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Full Length Research Paper

Influence of amendments on soil structure and soil loss under simulated rainfall China's loess plateau

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Macromolecule polymers are significant types of chemical amendments because of their special structure, useful functions and low cost. Macromolecule polymers as soil amendment provide new territory for studying China's agricultural practices and for soil and water conservation, because polymers have the ability to improve soil structure, increase rainfall penetration and control slope runoff. Through indoor laboratory experiments and outdoor artificial rainfall simulations, this study applied different consistencies of three amendments; polypropylene acid (PPA), polythene alcoholic (PTA) and urea-formaldehyde poly-condensate (UR) to China's Loess and determined their effects on soil physical properties and on runoff-sediment yield. The results indicate that as a result of applying the amendments, (1) the water-stable soil aggregates content increases by 17.3%, the soil permeability increases by 41.8%, the soil density decreases by 11.2% and the soil water content increases by 28.0% compared to the control; (2) three amendment applied on sloping land can delay runoff and decrease runoff velocity; decrease erosive forces of raindrop impact and flowing water, reduce surface crusting and improve water infiltration, delay runoff engenderation and decrease runnoff velocity and soil erosion yield. Finally, this study also ascertained optimal application quantities and the most effective sort in three amendments, which PPA is most effective at lowering surface runoff, reducing soil loss and increasing soil penetration. These three amendments have broad potential for soil and water conservation; however, the duration of their effect and the optimal application quantities need to be researched further.

Key words: Amendment, Runoff-Sediment Yield, Soil Physical Properties, Soil erosion

INTRODUCTION

The concurrence of drought, water shortage and soil and water loss is the greatest limiting factor for socially and economically sustainable development in arid-semiarid regions of China. Slope runoff is not only the greatest source of soil and water loss, but also an important water an important research field for China's agricultural soil and water conservation. In recent years, macromolecule polymers and other soil conditioners have been recognized resource in situations of drought and water shortage (Wu et al., 2003; Shao and Shi, 2000). As a result, the question of how to adjust and control surface runoff has become for their special structure, many functions and low cost. Runoff generation and soil loss were significantly reduced on all runoff plots during the first rainfall simulation, but the most dramatic results occurred when soil conditioner application was combined with raking (Wu et al., 2002; Lon and Zhang, 2000). This inhibited crust development and virtually eliminated runoff and soil loss.

To reduce soil erosion and improve soil quality, various soil conditioners were used. It is believed that soil conditioners can increase soil porosity, increase infiltration (Gal et al., 1992), enhance soil aggregation (Wallace, 1986), decrease plash detachment and enhance aggregate stability (Sutherland and Ziegler,1998), reduce soil

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Abbreviations: PPA, Polypropylene acid; **PTA,** polythene alcoholic; **UR,** urea-formaldehyde poly-condensate; **PAM,** polyacrylamide; **PVA,** polyvinyl alcohol; **PVAc,** polyvinyl acetate; **PVC,** polyvinyl chloride; **CK,** check.

sealing, ameliorate a degraded soil (Lon and Zhang, 2001), reduce soil crusting, decrease wind erosion and reduce soil erosion (He and Michael,1998; Gal et al., 1992; Brandsma et al., 2001). The use of various synthetic polymers and surfactants has been reported in the technical literature. For example, acrylate, polyacrylamide (PAM), polysaccharide polymer, polyvinyl alcohol (PVA) and polyvinyl acetate (PVAc) have been commonly used. Floyd (1981) used PVAc emulsion as a soil conditioner. Botha et al., (1980) discussed the effect of PVA on the liquid-solid contact angles of a fine sandy soil. Pini and Vigna (1994) used two uncharged polymers, PVA and detrans, to study the interaction of water soluble stabilizing agents with soil particles, resulting in the formation of soil micro-aggregation.

Among the synthetic polymer soil conditioners, PAM has been discussed more than any other. Levy and Miller (1999) showed that PAM adsorbed on both outer and inner surfaces of large soil aggregates larger than 100 mm and thus, enhance the resistance of aggregates to external forces. Chan and Sivapragasam (1996) showed that the addition of an anionic polymer (PAM) would significantly improve soil physical properties, namely increased water-stable aggregates, reduction in tensile strength and reduction in bulk density. Nadler and Perfect (1996) and Malik and Letey (1991) discussed the adsorption of PAM and polysaccharide polymer on soils and suggested that PAM and guar polymers did not penetrate the aggregates. Shainberg et al. (1992) showed that adding PAM to the soil improved aggregate stability and increased the permeability of the soil, and aggregate breakdown was suggested as the first step in seal formation, to be followed by surface compaction and clay dispersion. Fox and Bryan (1992) showed that a PAM soil conditioner would significantly delay runoff production and decrease erosion runoff yield.

