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DEGRDATION, REHABILTATION, AND CONSERVATION OF SOILS

Effect of the Water Temperature and Soil Moisture on the Erodibility of Chernozem Samples: A Model Experiment

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Abstract—The close almost functional relationship of the erosion rate and, hence, the erodibility of model soil samples with the temperature of the water used in the experiments has been shown. This suggests that the rupture of bonds between the particles of eroded soil samples is due to the electrostatic forces appearing between the monomolecular water layers around the adjacent soil aggregates similarly oriented with respect to the soil solid phase rather than to the hydraulic forces. The erosion parameters of the samples also strongly depend on the soil moisture. The lowest erosion rate of the heavy loamy chernozem samples is observed at an initial water content of 22–24%. The erosion rate increases and the variability of the results is reduced with both decreasing and increasing the initial water content.

Keywords: interaggregate bonds, electrostatic bonds, rupture of interaggregate bonds, van der Waals rule
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INTRODUCTION

The assessment of the erosion resistance and erodibility of soils and the mechanisms of soil erosion by shallow surface flows are fundamental problems of erosion science, the studies of which have an almost century-long history. Rotating cylinders [16] and hydrodynamic tubes [13] are used for this purpose. The basic experiments are performed in seepage tanks of different types [2, 3, 10–16]. The studies of the mechanisms of particle detachment and the erodibility of soil in seepage tanks allow one to relatively strictly control the hydrological conditions and water–physical parameters of a soil under the experimental conditions. Nonetheless, the obtained results are characterized by high variability. For example, in the work of Nearing et al. [16], the rate of erosion varied in a wide range in spite of the thorough standardization of the procedure for preparing the model soil samples. The mean variation coefficients of the results of two experimental series with different soils were 44.6 and 50.4%. The variability decreases to 18.9–34.5% in the experiments with the high erosion rate and increases (to 100% and more in some cases) at the low erosion rare.

This situation can be related to the visual determination of the end of the experiment. Nearing et al. [16] shaped the samples in a metal ring 12.7 cm in diameter. The thickness of a sample was about 2 cm. Separate large gullies with vortices were formed because of the large diameter of the sample, and the surface of the sample becomes broken, which results in significant changes of the erosion conditions. To avoid the nonuniformity of the erosion conditions, the experiment was stopped at the moment when approximately similar amounts of soil were washed out before the formation of large gullies in all the experiments, which obviously resulted in the subjective estimation of the erosion time. To exclude this factor of variability in our works [5–7], we continued the experiment to the complete erosion of the sample; the surface of the soil was maintained at the level of the seepage tank bottom by extruding the soil from the container with a pusher moved by means of a special screw, and the relative uniformity of the surface of the soil was ensured by reducing its area to 14 cm^2 (2 × 7 cm).

Another factor of the high spread of the experimental data on the erosion of soil is the temporal nonuniformity of the erosion, as was evidenced by visual observations. The long periods of stability of the soil sample alternate with those of the intense detachment of the soil particles. Such periodicity is clearly manifested at the low velocities of the water flow. Entire layers, rather than separate aggregates, are usually detached from the surface of the sample by the flow. The new methodology allowed reducing the variability of the results caused by the subjective determination of the end of the experiment and by the nonstationary detachment of soil particles by the water flow. For example, in the study of the erodibility of the model chernozem samples of different densities [6], the variability was significantly lower than in the above-mentioned experiments of Nearing et al. [16] and varied in the range from 15.5 to 27.0%. To reduce the variability of the experimental results, the procedure of preparing the soil samples for tests was also modified [5–7]. To avoid the nonuniform compaction of soils in the container, the sample was visually separated into four equal parts, which were successively placed into the container and compacted by means of a plunger with the surface regularly patterned with truncated pyramids 1.5–2 mm in height, whose faces are inclined at 60°. On the lateral sides of the plunger, four marks indicated the plunger positions ensuring the target density in each of the soil portions. However, observations of the soil erosion showed that the adhesion between the adjacent layers is lower than that within each portion in spite of the measures undertaken to increase the contact area between the adjacent layers. A wavy surface was frequently formed on the entire surface of the eroded soil after the removal of a layer because of the compaction of the soil portion with the patterned plunger surface. Therefore, the layering of the soil into the container followed by its compaction with a screw press was not used in the further studies. The sample was thoroughly mixed on parchment paper, transferred to the container, leveled, and manually compacted with a pestle of square section after the addition of each portion. The last portion was packed in an extension installed onto the container and also leveled. Then, the plunger, the height of which was equal to the height of the extension, was inserted into the extension and completely recessed with a screw press. To decrease the nonuniformity of the compaction of the sample, its height was reduced to 2 cm. However, the variability of the erosion rate and, hence, the erodibility remained relatively high: 15–27% [6].

