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The impact of natural polymer derivatives on sheet erosion on experimental loess hillslope

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ABSTRACT

Macromolecular polymers can effectively improve soil structure, increase soil penetration and control runoff and erosion on hillslopes. Simulated rainfall experiments on a bare soil investigated the impact of natural polymer derivatives (NPD) on soil properties and the characteristics of runoff and sediment yield of sheet erosion on experimental loessial hillslopes. A control (without NPD) and three concentrations of polymers (1, 3 and 5 g/m^2) were tested at rainfall intensities of 1, 1.5 and 2 mm/min and a slope gradient of 15°. NPD effectively altered the onset, volume and sediment content of the runoff. Higher concentrations of NPD provided earlier onsets, lower depth and lower sediment contents of the runoff. Compared with control, cumulative runoffs decreased by 49–68%, 61–70% and 69–79% at concentrations of 1, 3 and 5 g/m^2 NPD, respectively, while cumulative erosion modulus decreased by 31–37%, 39–47%, 56–61%, respectively. Additionally, NPDs significantly increased the shear strength and the composition of aggregates from soil surface. Shear strength was 2.71, 3.24 and 4.01 times higher at 1, 3 and 5 g/m^2, respectively, than in the controls. The percent mass of aggregates >0.25 mm increased to 52.5%, 62.65% and 73.0% from 8.9% in the control at the three respective concentrations. More research is needed to confirm the utility of NPDs in helping to control sheet erosion.

1. Introduction

Arid and semi-arid areas account for 70% of the land in China. These areas, especially on the Loess Plateau with its thick soil layer and loose soil texture, experience particularly serious losses of water and soil. Even though annual rainfall and erosion indices are lower (Agassi and Ben-Hur, 1992) in arid and semi-arid areas, crust can easily form on the surface, which decreases the rate of infiltration and causes the loss of water and soil (Ben-Hur et al., 1992; Chen et al., 1980). The development of new alternatives of management, based on understanding the mechanisms of erosion, is necessary to minimize the damage of this kind of soil degradation.

Efforts to inhibit crusting, increase infiltration, decrease runoff and retain rainfall can improve the use of the available water resources. Traditional means of soil and water conservation have limited effectiveness in controlling soil erosion because of the low amount and the high intensity of rainfall in arid regions. Chemical regulation is a non-traditional method of conserving water and soil.

Macromolecular compounds have been commonly used to improve soil structure by strengthening the stability of soil aggregates and preventing the dispersion of clay, thereby reducing crusting, increasing infiltration and controlling surface runoff and soil erosion (Santos et al., 2003). Polyacrylamide (PAM) was gradually applied in the 1980s in soil management as a typical soil amendment and was then used in soil and water conservation. As a soil amendment, polyacrylamide has been widely studied. PAM can effectively maintain soil structure and aggregates by adsorbing to particles (Kemper and Rosenau, 1984; Parfitt and Greenland, 1970) and can reduce crusting to maintain higher infiltration rates (Sepaskhah and Bazrafshan-Jahromi, 2006; Tang et al., 2002; Yu et al., 2010). PAM does not penetrate aggregates but only soil with 2–3 mm particle sizes, and only the outer surfaces of aggregates are stabilized (Malik and Letey, 1991). It can reduce crusting and increase aggregate size and thus reduce runoff and losses of sediments and nutrients (Bjorneberg et al., 2003; Santos et al., 2003; Wang and Yang, 2006; Yang et al., 2006). Nevertheless, PAM has little effect when the coverage or the concentration is low (Feng et al., 2001; Tang et al., 2003), and excessive application

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reduces the permeability of soil (Yuan et al., 2005). Finally the utility of PAM application is highly dependent on the properties of the soil (Lentz, 2003; Lu et al., 2002).

Numerous studies (Santos et al., 2003; Tang et al., 2003) have characterized the positive effects of PAM application, but there's also restrictions such as its disappointing impact on some low-quality or salty soils. Other researchers also adjust the soil with integrated different chemicals to pursue better results. With the development of society and technical, more natural and synthetic chemicals are developed, therefore, the exploration of a new field of soil conditioning and erosion controlling using chemicals is proceeding, and more effective chemical controls of soil erosion required further development to meet the needs of various types of soil. In this paper, the effects of a new derivative of a natural polymer extracted from bean embryo on sheet erosion of experimental loessial slopes were tested under simulated rainfall.

