The Sealing Process and Crust Formation at Soil Surface under the Impacts of Raindrops and Polyacrylamide

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Abstract: Soil seals and crusts are formed at soil surface due to the impacts of raindrops and break of aggregates. They can significantly reduce soil infiltration rate and subsequently lower the utilization of water resources, and increase runoff, which induces soil erosion. To understand the processes of seals and crusts, experiments were conducted with rainfall simulation under laboratory conditions. The experiments involved different rainfall intensities (50 mm • h^{-1}, 100 mm • h^{-1}, 150 mm • h^{-1}), slopes (8.74%, 17.63%, 36.4% and 46.63%) and surface treatments (one control and three PAM coverage rates: (A > B > C)). Comparing the micromorphology, with the aid of scanning electron microscopy (SEM), of soil surface layer of control with PAM treatments', it can be concluded that soil crust is formed by depositional and structural crust. The curves of infiltration for different treatments as a function of time show that crust have four forming statuses.

Keywords: seal and crust, polyacrylamide, structure, infiltration

Sealing formation and crust are very common phenomena in many soils worldwide, especially in arid and semiarid soils. Rainfall causes a series of interactions between water and soils: compaction, disintegration, detachment, entrainment and deposition. These actions result in the formation of seal, and subsequently the crust of soils. Crust is a thin layer at the soil surface characterized by a greater density, higher shear strength, and lower hydraulic conductivity than the underlying soil. Soil seals and crusts can significantly reduce infiltration rate and subsequently lower the utilization of water resources, and increase runoff, which result in soil erosion. Crust also has the apparent negative effect to the emergence of seedling[1~4]. From 30s of last century, many scientists have been studying the processes of seal formation and crust. Though the conceptual mechanism of crust in soils due to rainfall has been described in different ways, a predominant description has been proposed as follows: the mechanism of crust involves two main complementary processes: (1) physical action included disintegration of soil aggregates and soil particles compaction caused by impaction of raindrop, and (2) physical-chemical action included dispersion of aggregates, movement of soil particles and exchange of cations that clog the conducting pores and form a less permeable layer at topsoil region[2, 5~13]. The formation of seal and crust depend on many factors, including the texture and stability of soil, intensity and energy of rainfall, gradients and length of slope, and electrolyte concentration of the soil solution and rain water [14].

Sealing formation and crust can significantly reduce the infiltration of soil, and increase runoff at surface of soil, which in turn increase the transport capacity for entraining detached materials from soils [10]. The relation of crust and soil erosion is so closely related that more scientists have paid attention to the formation of sealing and crust. Both soil crust and soil erosion involve particles' detachment and transport processes. Although most erosion models do not take account for the affection of crust to erosion, new concepts have been introduced which involve the explicit delineation between detachment and transport processes[7]. So it is believed that the new soil erosion model should take the basic concept of sealing and crust as one of its supporting theories.

Many scientists have been studying the method to prevent the formation of sealing and crust. A lot of experimental studies were carried out with rainfall simulation under laboratory and field conditions.

Polymer showed some good properties to improve the physical structure of soil and to stabilize aggregates of soil. Recently, a new polymer, polyacrylamide（PAM），has been found to be very effective in increasing hydraulic conductivity and porosity of soil, reducing runoff. PAM can not only keep the stability of aggregates in water, but also be able to form new aggregates with its flocculation. Soils treated with PAM are modified some soil properties responsive for formation of sealing and crust[1, 3, 15~17].

Study of the mechanism of formation of sealing and crust is of very importance to understand the interrelations of runoff, infiltration, and soil erosion under rainstorms. The objectives of this study were to research the structure of the crust with the micromorphology of SEM. The comparison of the micromorphology of crusted soil with soil surface layer treated PAM will improve understanding of crust formation processes and mechanisms of seal and crust.