Further search resulted in the idea that the variability of the results in the study of model soil samples can also depend on the temperature of the water in the seepage tank and the water content of the soil material from which the model samples were shaped. It is known that, when the temperature rises, the viscosity of the water decreases and, hence, the hydraulic resistance to the water flow should decrease; consequently, the velocity of the water flow will increase with all the other conditions being equal. However, according to the third law of Newton, the impact of the flow on its bed and the surface of the soil sample remains constant in our case; therefore, no change in the rate of erosion of the sample can be expected. At the same time, single observations indicated that the rate of the soil erosion appreciably increases with a rise in the water temperature, which can, in turn, significantly affect the variability of the erosion rate of the soil samples, because the temperature of the water in the seepage tank varies in a relatively wide range because of the transformation of the mechanical energy (which is transferred to the water by the pump) into thermal energy.

It can be also supposed that the water content in the soil used for the preparation of the model sample will affect the cohesion between the soil particles and, hence, the rate of the erosion and erodibility.

In view of the aforesaid, the aim of this work was to study the effect of the water temperature and the water content in the soil used for the preparation of the model soil samples on the rate of their erosion.

MATERIALS AND METHODS

In our work, the erosion of soil samples was caused by a downward vertical jet of water, in distinction from the conventional seepage tanks used under laboratory conditions for studying the erosion properties of soils. When the jet of water encounters an obstacle whose surface is perpendicular to the axis of the jet the water uniformly spreads over the surface from the point of intersection with the water jet referred to as the stagnation point [4]. In thermodynamics, the velocity of the water spreading over the surface perpendicular to the axis of the water jet is taken equal to the velocity of the water jet falling; at the stagnation point (the center of the jet), it is taken equal to zero. The use of soil erosion by a falling water jet in our experiments is related to two reasons. The first is of technical nature. The unit for soil erosion by a falling water jet is very compact. It requires only 4–5 m^2 for the installation and operation, which can be a deciding factor when there is a deficit of space. On the other hand, this unit is suitable for testing soil samples at high velocities (up to the terminal velocity of falling water observed in high gully heads and even higher) that are inaccessible in seepage tanks. The data on the soil erosion in such a wide range of velocities under a falling water jet will be useful for revealing the mechanisms of the processes occurring at the study of the detachment of soil particles by a water flow and those of soil erosion in plunge basins at gully heads. Mirtskhulava [10] used the above concepts of the spread of a falling water jet over the bottom surface for the development of the equation of soil and sediment erosion in a gully head.

The unit for the erosion of soil samples used in our work is schematically presented in Fig. 1. To protect the observer from water drops, items *4, 5*, and *6* are covered with a dense polyethylene film in the form of an unfolded truncated cone. At the top, it is fixed with clips to the pipe feeding the water to a nozzle of square section (4 cm^2); its lower part is sunk into the container for the water (a polyethylene barrel). A dense nonwoven filter in the form of a truncated cone is installed in the barrel to exclude the contact between the major part of the surface of the filter and the internal surface of the water container (*8*). The filter is designed for retaining particles of the eroded samples, because the suspended sediments decelerate the erosion of the soil due to the silting of pores, which increases the adhesion between the particles on the surface of the soil and, hence, reduces the rate of the