2. Materials and methods

2.1. Soil and polymer

Experiments were conducted in the Simulation Rainfall Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources in China. The soil samples for testing were from Ansai County in the hinterland of the Loess Plateau (a typical region with hills and gullies). Ansai (109°19′ E, 36°51′ N) located in northern Shaanxi Province has a mean annual temperature of 8.8 °C and an annual precipitation of 500 mm. The soil used was a silt loam (USDA) collected from 0 to 25 cm depth of farming layer, with a organic matter content of 0.5% about. The d_{50} was 0.037 mm, with 8.7% clay content, 54.7% silt content and 36.6% sand content. The samples were air dried, crushed, mixed well and then passed through a 10-mm sieve. The polymeric compound tested was natural polymer derivatives (NPD), as a SOLVAY polymer that is extracted from bean embryo. It's a green chemical showing no irritating and no known adverse effects on aquatic species on which it was tested. It's conditioned as a free flowing powder and is easy to disperse in water.

2.2. Equipment

Experimental plots were constructed with metal frames of 1.2 m (length) × 0.4 m (width) × 0.25 m (depth), with adjustable gradients by a movable base. A metal outlet at the lower end allowed the collection of runoff samples. In the bottom of the plots, natural sand to a depth of 5 cm and overlaid with permeable gauze was set to drainage the infiltration water. The soil was packed to a depth of 20 cm in four 5-cm layers at a bulk density of 1.2 g/cm^3 (measured by a cutting ring in a compacted state). Before packing, the water content of the soil was adjusted to 14%, the typical level during the flood season on the Loess Plateau when most erosion occurs. After the soil was packed, NPD solutions of 1, 3 and 5 g/m^2 were prepared in 2 L of water to produce final NPD concentrations of 0.024%, 0.072% and 0.12% respectively, and uniformly sprayed on the surfaces of the containers. The simulated rainfall experiments began about 15 h later.

Four NPD concentrations (0, 1, 3, 5 g/m^2), three rainfall intensities (1, 1.5, 2 mm/min) and one slope gradient (26.8%, equivalent to 15°) were tested with two replicates, totalizing 24 experimental units. The duration of all simulated rainfall was 40 min.

2.3. Measurements

For each treatment, runoff samples were collected 1 and 3 min after the onset of runoff and then every 3 min until the end of the experiment. The runoff volumes were measured with a graduated cylinder, and the sediments were dried at 105 °C and weighed. The runoff rate was defined as runoff depth per unit area per unit time, while the erosion rate was defined as sediment weight per unit area per unit time. The cumulative erosion modulus was defined as the sum of the erosion rate multiplied by time per unit area in all the time. Aggregate sizes on the surface (0–1 cm) were measured by wet sieving after rainfall in the classes >5, 2–5, 1–2, 0.5–1, 0.25–0.5 and <0.25 mm. Each class of aggregates was dried and weighed. Three samples were measured for each treatment and averaged. After each simulated rainfall, six measurements of the shear strength of the soil surface were also taken using a 14.10 Pocket Vane Tester. Because shear strength is closely related to water content, we measured the water content continuously after each simulated rainfall. Soil water content was measured by alcohol burning method for rapid, and three samples were taken from surface soil of 1 cm. The final shear strength was measured when the water content dropped to 22–25% after air drying. All data were analyzed using SPSS by one-way ANOVA and least-significant difference (LSD) tests. For all analyses of Tables 1–3, the significant level was 0.05.

Table 1
The effect of NPD on the onset of runoff. Statistical comparisons for the NPD dose in the same rainfall intensity.

Rainfall intensity (mm/min)	Onset of runoff (min)			
	Control	1 g/m^2 NPD	3 g/m^2 NPD	5 g/m^2 NPD
1.0	6.81bc	8.66a	7.50b	6.66c
1.5	5.45a	5.17a	4.58a	2.86b
2.0	3.64a	3.50a	2.50b	2.00c

Table 2
The effect of NPD on shear strength. Statistical comparisons for the NPD dose in the same rainfall intensity.