Fullen and Cookson (1995) studied the effect of the anion surfactant soil conditioner ‘Agri-SC’ (a soil conditioner with anionic surfactant) and discovered a statistically significant decreases in soil bulk density values and increases in soil porosity and aggregate stability. Ziegler and Sutherland (1998) also used ‘Agri-SC’ to enhance soil resistance to erosion. Sutherland and Ziegler (1998) concluded that the use of ‘Agri-SC’ would produce a less erodible surface and decrease the transportability of sediment. The reduced erodibility may reflect a preferential absorption of anionic surfactant on the positively charged sites of soils. Shulga et al. (2001) used amino-containing soil conditioners based on lingosulphonate and concluded that the lignin-based interpolymer complexes in which polyamines or oligomer amines were used as their component may be offered as soil conditioners for the creation of an artificial soil structure, as well as for erosion control due to the stabilization of the surface layers on sandy soil. Bouranis et al. (1995) gave a detailed discussion on synthetic materials that are designed to function as soil conditioners and discussed the combination of materials and/or properties.

There is still a shortage of contradistinctive and systemic experimental studies concerning the effect of many polymers on soil physical properties; namely, water-stable soil aggregates, bulk density, soil permeability, soil water content and runoff-sediment yield. This study selected dozens of the more effective soil amendments through a literature search and determined their ability to affect water infiltration indoors after mixing with a quantitative soil. Finally, three effective polymers were selected for use in this study. Through indoor experiments and outdoor artificial rainfall simulations, the effect of polymers with various concentrations on soil structure, runoff and soil and water loss is discussed contrastively and systemically, and their appropriate usage concentrations are ascertained.

MATERIALS AND METHODS

The three polymers chosen for the experiment—polypropylene acid (PPA), polythene alcoholic (PTA) and urea-formaldehyde resin (UR) — are all materials that are easily dissolvable in water and do not contaminate the environment. They are commonly used to enhance soil flocculation, soil cementation and as soil amendments. The study was conducted at the experimental station of water-saving irrigation, located in an arid-semiarid region of northwest China (Yangling, Shaanxi). The soil is a loamy clay of loess origin, with a particle-size distribution of 0.1% 1.00 - 0.25 mm particles, 2.30% 0.25 - 0.05 mm, 36.70% 0.05 - 0.1 mm, 14.60% 0.01 - 0.005 mm, 13.30% 0.005 - 0.001 mm, 32.90% < 0.001 mm, 60.00% < 0.01 mm and 3.00% water-stable aggregates.

To prepare the soil sample, weeds and scree were first removed, then passed through a 2 mm sifter and placed in a polyvinyl chloride (PVC) column (25 cm high, with a diameter of 18 cm). Soil bulk density and water content were maintained at 1.20 g cm^{-3} and 170 g kg^{-1} in the soil column, respectively. For each of the three polymers, there was a check (CK), without the addition of any polymers, along with five treatments at different concentrations (Table 1). After the soil sample disposal wells were placed indoors for one week, water infiltration was determined by invariable hydraulic pressure titration. Water retention was measured indoors by weight in a soil sample each day. Bulk density was determined using a stainless steel ring and oven-dried at 105℃. The content of water-stable aggregates was determined using wetting-sifting.

Artificial rainfall simulation using a micro-sprayer assemblage was used to carry out a slope eroding experiment by simulating natural rainfall. The intensity and duration of the rain was controlled at 1.0 mm min^{-1} and one hour, respectively. Three 0.66 m × 5.1 m runoff plots were constructed with their longer sides parallel to the 6° slope and an instrument was added at the bottom to measure runoff and sediment yield. Layout and design of the experiment plots are shown Figure 1. Cement block borders, 30-cm high, were installed around each plot to define the catchments areas and to improve the accuracy of runoff measurements. The three plots were filled with 40 cm of soil having a density of 1.2 g cm^{-3} and a water content of 170 g kg^{-1}.

RESULTS AND ANALYSIS

Soil properties

Soil samples, from the trials using varied application rates of the three polymers to the soil surface, were tested for waterstable aggregates, water infiltration, soil bulk density

Table 1. Macromolecule polymer application concentrations.