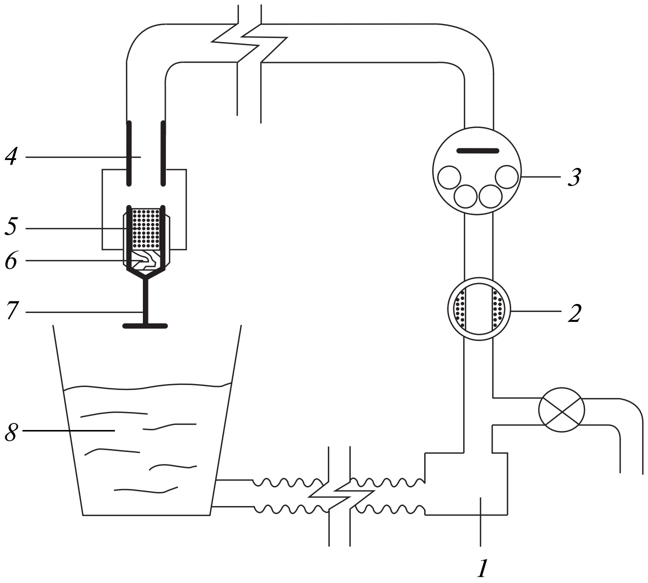

Fig. 1. Diagram of the unit for studying the degradation of soils and sediments under the impact of a water jet: (*1*) pump; (*2*) plug valve; (*3*) flow meter; (*4*) nozzle of the square section, (*5*) cartridge with soil samples; (*6*) plunger; (*7*) feed screw; (*8*) container for water. Items *5, 6*, and *7* are combined into a block that can be linked to item *4* through the frame with two screws (at the left and right sides) and rotate around these screws in the plane perpendicular to the diagram plane.

soil erosion [7]. Screw *7* designed for extruding the soil sample from the container is put in motion through a flexible shaft, which runs up to the external surface of the barrel in its upper part and terminates with a handle; the observer turning the handle maintains the surface of the soil at the level of the rim of the barrel. The state of the surface of the soil cannot be reliably assessed due to the splash of water against the sample. To improve the visibility of the surface of the soil in the container, the jet of water is covered with an elastic band of transparent celluloid slightly wider than 2 cm. The pressing of the band to the container in the zone of the impact of the jet can eliminate the spread of water from the side of the observer, which enables the reliable monitoring of the erosion of the sample. The lighting of the zone of the jet impact with a miniature light emitting diode lamp further increases the visual observability of the process, including the detachment of separate soil particles, and improves the conditions for photographing the profile of the eroded soil sample. A typical profile of an eroded sample is given in Fig. 2. The profile is characterized by a volcano-like shape with a peak in the place of the crater. The peak apparently corresponds to the stagnation point.

The reason for the appearance of the concave surface forms is not clear. The following supposition can only be made. A possible reason can be that, contrary to the theoretical premise that the velocity of the spreading of the water jet over the surface perpendicular to its axis is equal to the velocity of the water in the jet, the velocity of the spreading does increase with the distance from the stagnation point and the profile of the eroded soil sample acquires a biconcave shape. Another explanation of the volcano-shaped profile of the eroded sample can be as follows. The water jet exerts a dynamic pressure on the surface of the soil sample with the pressure being apparently maximum at the stagnation point and decreasing to the periphery of the surface of the sample. According to Makkaveev [9], an effect of inhibition can be manifested as the deceleration of the detachment of the soil particles by the flow with the increase in hydrostatic pressure with all the other conditions being equal. The dynamic pressure can have a similar effect. Consequently, its decrease to the periphery of the sample should result in an increase in the detachment velocity of the soil particles from the surface of the sample when going from the center of the sample (stagnation point) to the periphery.

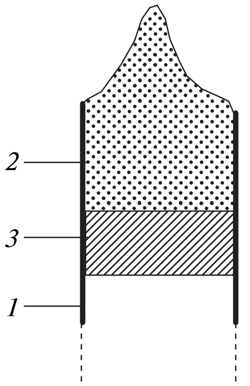

Fig. 2. Typical section plan along the vertical axis of the soil sample eroded by the falling water jet: (*1*) container wall; (*2*) soil; (*3*) plunger.