Rainfall intensity (mm/min)	Shear strength (g/cm^2)			
	Control	1 g/m^2 NPD	3 g/m^2 NPD	5 g/m^2 NPD
1.0	0.262d	0.696c	0.827b	1.032a
1.5	0.249d	0.698c	0.877b	1.054a
2.0	0.271d	0.718c	0.823b	1.045a
Average	0.260d	0.704c	0.842b	1.043a

3. Results and discussion

3.1. Effects on runoff

Surface runoff is influenced by the vertical movement of moisture, under the combined effects of various factors, and by the redistribution of rainfall below the surface. Rain falling on a bare soil surface will first infiltrate the soil, and runoff will occur when the rainfall intensity exceeds the infiltration capacity of the soil. By detaching the topsoil on hillslopes, runoff is one of the main causes of water erosion. Under normal circumstances, more runoff will produce more soil erosion.

Fig. 1 shows the runoff under the various concentrations (control, 1, 3 and 5 g/m^2 NPD) at different rainfall intensities (1, 1.5 and 2 mm/min) at a slope gradient of 15°. Runoff rates increased gradually and eventually tended to stabilize over time. and there's been less obvious differences between the runoff curves of the NPD treatments. Higher NPD concentrations produced earlier onsets of runoff (Table 1) and lower runoff depth. In experiments with different rainfall rates, the onset of runoff at 1.5 and 2.0 mm/min was earlier than that on bare soil, while that at 1.0 mm/min occurred later, except at the NPD concentration of 5 g/m^2. Runoff under different treatments, however, was lower than that of the

Table 3
The effect of NPD on aggregates. Statistical comparisons for the NPD dose in the same size.

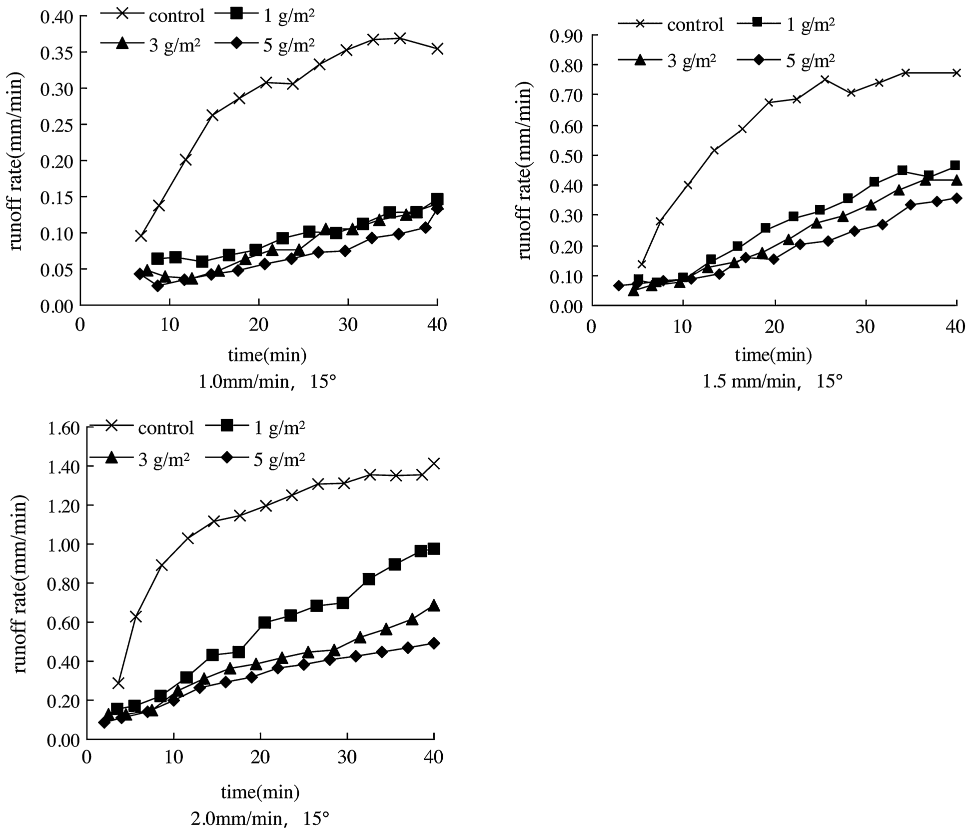
Size distribution (mm)	Mass fraction of size classes (%)				Increasement compared to control (%)		
	Control	1 g/m^2 NPD	3 g/m^2 NPD	5 g/m^2 NPD	1 g/m^2 NPD	3 g/m^2 NPD	5 g/m^2 NPD
<0.25	91.1a	47.5b	37.4c	27.0d	−50	−60	−70
0.25–0.5	3.3c	16.5a	11.8b	13.5b	400	260	310
0.5–1	2.5c	12.2a	10.1b	11.4ab	390	300	360
1–2	2.0c	14.2b	16.1ab	17.8a	620	710	790
2–5	1.1c	9.1b	20.8a	24.0a	700	1730	2020
>5	0.0c	0.9c	3.6b	6.3a			
>0.25	8.9d	52.5c	62.6b	73.0a	490	600	720

