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Preferential water flow, local soil biota and structure degradation in chernozem 20 years after land-reclamation**,***

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Abstract. Technogenic soils (technozems) were created nearly 20 years ago in open-cast ore mining and have been in agricultural use since that time. Land reclamation consisted in creating a 60 cm chernozem soil layer above a thick sand layer. Dramatic changes occurred in the soil structure of the chernozem layer: typical granular soil aggregates of 1-5 mm in size transformed into coarse prismatic 50 mm peds with flat or rounded surface and columnar 100 mm vertically oriented blocks covered with brown coatings. The coatings on ped faces at the depths of 20-40 and 40-60 cm had an increased content of Fe and Ca ions, and the soil texture became coarser under conditions of alkaline medium. Study of the soil water regime showed the formation of temporary perched water above the sandy layer during intensive spring and summer rainfalls. Field starch tracer experiments revealed the existence of preferential water passageways through the chernozem layer. The vertical preferential flow occurred along the block surfaces downward, saturated the blocks and created favourable conditions for the soil gleyzation inside the ped, and for anaerobic microbiota formation (*Clostridium limosum, Cl. supterminal* and others); after a period of the preferential flow functioning the period of ped draining began and aerobic microbiota (*Rhodococcus terrae*) were developed on the surface of the ped. Such a distribution and functioning of soil biota favour the movement of Fe-ions to the surface of peds, the appearance of coatings, and the formation of prismatic coarse peds.

Keywords: soil, preferential water flow, degradation of soil structure, land-reclamation, soil biota

INTRODUCTION

The problem of land reclamation and rehabilitation of disturbed soils is one of the pressing problems in the world. Reclamation technologies include, in particular, works on the restoration of the fertile humified soil layer *via* application of material of soil humus horizons preliminarily removed from the surface upon the territory preparation for mining works (Gerasimova *et al*., 2003). To apply this material as the fill, plots are subjected to surface levelling. Rehabilitation of the disturbed lands of technogenic landscapes has a nonrecurring character and includes a number of technological procedures, including fertilization. Further works on the ecological monitoring of reclaimed soils are rarely performed (Abakumov and Gagarina, 2003). At the same time, significant changes in the agrophysical properties of such soils may take place upon their exploitation, and result in the development of soil degradation. The essence of the physical processes leading to degradation of reclaimed soils upon their exploitation remains poorly known.

The aim of the work was to study the physical and biological properties, processes and structure degradation in artificially created layered technogenic soils (technozems).

MATERIALS AND METHODS

The object of the study was technogenic soils formed within the reclaimed area of a former sludge pond, the sand-chalk mixture being covered with a thick layer of loess-like loam. After drying of the sand and loam, the material of the humus horizon of a typical chernozem was used as a fill. It was applied in the dry state. The thickness of the applied chernozemic layer was about 60 cm. In 1986, an artificial layered soil was created on the former sludge pond surface. After that, the area was involved in agricultural use.

A soil profile was excavated in the south-western part of the former sludge pond. The technozem included the following layers:

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- layer I (0-22 cm): dark grey heavy loamy plough horizon with fine crumb structure and smooth lower boundary, numerous roots oriented in both vertical and horizontal directions;
- layer II (20-26 cm): dark grey heavy loam, crumb-granular structure, smooth boundary, some aggregates of up to 5 mm in diameter;
- layer III (26-35 cm): brownish dark grey heavy loam, angular blocky, the size of peds increases down the soil profile; abundant roots of predominantly vertical orientation;
- layer IV (35-60 cm): brownish dark grey heavy loam, coarse angular blocky structure with ped diameters of 20-40 mm, ped faces covered with brown coatings. In the lower part, the columnar-prismatic structure is clearly seen; roots stretch along the vertical faces; the columnar aggregates are relatively loose and can be mechanically destroyed into separate fragments;
- layer V (> 60 cm): sand layer, in some places, fragments of a thin (1-2 cm) crust can be seen on the sand surface. This crust could be formed on the sand surface due to the uneven deposition of the sand pulp.

The soil bulk density, solid phase density, and aggregate-size distribution were analysed by routine methods (Shein, 2001; Vadyunina and Korchagina, 1986). The coefficients of water infiltration for separate layers were obtained according to the Horton equation from the results of infiltration tests with the method of water tubes with variable head, which made it possible to estimate the coefficients of infiltration (unsaturated hydraulic conductivity) in the area close to the saturated hydraulic conductivity (Shein, 2005; Shein and Karpachevskii, 2007). The particle-size distribution analysis was performed with the method of laser diffractometry on an Analysette 22 NanoTec device after the pretreatment with 4% $Na_4P_2O_7$ and ultrasonic dispersion.