Materials And Methods

Experiments were conducted with rainfall simulation under laboratory conditions. These experiments involved three different rainfall intensities (50 mm • h^{-1}, 100 mm • h^{-1}, and 150 mm • h^{-1}), four slopes (8.74%, 17.63%, 36.4% and 46.63%) and four soil surface treatments (one control and three PAM coverage rates: 80%, 60%, and 40%). The flume used for the experiments was a platform, which is adjustable from 0 to 46.63% slope. The flume of 3 by 8 m was sub-divided with PVC plates into fifteen sections of 8 m long, 20 cm wide, and 38 cm, for different soil treatments under the same laboratory conditions. The rainfall simulator is adjustable for its rainfall intensity, from 20 mm • h^{-1} to 300 mm • h^{-1}, and drop sizes from 0.6 mm to 3 mm.

Experimental soils used in this study were from Inner Mongolia: typical loess sampled from top layer of cultivated soils. The soil contents about 60% of silts and about 15% of clays.

Soils, air-dried before passing through a 10 mm sieve, were slightly compacted into the flumes for 15 cm in depth, over a 20 cm thick layer of sand. The bulk density was 1.2 g •cm^{-1}, about the same as that of the cultivated field. PAM mixed with dry soil was applied uniformly at the soil surface for different coverage rates of PAM accordingly.

Each individual experiment run was divided into two consecutive stages. At the first stage, the designed rainstorm was turned on and runoff and sediment samples were collected from the downstream outlets in regular time intervals (1, 3, 3, 5, 5, 5, and 5 min). As soon as the last sample was taken, the first experimental stage ended. After the first stage of experiment, the soil was set for 24 h^{-1} before the second rainstorm was put on.

Three replicates were adopted for each individual experiment.

Moist crust samples were taken at lower part of the flume and packed with filter paper and gauze. Samples were dried for at least ten days. After further desiccated, a small piece of the top layer of sample (crust) was severed carefully, then fitted on the top of the microscope stub with a thin layer of gold covering. The prepared sample was put into the scanning electric microscope (SEM). A series of vertical and horizontal photograph were taken at magnification of 1,500 to 3,500 times.

1 Results And Discussion

Photograph of sem and structure of crust

SEM photographs showed that the soil surface of control tended to have more compacted piling up of particles or small particles in between bigger particles’ pores , higher bulk density, and smaller pores (Fig. 1, 2 and 3). But on the other hand, the surface soils treated with PAM had more stable aggregation and higher porosity (Fig. 4).

Classification of crust structure is of very importance in crust study, which illustrates the dynamical mechanism of crust formation. Since the time when Chen *et al.*[18] has given the definition of depositional crust and structural crust in 1980, crust classification varies in literature but there is an agreement on two major types: structural crust, which is formed with no involvement of any external imported material, and the depositional crust, which always involves external material into its construction[6, 19].

Fig.1 SEM micrograph of structural crust. Original magnification (O.M.) 3500×

Fig.2 SEM micrograph of depositional crust. (O.M.) 1500×

Fig.3 SEM micrograph of depositional crust. (O.M.) 2000×

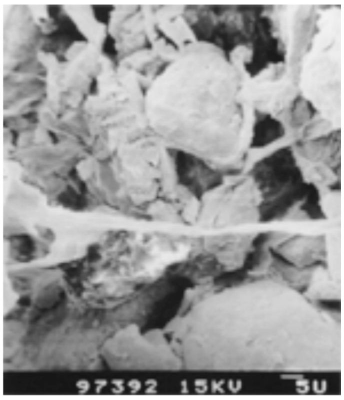

Fig.4 SEM micrograph of soil treated with PAM. (O.M.) 1500×

Structural crust is formed by the rearrangement of soil particles in situ and compacted pilingup of soil materials at surface of soil due to the impacts of raindrops. The process is demonstrated by the SEM micrograph of the crust (Fig. 1). Fig. 1 shows the micrograph of structural crust formed under the conditions of rain intensity 50 mm •h^{-1}, and slope of 8.74%. Due to the continued impact of raindrops, the big aggregates were broken down into small individual particles. At the same time, soil particles come to shake and displace at surface of soils in situ, during the process of shake and displacement, soil particles appear to have a trend to readjust themselves to stable state. The compacted layer at soil surface, soil structural crust, was formed with the soil particles contacted tightly.