controls. The amount of runoff decreased as the amount of NPD increased. After 40 min of rain, the cumulative runoff at 1 g/m^2 NPD decreased by 68% at a rainfall intensity of 1 mm/min, by 54% at an intensity of 1.5 mm/min and by 49% at an intensity of 2 mm/min. The cumulative runoff at 3 g/m^2 NPD decreased by 70% at a rainfall intensity of 1 mm/min, by 61% at an intensity of 1.5 mm/min and by 64% at an intensity of 2 mm/min. The cumulative runoff at 5 g/m^2 NPD decreased by 79% at a rainfall intensity of 1 mm/min, by 69% at an intensity of 1.5 mm/min and by 70% at an intensity of 2 mm/min. The reduction of runoff was greater at lower rainfall intensities. NPD was thus able to reduce surface runoff.

3.2. Effects on erosion

Runoff and erosion occurred and evolved simultaneously and are thus closely related. Runoff causes erosion, so a reduction in runoff led to less erosion. Fig. 2 shows the erosion that occurred with the different NPD concentrations (1, 3 and 5 g/m^2 NPD, and the control) and rainfall intensities (1, 1.5 and 2 mm/min) at a slope gradient of 15°. The erosion rate increased rapidly during the first 10 min of rainfall and then stabilized as the rainfall continued. This variation between sheet erosion and rainfall duration can be attributed to a combination of factors. Early in the rainfall, the moisture content of the bare surface soil was low, so erosion was caused mainly by the splashes of the raindrops. Many soil particles became detached, rapidly increasing the erosion. As the rainfall continued, soil moisture gradually reached saturation to generate runoff. The flow became more turbulent, and the depth of runoff became greater, causing more intensive erosion. Infiltration and rainfall eventually reached an equilibrium, and the intensity of the runoff and erosion tended to stabilize.

Fig. 2 showed that NPD can apparently reduce the erosion, and in experiments at different NPD concentrations, erosion rates under different treatments were lower than in the controls. As NPD concentrations increased, erosion intensities decreased. At NPD concentrations of 1, 3 and 5 g/m^2, the cumulative erosion modulus decreased by 31%, 47% and 61%, respectively, at a rainfall intensity