Polymer	Concentration treatments					
	CK	**T1**	**T2**	**T3**	**T4**	**T5**
PPA	0	12	24	36	48	60
PTA	0	4	8	12	16	20
UR	0	25	50	75	100	125

PPA = Polypropylene acid; PTA = polythene alcoholic; UR = urea-formaldehyde resin; CK = check, (that is, without any polymers addition); T1, T2, T3, T4, T5 indicate five concentration treatments [that is, the mass (g) of polymers in 1,000 g water (unit:g kg^{-1})].

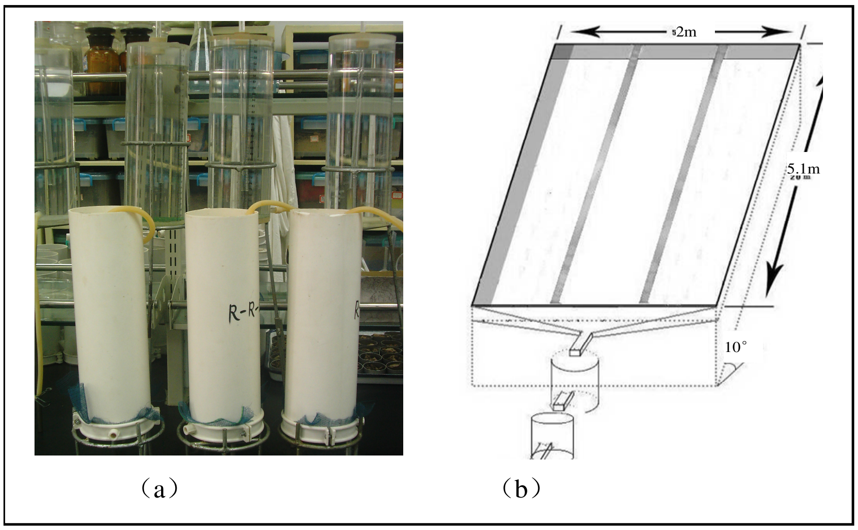

Figure 1. Design of physical experiment indoor (a) and experiment plots outdoor (b).

and water content. The results are shown in Table 2. Application of the polymer amendments to soil not only made separate mineral granule-forming artificial aggregates, but also enhanced the stability of crude granules, which will greatly improve soil structure as well as the physical and chemical qualities of the soil, including porosity, ventilation, stability and microorganism activity. Adding polymers changed the water-stable aggregate content of the soil. The largest improvements compared to the control occurred in the PPA treatment. For each polymer, increasing the number of applications led to gradually increasing water-stable aggregate contents.

Soil infiltration is an important indicator of soil condition reflecting a soil's capability to transport and store water. Adding each of the three polymers to the soil increased infiltration by an average of 0.813 mm min^{-1}; an increase of 25.6% over the control. Increasing the number of polymer applications gradually increased water infiltration rates until the infiltration levelled off under the PPA and UR treatments, whereas under the PTA treatment, soil infiltration initially increased and subsequently decreased. This decrease was attributed to the PTA molecule taking on the granule state and thus, not easy to diffuse in the soil when the sprinkling consistencies were superfluous and the formation of lamella membrane cemented soil granules greatly block soil water infiltration.

In all treatments, soil bulk density decreased compared to the control, because the soil became loose and lacunars after polymer application. The looser soil permits more rapid rainfall infiltration, facilitates microorganism movement and allows exchanges of water, gases and heat in the soil. Similar to soil infiltration, the greatest effects were obtained under the PPA treatment, during which soil density increased by 13.2% compared to the control. Under the UA treatment, the effect was 11.8%; the least effect (8.5%) was seen under the PTA treatment.

After the soil samples were placed in water for a long time (until saturated), the soils that had been treated with polymers had a higher mass than control soils, indicating an increase in soil porosity and infiltration. Soil saturation increased the most under the PPA treatment (490 g kg^{-1}), followed by the PTA (439 g kg^{-1}) and UR (417 g kg^{-1}) treatments. All three polymer treatments resulted in greater increases in soil saturation than the control situation (379 g kg^{-1}).

Next, the soil water was gradually evaporated over

Table 2. The effect of three amendments polymers on soil physical characteristics.