Depositional crust is formed due to the movement, deposition, and clog of particles, which involve external materials into its construction. The effects of clog and deposition are also demonstrated respectively by the SEM micrographs of the crusts (Fig. 2 and Fig. 3). Fig. 2 is the micrograph of depositional crust formed also under the conditions of rain intensity of 50 mm •h^{-1}, and slope of 8.74%. In this micrograph, the phenomenon that fine external particles clog the pores of soil is showed clearly. Fig. 3 is the micrograph of depositional crust formed under the conditions of rain intensity 150 mm • h^{-1}, and slope 17.63%. It is evident from Fig. 3 that the pores lodge the external fine materials. Although both Fig. 2 and Fig. 3 demonstrate the features of depositional crust, the external materials in structure of crust reflect different “washed in” processes of soil particles. In Fig. 2, fine particles clog pores of soil due to moving in with rain permeating in soil, or due to splashing by raindrops. In Fig. 3, fine particles are captured by soil pores because the surface of pore is a unbalanced double layer of positive and negative charges [20]. When flow entrained fine particles infiltrates into soil, the velocity of flow will be reduced sharply. The kinetic energy of particles will also be reduced, so the adsorption and reaction of cation exchange are easy to occur.

The micrograph features of Fig. 2 and Fig. 3 are quite different from Fig. 1. From the SEM micrographs of the crust, the effect of rain and runoff on soils was demonstrated. The impact of rainfall drops caused in situ movement of soil particles to form structural crust, and splash of raindrop and chemical dispersion caused downward movement of soil particles into pores to form depositional crust.

PAM treatment of soil surface prevents disintegration of soil aggregates and improves soil structure. Well-aggregated soil surfaces were observed on the SEM micrograph of soils treated with PAM. The effect of PAM treatment with coverage rate 80% is shown in Fig. 4, which shows the morphological features of the “non-crusted” upper layer of soil, being subject to rain intensity of 50 mm • h^{-1}, and slope of 46.63%. The SEM micrograph of the upper layer soil treated with PAM did not show fine particles clogging or deposition in pores, whereas it is easy to find that a lot of flocci of PAM spread at upper layer soil. Flocci of PAM have very strong bonds to contract particles of soils together, which is very important to increase the stability of aggregates, or to form new and bigger aggregates in soils. The disintegration of aggregates, clogging and deposition of disintegrated particles, is the basic condition of crust formation. The flocculation of PAM, seeming to be like “chemical bond” to hold particles together, produce stable structure of soils and present soils with resistance to erosion.

2 Infiltration and crust

As illustrated above, crust occurs in soils of control, and no crust in soils treated with PAM. The comparison of infiltration rate curve of crusted soil with that of non-crusted soil reveals the processes of sealing. The phenomenon of sealing during rainfall is a very complex process and is influenced by many factors, including intensity and energy of rainfall, slope, stability of aggregates and soil texture. In many literatures, there is no strict distinction between sealing and crust. Remley and Bradford (1989) defined sealing as the initial phase or wetting phase in crust formation, crusting as the subsequent drying phase [14]. In fact, sealing is a process of reducing infiltration, including a series of physical and chemical actions, such as compacting at soil surface due to impact of raindrops, clogging pores and depositing clay particles at soil surface. And crust is the effect of sealing, which is a thin layer with greater density, higher shear strength, and lower hydraulic conductivity than the underlying soil.

The change in infiltration rate with time or cumulative rainfall reflects the process of sealing. The soil infiltration rate is limited by sealing, which acts like a valve at surface layer of soil. Fig. 5, 6, and 7 are infiltration rate curves for the control and PAM treatments subject to different conditions. These figures show infiltration rates in control is much lower than those of soil treated with PAM, and the bigger the coverage rate of PAM is, the higher the infiltration rate.

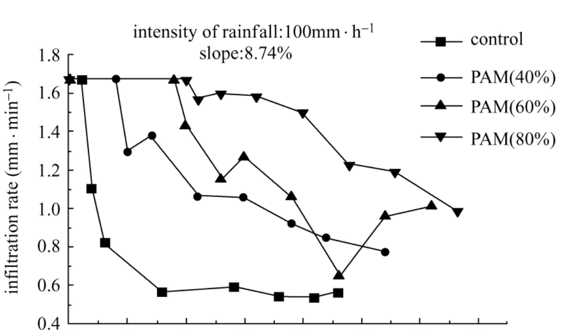

Fig.5 The infiltration rate curves vs. time under different PAM treatment (rainfall intensity: 100 mm • h^{-1}, slope: 8.74%.)