As in our previous works, two fractions were used for the experiment: the fraction of 0.5–2 mm and that of <0.5 mm at a ratio of 6 : 1; the fractions were prepared by the dry sieving of a heavy loamy chernozem taken from the plow horizon in the Volovo district of Tula oblast. All the experiments were performed with model soil samples of the same density (1.4 g/cm^3) at a constant jet velocity of 1.42–1.43 m/s. The effect of the water temperature on the erosion rate was studied in the range from 0 to 30°C. The water temperature was measured with an interval of 5°C. The water temperature was maintained at the target level with an accuracy of ±0.5°C by adding hot water or snow. The soil samples were prepared from the soil portions wetted with water to 24% and exposed in weighing cups for 10–12 h.

The effect of the water content in the soil used for preparing the experimental samples on the erosion rate was studied at a constant temperature of 20°C at the same jet velocity and sample densities as in the former case. The water content in the soil was varied in the range from 16 to 30% with an interval of 2%. After wetting to the target water content, the samples were exposed in weighing cups for 10–12 h. In each container for the samples with an internal size of 17 × 71 × 60 mm, a pusher with a section of 17 × 17 mm and a height of 30 mm was inserted after its covering with white paper so that the appearance of the paper in the vision of the observer was a signal to stop the timer. The height of the model soil sample was 30 mm. The experiments were performed in 5 to 10 replicates.

The erosion rate was determined as the quotient of the sample weight (g) by the erosion time (s) per unit of surface area (m^2). The erodibility of the model samples was calculated by dividing the erosion rate by the cubed jet velocity and the water density, as was proposed in the hydrophysical model of erosion in [8].

Table 1. Effect of the water jet temperature on the erosion rate and erodibility of soil

Water temperature, °C	Replicate	Soil erosion rate			Soil erodibility		
		M	σ	*Cv*, %	*M*	σ	*Cv*, %
		g/(s m^2)			m^{-2} s^2		
0	5	27.5	8.6	31.2	9.5	2.9	30.0
5	5	38.9	10.2	26.3	13.3	3.5	26.4
10	5	52.9	10.5	19.9	17.7	3.5	19.8
15	5	63.1	22.8	36.2	21.3	7.6	35.9
20	5	86.2	29.3	34.0	29.3	10.1	34.4
25	4	104.8	31.6	30.1	36.6	11.5	31.3

Here and in Table 2, *M* is the mean value, σ is the standard deviation, and *Cv* is the coefficient of variation.

RESULTS AND DISCUSSION

The results of studying the effect of the temperature of the vertical water jet on the erosion rate and erodibility of the samples are given in Table 1 and Fig. 3a. The extremely high effect of the water temperature on the erosion rate of the model soil samples is first conspicuous. This phenomenon cannot be related to the decrease in the water viscosity with the rise of the temperature. From the general considerations, the decrease in the liquid viscosity should lead to an opposite effect, because the impact of the water flow on the substrate should decrease in this case.

The calculation of the soil erosion rate in the entire studied temperature range with an interval of 10°C gives the following series: 1.93, 1.62, 1.63, and 1.66, which well agrees with the Van't Hoff rule, according to which the rate of a chemical reaction in gaseous and liquid mixtures increases by 2–4 times when the temperature rises by 10°C. This rule follows from the kinetic theory of gases: the frequency and strength of the molecular collisions in a gas mixture, which can result in a chemical reaction, increases with the temperature, which suggests that the water temperature can significantly affect the detachment of soil particles by the water jet. This supposition can be explained as follows. Water molecules are dipoles, and soil particles can carry electrical charges on their surface; therefore, the molecules touch the surface of the particle by the oppositely charged side. The following layer of water molecules joints the first layer also by the opposite sides of its dipoles, etc. Analogous phenomena can be expected for the adjacent soil particle. Then, the layers of water molecules attracted to the adjacent soil particles will face with the similar ends of their dipoles and, hence, repulse, which can cause the decrease and (or) complete adhesion of the adjacent soil particles. The velocity of the water molecules increases with the water temperature; therefore, the relationship