The results of soil analyses (Mineev, 2001) demonstrated alkaline reaction of the soil mass and the absence of a clear differentiation of organic matter and carbonates in the soil profiles (Table 1).

The elemental composition of brown films on the surface of peds was determined by laser spectrometric analysis. The measurements were performed in seven replications, and the area of measurement points was about 1 μm^2. Element spectra with characteristic peaks of separate elements were obtained.

In order to study preferential water flows in the soil, the method of starch label (Ananeva, 2004) was applied in a field experiment. Frames of 16 cm in diameter were installed on the soil surface and filled with 2% starch solu- tion. There were two variants of the experiment. In the first variant, the frames were initially filled with water (about 5 l/frame), after which the starch solution was applied. In the second variant, starch solution was applied without the preliminary filtration of water, which made it possible to trace the formation of water flows in the studied technozems at the initial stage. After the end of the starch solution infiltration the soil was cut down in 5 to 10 cm thick layers; on their horizontal surfaces (after cutting of the overlying layer), the pattern of water flows was fixed via staining the remaining starch with iodine water. The morphology of such sections was described, and the distribution of starch label was recorded with a digital camera. For the control, it was also plotted on polyethylene films. Then, the areas of starch-impregnated mottles were determined.

The investigations of soil biota structure of the chernozemic layer were realized by means of Gas Chromatography Mass Spectrometry (GC-MS) (Osipov, 1994).

Table 1. Some physical and chemical properties of technozem

Layer (cm)	Bulk density (g cm^{-3})	Soil particle density (g cm^{-3})	K_{inf} (cm min^{-1})	Σ WSA (>0.25 mm, %)	Grain size distribution (%, dia in mm)			pH_{H_2O}	C_{CaCO_3} (%)	C_{org} (%)
					0.05-1	0.002-0.05	<0.002			
0-10	1.04	2.62	0.72	60.4	4.37	75.26	20.37	8.73	0.69	2.99
10-20	1.22	2.65	0.63	61.4	3.91	76.22	19.87	8.74	0.73	2.87
20-30	1.28	2.67	0.44	71.4	3.03	76.78	20.19	8.75	0.77	2.98
30-40	1.22	2.68	0.93	77.2	2.53	76.88	20.60	8.71	0.78	2.83
40-50	1.35	2.68	1.80	84.8	2.44	76.61	20.95	8.57	0.63	2.84
50-60	1.37	2.66	2.60	80.2	1.41	77.86	20.73	8.52	0.76	2.84
60-70 (sand)	1.4	2.66	9.26	–	96.61	2.86	0.53	9.17	3.57	0.03

Note: K_{inf} – the coefficient of water inflitration; C_{CaCO_3}, C_{org} - content of mineral and organic carbon.

RESULTS AND DISCUSSION

The structure of the filled chernozemic layer in the studied technozems differs considerably from the classical granular structure of chernozems, from which this material was taken. During 20 years, the classical chernozemic structure has degraded in the sub-plough horizons and, particularly, in the lower part of the chernozemic layer (40-60 cm). Field studies demonstrated that the increase in the size of angular blocky (and columnar-prismatic) peds is accompanied by an increase in the soil bulk density (Table 1). The study of water stability of the aggregates in the upper 10 cm showed that coarse aggregate fractions are completely destroyed upon slaking in water. In the lower part of the upper chernozemic layer, soil aggregates have an increased water stability against the background rise in the soil bulk density. A sharp change in the structural status of technogenic soils with an increase in the content of very coarse aggregates has already been noted in literature (Horn and Peth, 2009; Shein *et al*., 2006). Significant changes in the structural state of the soil and the development of inter-ped fissures have resulted in the very high hydraulic conductivity within the upper (chernozemic) soil layer, particularly below 40 cm.

An analogous change in the structure of chernozems can be observed in natural soils upon increasing duration of temporary soil waterlogging. For instance, an increase in the size of aggregates and aggregate water stability down the soil profile has been noted for meadow-chernozemic soils of the Tambov Plain. The peds in those soils acquire prismatic shape (Nikiforova and Stepantsova, 2003). The high content of humus and smectitic clay minerals in the chernozems contribute to the high sensitivity of those soils to a rise in the soil water supply (Dobrovolskii, 2002).