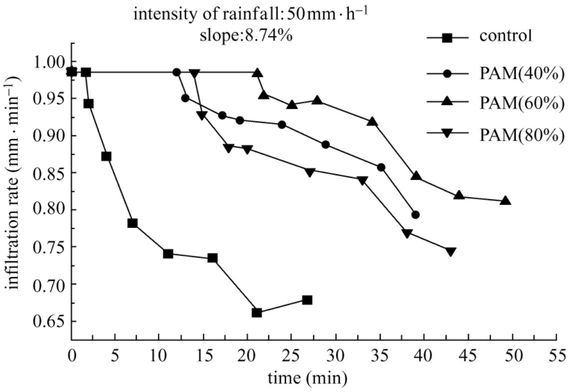

Fig.6 The infiltration rate curves vs. time under different PAM treatment (rainfall intensity: 50mm • h^{-1}, slope: 8.74%.)

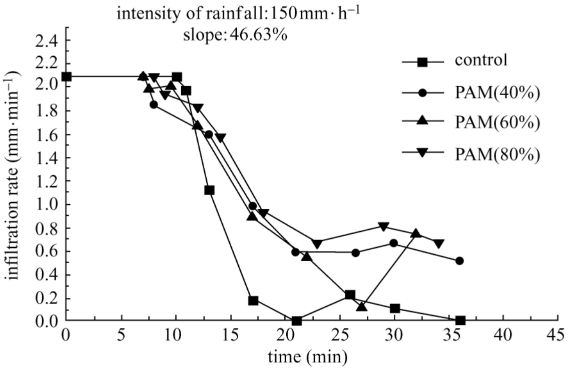

Fig.7 The infiltration rate curves vs. time under different PAM treatment (rainfall intensity: 150mm • h^{-1} , slope: 46.63%.)

From the infiltration curves, some people provided a three-phase model of crust formation [8, 13, 18, 21]: (1) from the start of rainstorm to the occurrence of runoff; (2) from initial runoff to the steady state of runoff; (3) from steady runoff to the stop runoff. Our experiments also confirmed the model. As it is shown in Fig. 5, the infiltration rate curve with time in control appears clearly the feature of the three-phases. The different action of sealing predominates in different phase. From the beginning of rainfall to runoff initiation is the first phase of sealing. At this stage, the rainfall intensity is lower than the infiltration rate, in other words, the infiltration rate equals to the rainfall intensity. The impact of raindrops is the dominant action of sealing. This phase for soil treated with PAM extends dramatically. From initial runoff to the steady state of runoff is the second phase of sealing. The infiltration rate in the control treatment declined rapidly with time, implying the rapid formation of crust, while the infiltration rate in the PAM treatments declined slowly with time, implying the prevention of PAM of sealing. At this stage, the plugging or deposition of fine particles predominates in action of sealing. From steady runoff to the stop runoff is the third phase, At this phase, infiltration rate reaches its steady state, the action of sealing is balanced with suction gradient of soil.

In addition, the post-rainfall phase should be paid attention to. It is the last stage of crust formation, it may be called as the forth phase of crust. This phase is of significance in crust formationt, because when rainfall stops, the sediment still remains at soil surface in ponded water. When ponded water infiltrates into soil, all sediments deposit at surface of soil to form crust.

3 Conclusions

Comparing the micromorphology of soil surface layer of the control with those treated with polyacrlamide (PAM), evidences were found that soil crusts are formed by depositional crust and structural crust. The conceptual model of soil crust has two main complementary processes: (1), physical disintegration of soil aggregates and soil compaction caused by raindrops, and (2), chemical dispersion and movement of particles that clog the conducting pores and form a less permeable layer below soil surface.

The infiltration curves for different treatments with time indicated the processes of seal formation. Seals were the processes of crusts, on the contrary, crusts was the effect of seals. The infiltration curves showed that there are four stages of crust formation: (1) from the start of rainstorm to the occurrence of runoff; (2) from initial runoff to the steady state of runoff; (3) from steady runoff to the stop runoff; and (4) infiltration of ponded water.