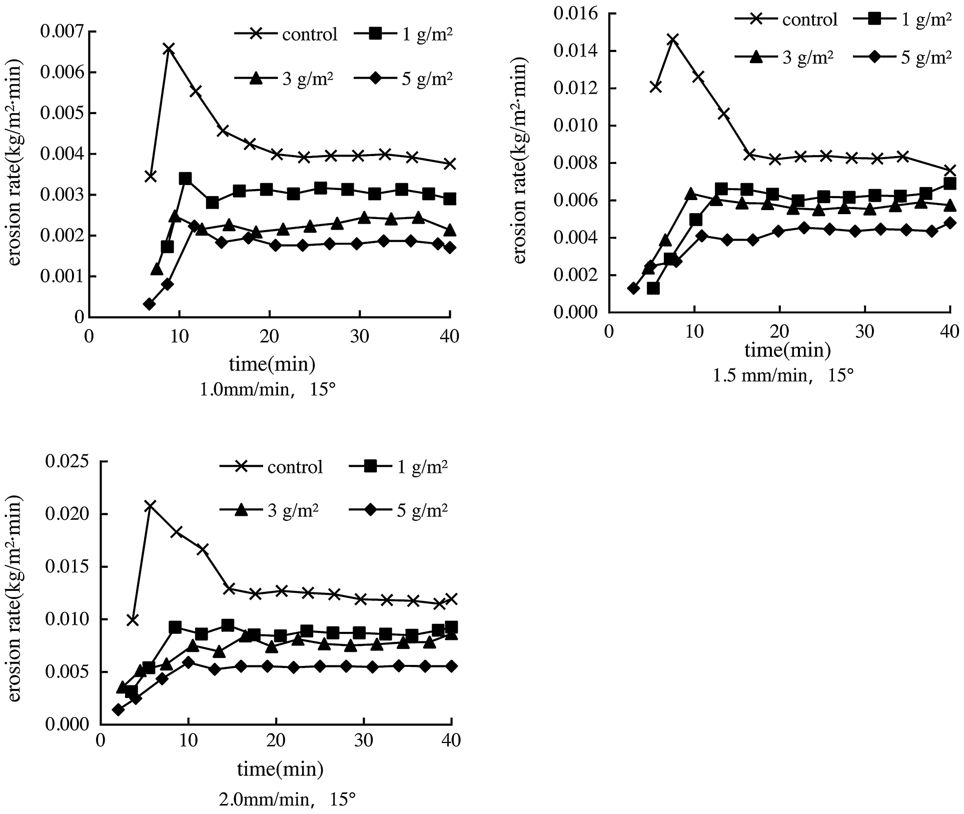


1.0mm/min, 15°

1.5 mm/min, 15°

2.0mm/min, 15°

Fig. 1. Comparisons of runoff rates under different treatments.



1.0mm/min, 15°

1.5 mm/min, 15°

2.0mm/min, 15°

Fig. 2. Comparisons of erosion rates under different treatments.

of 1 mm/min, by 36%, 39% and 56%, respectively, at a rainfall intensity of 1.5 mm/min and by 37%, 44% and 60%, respectively, at a rainfall intensity of 2 mm/min. Under the experimental rainfall intensities, erosion masses decreased by 31–37%, 39–47% and 56–61% at the NPD concentrations of 1, 3 and 5 g/m^2, respectively. The amounts of sediment in the runoff at the three concentrations of NPD were all lower than those of the controls.

3.3. Effects on shear strength and aggregates

In addition to erosion forces (rainfall, wind, etc.), topography (slope, slope length, slope shape, slope sections, etc.) and surface conditions (roughness, covering, etc.), the ability of soil to resist the dispersion of rainfall and runoff is closely related to soil erosion. In this experiment, the shear strength of the topsoil is an important factor in soil erosion. The average shear strength was surveyed after each rainfall when the water content dropped to 22–25% (Table 2). Higher NPD concentrations produced higher shear strengths. Shear strength had little relationship to rainfall intensity but was mainly due to the concentrations of applied NPD. The average shear strength was enhanced by 171%, 224% and 301% in the treatments of 1, 3 and 5 g/m^2 NPD, respectively, in all experiments. Increased concentrations of NPD decreased erosion masses, even though shear strength varied little under the three rainfall intensities and cumulative erosion masses increased with rainfall intensity. NPD thus had an obvious effect of strengthening the stability of soil particles and resisting the damage from rainfall and runoff, so it could effectively reduce sediment yield.