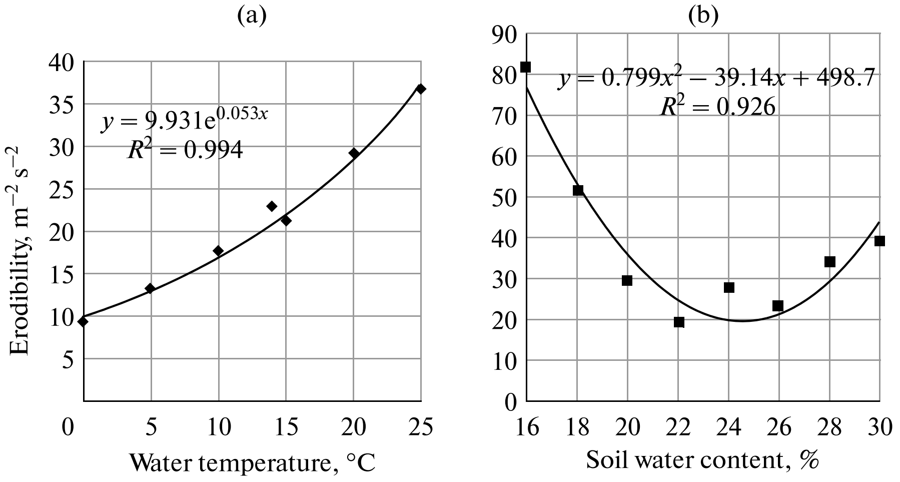

Fig. 3. Erodibility of model soil samples as a function of (a) the water jet temperature and (b) the soil water content.

Table 2. Effect of the water content on the erosion rate and the erodibility of the soil

Water temperature, °C	Replicate	Soil erosion rate			Soil erodibility		
		M	σ	Cv, %	M	σ	Cv, %
		g/(s m^2)			m^{-2} s^2		
16	5	237.5	33.3	14.03	81.8	11.1	13.6
18	5	151.6	31.5	20.7	51.7	10.7	20.7
20	5	85.8	16.6	19.3	29.4	5.9	20.0
22	10	57.5	13.2	23.0	19.7	4.8	24.4
24	10	82.1	22.2	27.0	28.2	7.6	27.0
26	5	68.6	18.2	26.5	23.5	6.5	27.7
28	5	98.2	12.2	12.4	34.0	4.5	13.2
30	5	112.7	7.3	6.45	39.2	2.7	6.9

between the rate of the soil erosion and the water temperature well agrees with the Van't Hoff rule.

As for the effect of the water temperature on the variability of the results of determining the erosion parameters of the soil samples, it was demonstrated that its studies should be performed under the strict control of the water temperature, which strongly affects the erosion rate of soil or at least the artificially shaped soil samples. At the same time, the maintenance of the temperature within the range ±0.5°C had no significant effect on the variability of the studied erosion parameters. The coefficients of variation fall within the ranges found in our previous works [5, 6, 8]. It is possible that the erosion parameters should be determined under even more strict control of the water temperature. At the same time, it should be noted that the data on the temperature of the water in the seepage tank should be also presented in the publications on the determination of the erosion properties of soils so that the reader can compare the results of different authors with the correction for temperature.

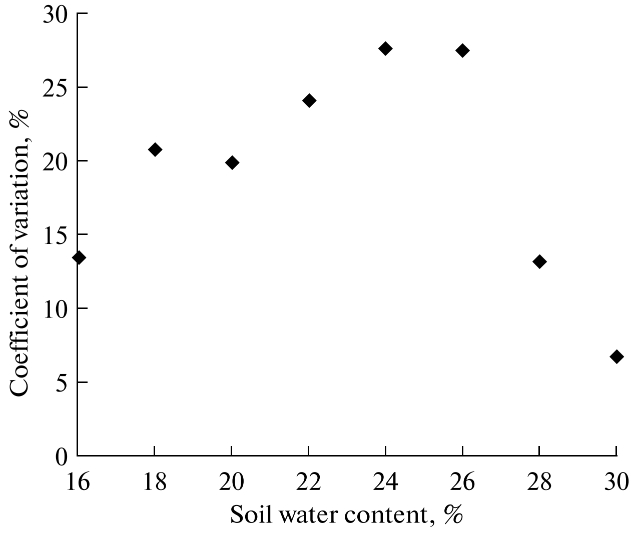

Fig. 4. Variability of the erodibility as a function of the water content of the model soil samples.

