, the experiment should be combined with either natural rainfall experiments or with rainfall simulation carried out over natural soil beds.

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