References

[1] Smith H J C, Levy G J and Shainberg I. Water-droplet energy and soil amendments: effect on infitration and erosion. *Soil Sci. Soc. Am. J.*, 1990. **54:**1084-1087.

[2] Gal M, Arcan L, Shainberg I, *et al*. Effect of exchangeable sodium and phosphogypsum on crust structure —Scanning electron microscdpe observations. *Soil Sci. Soc. Am. J.*, 1984.**48:**872-878.

[3] Helalia A M, Letey J, Graham R C. Crust formation and clay migration effects on infiltration rate. *Soil Sci. Soc. Am. J.*, 1988.**52:**251-255.

[4] Beh-hur M and Letey J. Effect of polysaccharides, clay dispersion, and impact energy on water infiltration. *Soil Sci. Soc. Am. J.*,1989. **53:**233-238.

[5] Duley F I. Surface factors affecting the rate of intake of water by soils. *Soil Sci. Soc.Am. Proc.*, 1939.**4:**60-64.

[6] Morin J and Van Winkel J. The effect of raindrop impact and sheet erosion on infiltration rate and crust formation. *Soil Sci. Soc. Am. J.*, 1996.**60:**1223-1227

[7] Bissonnris Y L,.Fox D, Bresson L-M.. Incorporating crusting processes in erosion models. NATO ASI Series, Vol.155.p237-246. Modelling soil erosion by water. Edited by John Boardman and David Favis-Mortlock.© Springer-Veriag Berlin Heideberg 1998.

[8] Onofiok O and Singer MJ. Scanning electron microscope studies of soil surface crusts formed by simulated rainfall. *Soil Sci. Soc. Am. J.*, 1984.**48:**1137-1143.

[9] Giménez D, Dirksen C, Miedema R, *et al*. Surface sealing and hydraulic conductances under varying-intensity rains. *Soil Sci. Soc. Am. J.*, 1992.**56:**234-242.

[10] Levy G J, Levin J L and Shainberg I. Seal formation and interrill soil erosion. *Soil Sci. Soc. Am. J.*, 1994.**58:**203-209.

[11] Agassi M, Shainberg I and Morin J. Effect of electrlyte concentration and soil sodicity on infiltration rate and crust formation. *Soil Sci. Soc. Am. J.*, 1981. **45:** 848-851.

[12] McIntyre D S. Permeability measurements of soil crust formed by raindrop impact. *Soil Sci.*, 1958.**85:**813-817

[13] Cai Q G，Wang G P and Chen Y Z. Process and simulation of small watershed soil erosion in Loess Plateau.Beijing: Science Press.1998. (in Chinese)

[14] Remley P A and Bradford J M. Relationship of soil crust morphology to inter-rill erosion parameters. *Soil Sci. Soc. Am. J.*, 1989. **53:**1215-1221.

[15] Aly S M and Letey J. Physical properties of sodium-treated soil as affected by two polymers. *Soil Sci. Soc. Am. J.*, 1990.**54:**501-504.

[16] Ben-hur M, Letey J and Shainberg I. Polymer effects on erosion under laboratory rainfall simulator conditions. *Soil Sci. Soc. Am. J.*, 1990. **54:**1092-1095.

[17] Nadler A, perfect E and Kay B.D. Effect of polyacrylamide application on the stability of dry and wet aggregates. *Soil Sci. Soc. Am. J.*, 1996. **60:**555-561.

[18] Chen Y, Tarchitzky J, Brouwer J, *et al*. Scanning electron microscope observations on soil crusts and their formation. *Soil Sci.* 1980.**130:**49-55.

[19] Bresson L M and Cadot L. Illuviation and structural crust formation on loamy temperate soils. *Soil Sci. Soc. Am. J.*, 1992.**56:**1565-1570.

[20] Marshall T J and Holmes J W. Soil physics. © Cambridge university press. 1988.

[21] Moore D C and Singer M J. Crust formation effects on soil erosion processes. *Soil Sci. Soc. Am. J.*, 1990. **54:**1117-1123.