The stability of aggregates is another property of soil depending on NPD incorporation. Polymeric compounds can conserve soil and water due to their enhancement of infiltration and the stabilization of soil structure. The reduction of erosion is mainly due to the compound's binding capacity, which weakens the ability of rainfall and runoff to separate soil particles. Aggregates >0.25 mm have an important influence on soil structure. The size, mass and stability of soil aggregates determine the size of soil pores and the stability of soil structure. Table 3 shows the effects on the aggregates of the soil surface after applying NPD. The results are averages of all experiments at the same concentration of NPD. NPD effectively promoted the aggregation of small particles into larger particles. The percent mass of particles <0.25 mm was drastically lowered, while the mass of each class >0.25 mm increased. In the control, the percent mass of aggregates >0.25 mm was only 8.9%, but the percentage increased to 52.5%, 62.6% and 73.0% in the treatments of the three NPD concentrations. The improvement in the 0.25–0.5 and 0.5–1 mm classes to the three concentrations was similar, while the improvement in the 1–2, 2–5 and >5 mm classes was significant, especially at concentrations of 3 and 5 g/m^2 NPD. The improvement by the three concentrations on particles of every class varied, but the treatments with higher concentrations had more particles >0.25 mm.

The viscosity of polymers can increase the stability of soil aggregates and structure (Green et al., 2004), thereby leading to stabilization of the soil surface against shear-inducing detachment (Lentz and Sojka, 1994), decreasing soil erosion (Bjorneberg and Aase, 2000). A high stability of soil aggregates can also maintain an appropriate region of penetration for reducing surface runoff and eroded sediment. In this experiment, the additions of NPD can effectively lead to the improvement of soil shear strength and aggregates, and this observation of PAM on the aggregate and soil structures was reported by Mamedov et al. (2010), showing that PAM could lead to an increase in the stability of the aggregates compared with the untreated ones.

The addition of polymers can change physical conditions of soil for the interaction between soil particles and polymeric substances, and Schamp et al. (1975) explained this phenomenon as that polymers can enhance the stability of aggregates by adhesions and adsorptions. Polymers adsorptions of soil particles could reduce the repulsive force between soil particles, and adhesions of polymers could bind the soil particles (Ben-Hur, 1994). Shainberg and Levy (1994) noted that increasing aggregates stability reduced seal formation, so use of polymers could effectively reduce seal formation by improving aggregate stability (Ben-Hur and Letey, 1989). For the above, the additions of NPD was assumed that it acted as binding agent to stabilize the soil aggregates to resist seal formation and increase the infiltration, all leading to the control of runoff and erosion, the same with polyacrylamide (Santos et al., 2003).

Conclusively, the application of NPD on the soil surface can effectively change the structure of the soil surface, maintain a high infiltration rate to limit runoff, reduce the detachment and transport of soil particles and ultimately reduce erosion. Simultaneously, the resistance to erosion and the scouring of soil can be enhanced by increased binding between particles and by the higher content of water stable aggregates. A combination of altered soil properties and levels of runoff can lead to a reduction in erosion.

4. Conclusions

Different concentrations of NPD were tested with simulated rainfall for their efficacy in affecting the characteristics of runoff, soil aggregates and sediment yield in sheet erosion on a loessial hillslope in experimental plots. NPD effectively influenced the onset of runoff, the amount of runoff and loss of sediments, shear strength and the composition of soil aggregates. In experiments with different NPD concentrations, the onset of runoff under different rainfall conditions was variable, while the rates of runoff and erosion under the different treatments were lower than those of the controls. Higher concentrations shortened the onset of runoff and reduced the amount of runoff and sediment yields. NPD also played a significant role in improving shear strength and the composition of surface-soil aggregates, and the effects were larger as the concentration increased. The mass of each class of aggregates >0.25 mm increased effectively.

Our tests indicated that the macromolecular polymers were generally effective at improving soil properties, increasing soil penetration and controlling runoff and soil sheet erosion on experimental loessial hillslopes. We examined only simple sheet erosion at three rainfall intensities, so the effects of more complicated erosional processes, such as rill erosion, and other conditions remain unknown. The prevention and control of erosion thus requires more comprehensive study and discussion. Further research should be performed under different rainfall conditions, polymeric concentrations, soils and applied ways (dry or spraying). The effects of longer or more intensive rainfall and other types of erosion should also be tested. More importantly, field tests should be performed to obtain data from natural and disturbed environments.

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