The creation of an artificial layered technozem with abrupt boundaries between the separate layers has changed the water regime in the upper chernozemic layer. Even a short-term overwetting of chernozems and alternation of wetting-drying stages lead to structural rearrangement of the soil profile; often, vertic features appear in the soil. The degree of transformation of separate horizons of chernozemic soils (including filled chernozem in the technogenic soil) depends largely on the degree and duration of the soil waterlogging with water stagnation in the profile. Water stagnation in chernozems leads to a rapid substitution of anaerobic conditions for aerobic conditions. The reverse process upon the gradual soil drying takes a long time (Nikolaeva and Eremina, 2006). The heavy texture of the studied technozem (Table 1) and the presence of smectites in the clay fraction specify the high water retention capacity in the chernozemic layer. Differences in the texture of the upper chernozemic and underlying sandy or loamy layers may lead to the formation of a horizon with perched water above the lithological contact. Such a horizon worsens the water regime of the entire technozem profile. An abrupt boundary between separate soil layers favours temporary water stagnation above this boundary and a horizon of perched water is formed above the boundary between the upper heavy loamy (chernozemic) and the underlying sandy layers. In turn, water stagnation and its spreading over the surface of the underlying layer contribute to changes in the physicochemical and chemical properties of the soil and to differentiation of the peds into the surface and inner parts. These processes transform the structural state of the soil.

This conclusion is supported by the data on the particle-size distribution in the inner and outer parts of the peds in the variant of chernozemic layer on sand: the inner part of the peds has a heavier texture favouring high water retention capacity (Table 2). The differences in the texture between the inner and outer parts of the peds are most pronounced in a layer of 20-30 cm, in which compact and well-shaped angular blocky peds appear. In the lower layer, this difference becomes less pronounced. In the lowermost chernozemic layer (50-60 cm), it disappears. Note that the textural differences between the inner and outer parts of the peds are mainly due to differences in the contents of the fine and medium silt fractions. Such a kind of soil mass transformations may be due to the specific water regime formation with the dominance of preferential water flow movement through the chernozemic layer and possible stagnation on the sand boundary.

Table 2. Contents of physical clay (<0.01 mm)/ sludge (<0.001 mm) particles (%) in the technozem layers

Layer (cm)	Ped faces	Ped interiors
20-30	46.79/6.92	58.08/7.83
30-40	48.02/6.83	56.59/9.36
40-50	47.80/6.58	54.80/9.47
50-60	48.29/6.88	49.25/9.51

In order to confirm (or reject) the hypothesis about the transformation of the soil structure in the chernozemic fill under the impact of water stagnation at the boundary between separate soil layers, a field experiment on the preferential paths of water flows with the help of starch label was conducted. The results of this experiment (the distribution of starch mottles in the soil mass within separate horizontal soil sections) are shown in Fig. 1.

In our field experiments the frames were installed on the soil surface and at a depth of 45 cm. The distribution of starch mottles shows that transition from the upper layer with fine crumb structure to the underlying layer with coarse angular blocky structure is accompanied by strong concentration of the water flow. This is especially well seen in the distribution of starch added with water at a depth of 45 cm. Within the lower part of the chernozemic layer, water infiltration proceeds mainly along the prisms and columns.

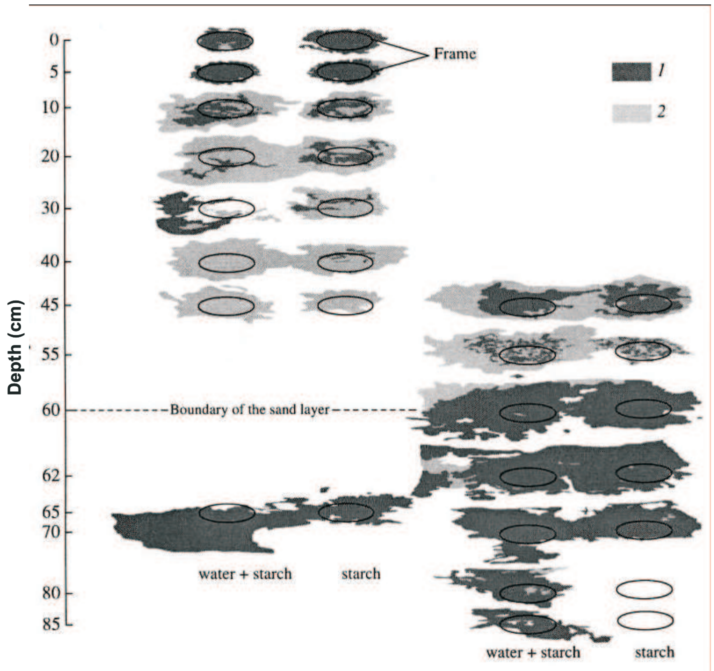

Fig. 1. Major paths of water filtration as judged from coloring of the applied starch in soil profile (chernozem/sand): 1 – distinct colouring of the label and 2 – indistinct coloring in the zones of capillary sorption of starch.