Polymer	Treatment concentration	Water-stable aggregates	Increase compared to the CK	Coefficient of infiltration	Increase compared to the CK	Bulk density	Decrease compared to the CK
	g kg^{-1}	%	%	mm min^{-1}	%	g cm^{-3}	%
CK	0	53.3	0.0	0.592	0.0	1.24	0.0
PPA	12	58.4	25.6	0.642	38.6	1.12	13.2
	24	64.5		0.710		1.10	
	36	65.0		0.912		1.09	
	48	69.7		0.930		1.07	
	60	70.1		0.907		1.01	
PTA	4	54.5	11.8	0.759	43.7	1.15	8.5
	8	56.0		0.824		1.140	
	12	58.7		0.970		1.14	
	16	61.5		0.941		1.13	
	20	61.3		0.760		1.13	
UR	25	54.4	14.4	0.620	29.7	1.12	11.8
	50	55.8		0.772		1.11	
	75	61.5		0.810		1.11	
	100	63.5		0.841		1.07	
	125	64.7		0.798		1.06	

Note: CK is the control case.

time to lower the soil water content. After ten days, the water content decreased to 61 g kg^{-1} under the control treatment and to 191, 152 and 173 g kg^{-1}under the PPA, PTA and UR treatments, respectively. These decreases were equal to 3.1, 2.9 and 2.5 times that of the control treatment. Thus, it can be seen that the application of polymers to soil, especially the PPA treatment, significantly improvedsoil water-retention and restricted soil water evaporation. Finally, Effect of Amendments (PPA) on enhancing the water-stable aggregate content, improving porosity and restraining evaporation is very remarkable in the 48-60 g kg^{-1} concentration treatment.

Runoff

Runoff production on slopes is a result of water flow along the earth's surface, as well as rainfall entering the soil. Rainfall infiltrates the soil and runoff commences when rainfall intensity exceeds infiltration intensity. Our research shows that when the sprinkling consistencies were in the range of 48 - 60, 16 - 20 and 100 - 125 g kg^{-1} for the PPA, PTA and UR treatments, respectively, there were significant improvements in the soil infiltration bulk density and water-stable aggregates. Figure 2 shows the mean times and velocity of runoff production, as well as the evolution of runoff yield for those treatments exposed to a rainfall intensity of 1.0 mm min^{-1} for one hour. The effect of polymers on the duration and velocity of runoff production is remarkable.

The runoff duration was an average of 4.25min (24.3%) less than the control treatment. The velocity of runoff produced during runoff commencement gradually increased, but the velocity stabilized with the postponement of rainfall duration. This was mostly attributed to a slight increase in runoff over the study period as a consequence of the saturation of upper horizon and the effect of soil sealing. The effects of the time lag and decrease in velocity of runoff in the PPA treatment were the most remarkable, with a time lag of 8 min and a decrease in velocity of 38.7% compared to the control. The runoff production curves follow a logarithmic pattern:

R_S = 0.9646Lnt + 0.3423 r = 0.9547 (CK) $F=21.416^{**} > F_{0.01}$

R_S = 0.6749Lnt + 0.9518 r = 0.9427 (PTA) $F=6.612^{*} > F_{0.05}$

R_S = 0.5641Lnt + 0.7987 r = 0.9406 (UR) $F=5.424^{*} > F_{0.05}$

R_S = 0.4199Lnt + 0.8009 r = 0.9615 (PPA) $F=9.977^{**} > F_{0.01}$

Where, R_s is the runoff velocity (L.min^{-1}); t is the rainfall duration; r is the correlation coefficients; and F is an index to verify prominent correlation.

The greatest correlations were under the PPA and control treatments and correlations were also found under the PTA and UR treatments. The equations show that the velocity of runoff production increases with increasing rainfall duration.