The results of studying the effect of the water content in the soil used for the preparation of the experimental samples on their erosion properties are given in Table 2 and Figs. 3b and 4. This series of experiments showed that the model samples shaped from the soil material containing 22 and 24% water have the minimum erosion rate and, hence, the minimum erodibility, which indicates the attainment of the maximum cohesion between the aggregates possible in the studied soil samples. In most of our earlier works devoted to studying the erosion properties of model soil samples, the amount of water necessary for reaching a water content of 24% was added to the sample. The heavy loamy chernozemic soil with this water content on a loess-like loam is plastic; after compaction, it agglomerates and retains the shape acquired. This water content is optimum in both technical and substantive terms. The erosion rate of the model samples increases and the variability of the results decreases with both increasing and decreasing the water content of the soil sample, as was noted by Nearing et al. [16]. The maximum decrease in the variability (to 6–7%) is observed for the soil sample containing 30% water. The mean rate of the soil erosion is 112 g/(m^2 s) in this case. At the same time, the variability of the erodibility is higher at the low water content of the samples (13–54%), although the rate of erosion for these samples exceeds that for the samples with 30% water. It follows that the uniformity of the erosion and the low variability of the results depend not only on the rate of the process but also on some other factors. It can be supposed that these factors include the isotropicity of the cohesion between the soil particles in the sample.

If this supposition is correct, the samples shaped from the relatively dry soil (16%) should be characterized by lower isotropicity than the samples shaped from the soil with 30% water. This could be related to the behavior of the soil particles under compaction. At the compaction of the relatively dry soil, the aggregates are of low plasticity; they are degraded and not deformed under compression. At the high water content, the aggregates are not only plastic; it cannot be excluded that, due to the presence of water acting as a lubricant in this case, they are capable of moving not only along the compression line but also at some angle. This can result in the uniform distribution of aggregates in the sample, which should increase the isotropicity of the cohesion between the aggregates.

As for decreasing the variability of the erosion parameters of the model soil samples, the only possibility is an increase in the accuracy of reaching the target water content of the samples.

CONCLUSIONS

The results of determining the erosion parameters of model soil samples showed that, with all the other conditions being equal, the rate of the soil erosion strongly depends on both the temperature of the water used in the experiments and the initial water content of the soil used for the shaping of the experimental samples; therefore, these parameters should be maintained in as narrow a range as possible to decrease the variability of the erosion rate and the erodibility of the samples.

The effect of the water temperature on the erosion rate and erodibility of the soil was unexpected and inexplicable from the hydraulic principles. The similarity to the relationship between the soil erosion rate and the water temperature to the Van't Hoff rule for the temperature dependence of reaction rates in solutions and gases allows supposing the rupture of bonds between the soil particles by the electrostatic (and not hydraulic) forces: the mutual repulsion of the monomolecular water layers around the adjacent soil particles similarly oriented with respect to the solid phase. The formation rate of these similarly oriented monomolecular water layers around the soil particles depends on the velocity of the liquid molecules, which is in turn determined by the temperature; therefore, the erosion rate of the soil or, more precisely, the rate of rupture of the bonds between the soil particles is described by a temperature dependence based on the Van't Hoff rule.

In view of the aforesaid, the erosion parameters of the soil or at least the erosion parameters of the model soil samples should be studied at a standard temperature. A temperature of 20°C can be taken as the standard temperature, as is customary at the determination of the physical properties of liquids in physics. Otherwise, the water temperature should be indicated in the publications so that the reader can apply temperature corrections.

The maximum erosion stability is typical for the model samples shaped from a heavy loamy chernozem (on loess-like loams) with 22% water. As was shown by
1 Vasilenko [1], this value depends on the particle size and mineralogy of the soil; therefore, it can vary among the soils. At the current level of knowledge, it can be determined only experimentally.

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