The irregular distribution of starch was more distinct in the experiments when starch was added immediately, without the preliminary adding of pure water. In the case of the preliminary soil moistening with water, the infiltration of starch followed the steady-state pattern; the starch label passed quickly downwards through the soil profile along the fissures, so that no distinct colouring of the starch in the soil mass under the frame was seen. However, some bluish tint from the applied starch could be detected on digital photos processed.

It is evident from Fig. 1 that starch spread over the boundary with the underlying sandy layer and formed extensive zones of continuous colouring. It should be noted that the underlying sandy (sand-chalk) layer also had a layered character, which could not be seen upon the visual morphological description of the soil profile, but was clearly seen from the distribution of the starch label. On the vertical wall of the pit, the layered character of the zones of most active starch colouring in the sandy material was clearly expressed.

Morphological study of the soil profile coupled with data on the elemental composition of the soil mass from the inner parts of the peds and the coatings on their faces in the layer of 50-60 cm (chernozem/sand) indicate that the brown coatings on ped faces are enriched in iron, which may attest to periodical overwetting of this part of the technozem profile. The immobility of iron hydroxide in an alkaline medium (Table 1) excludes the illuvial origin of these coatings. It is probable that their formation is related to microbiological processes causing some differentiation of the material of the aggregates. In any case, an increased content of iron ions with structural bonds of crystallization type facilitates the stability of the aggregates. In turn, this contributes to increased inter-aggregate porosity and, hence, to increased water infiltration through intra-ped fissure pores. Such changes in the filtration characteristics of the soil mass with the formation of a specific type of soil water regime have already been described in literature (Anderson and Bouma, 1973; Bouma, 2006; Shein and Umarova, 2002; Umarova and Kirdyashkin, 2007).

Thus, the inner parts of the peds in the soil layer formed upon the structural transformation of the initial chernozemic material are subjected to relatively long periods with anaerobic conditions. As a result, the zones with the high water content in the central parts of the peds are preserved for a long time, even in the case of a general drying of the soil mass. We proposed that such a kind of air-water mesoregime of the soil peds may have influenced the distribution and functioning of the soil biota.

The results of the soil biota investigations are represented in Figs 2 and 3. The total content of microorganisms is not changed through the depth of soil construction, but the aerobes are dominant (Fig. 2a). Clear differences are noted in the aerobes and anaerobes distribution on the inner and surface parts of the peds (Fig. 2b). On the surface the aerobes are dominant: the numbers of aerobes exceed 3-4-fold those of the anaerobes. But in the inner part the numbers of the microorganisms decrease, and the differences between aerobes and anaerobes are decreased. Depending on the water-air relations and the oxidation-reduction conditions, aerobes