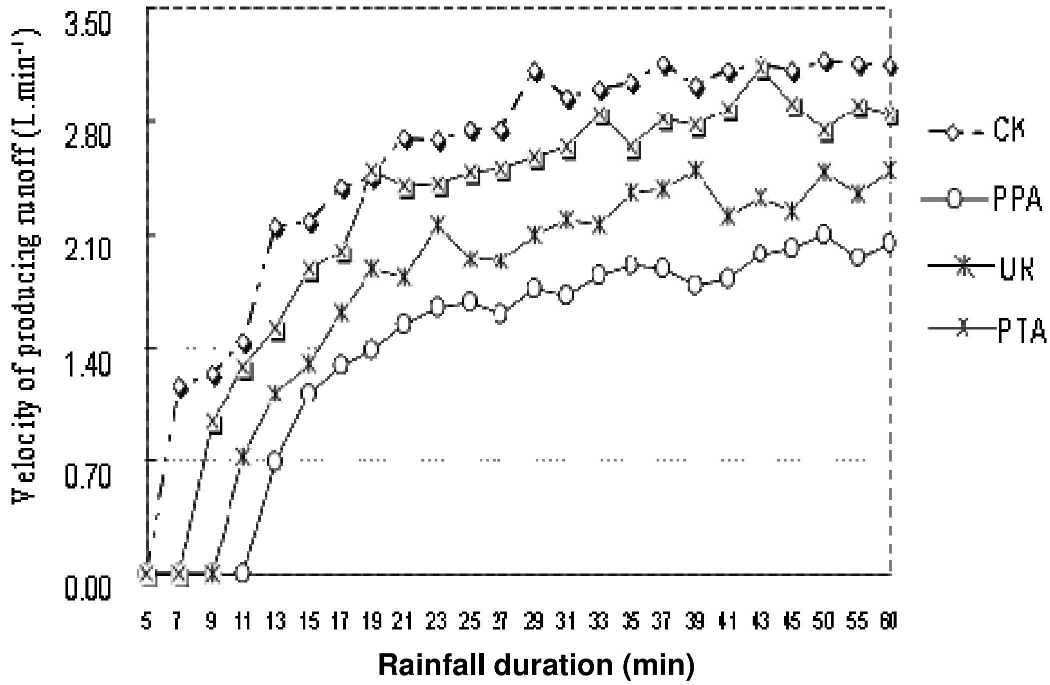

Figure 2. The effect of macromolecule on producing slope runoff.

Table 3. The best concentrations and dosages of macromolecule polymers.

Polymers	PPA	PTA	UR
Appropriate consistencies (g kg^{-1})	48-60	16-20	100-125
Appropriate dosage (ml m^{-2}, or g m^{-2})	116-145[a]	36-40[b]	180-240[a]
Price (RMB kg^{-1})	10	15	5
Percentages of decreasing runoff yield compared with CK (%)	49.7	12.3	25.4
Percentages of decreasing sediment yield compared with CK (%)	79.4	61.0	71.3
Charge (RMB m^{-2})	1.56	0.65	1.64

[a]Unit of appropriate dosage indicate volume of polymers in per square meter; [b] unit of appropriate dosage indicate weight of polymers per square meter.

Effect of macromolecule polymers on soil erosion

According to extensive erosion research, the scouring power of slope runoff is one of the most dynamic forces for producing soil and water erosion. In general, the greater the runoff produced, the greater the soil erosion. As a result, decreasing surface runoff can correspondingly reduce soil loss. After experiment of artificial rainfall simulations, three conclusions can be drawn: (i) Sediment yield due to runoff was less than in the control case after polymer treatment; (ii) the most significant decrease in soil erosion in this study was observed under the PPA treatment (71.9%) for the PPA, PTA and UR treatments, respectively, there were significant reductions in soil erosion. The best concentrations and dosages of macromolecule polymers were determined and are shown in Table 3.

DISCUSSION

Previous polymer application research and the current study have analogous conclusions: the polymers significantly improve soil physical properties, including increasing the content of water-stable aggregates, improving soil porosity and soil penetrability, improving water retention and decreasing soil bulk density and evaporation. In addition, the improved soil structure and infiltration generated through the rainfall simulation resulted in an increased time lag and decreased velocity of runoff and sediment yield compared to the control. The PPA reduced surface runoff to the greatest extent, thereby also reducing soil loss and increasing water penetration. When the PPA, PTA and UR were applied respectively at concentrations of 48 - 60, 16 - 20 and 100 - 125 g kg^{-1}, the most significant effects were seen for soil structure amendment thus preventing soil and water loss. However, it was found that when application consistencies of polymers were superfluous, micro-molecules were not easily diffused into the soil and the formation of lamella membrane on the soil surface significantly decreased soil water infiltration, resulting in increased runoff and erosion yield. On the other hand, high application consistencies of polymers can cause increased cost and a small quantity of using polymers has insignificant effect. Consequently, it is very important to use an appropriate polymer amount for soil amendment.

The effects of micro-polymers on decreasing runoff and sediment yield and on preventing soil and water erosion are primarily the result of two phenomena. Soil erosion decreased due to the addition of soil aggregates after polymers sprinkled on the soil surface accelerated soil water infiltration. In addition, soil resistance to erosion was enhanced, because greater soil adhesiveness increased the stability of the soil granules, thus inhibiting the capability for water to detach and erode.

Thus, it can be seen that these three macromolecule polymers have broad potential applications for soil and water conservation in loess plateaus. Moreover, integration of this technique with traditional methods of soil and water conservation—such as tree planting and afforestation, slope terracing and contour farming—may help prevent soil and water loss. Further research is needed about the duration of the polymers' effects and the optimal application quantities for different soil textures and climate conditions.

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