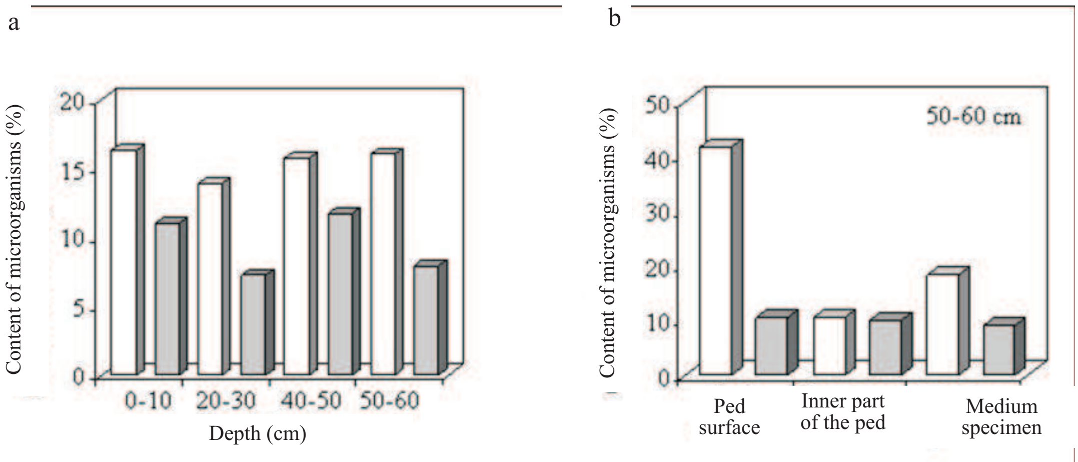

Fig. 2. Anaerobes and aerobes conte nts on the different depth of the soil construction: a – on the surface, inner parts of the ped and in medium soil specimen, b – on the depth 50-60 cm. Note: In the group Anaerobic the obligate and facultative anaerobes were included, but in Aerobic group the obligate microorganisms and microaerofiles were included.

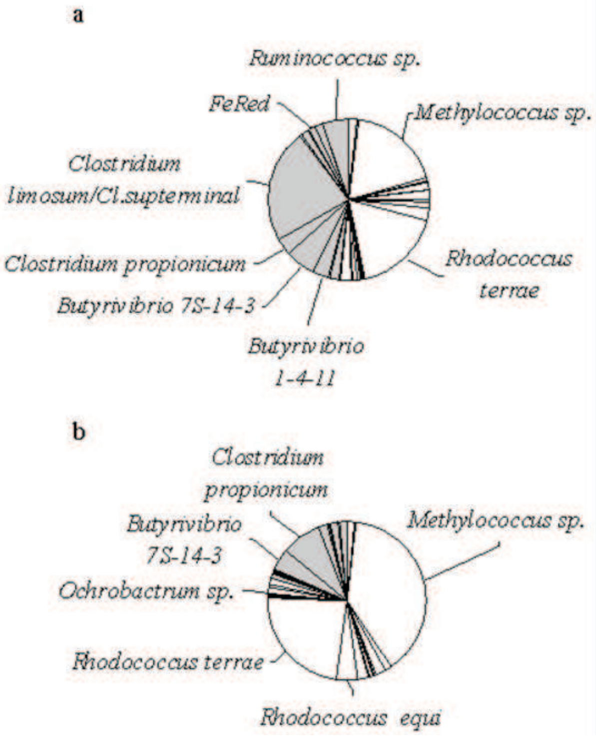

Fig. 3. Microbiological composition in the inner part: a – on the ped surface, b – from the depth 40-60 cm of the chernozemic layer of the soil construction.

or anaerobes will be developed. In periods of temporal water saturation of the inner part of the ped the anaerobes consortium is functioning (Fig. 3a). This dominant consortium is created from bacterium-anaerobes genera *Clostridium, Butyrivibrio* and *Ruminococcus*. Also the group of Fe-reducing bacteria and other microorganisms with Fe-reduction abilities are developed. So, the processes of the Fe^{3+} to Fe^{2+} reduction in the period of the inner part saturation, and movement of Fe^{2+} to surface are carried out by the bacterium-anaerobes consortium, and the oxidation of F^{2+} to Fe^{3+} on the surface of peds is carried out by the soil biota. The bacterium of the genera *Ochrobactrum, Rodococcus* and others (Fig. 3b) are conducive to this process.

CONCLUSIONS

1. In 20 years of functioning of the artificially created technogenic soil composed of an upper 60 cm-thick chernozemic fill underlain by sand or loam, considerable changes in the soil properties have taken place. From a depth of 35-40 cm, the granular structure of chernozem is transformed into a coarse blocky structure with high water stability. In the lowermost part of the fill layer, such blocks compose prisms and columns. The indications of temporary water stagnation in this zone are clearly expressed in the form of iron-rich coatings on ped faces, rusty mottles above the contact zone, and vertic features. These features are developed under the impact of a specific water regime in the technogenic soil with the formation of preferential water flows. Under these conditions, the participation of intra-ped pores in the water migration is negligibly small. Preferential water flows are concentrated along fissures separating prismatic aggregates, which has been confirmed in the experiments with starch label. The study of the spatial pattern of soil water flows made it possible to detect horizontal spreading of water above the contact with the underlying sandy layer. As a result, the stagnation of water and the development of anaerobic conditions take place. Gleyzation is developed, particularly in the inner zone of peds. Iron compounds are concentrated on ped faces.

2. Soil biota distribution contributes to movement of iron ions to ped surface because in alkaline conditions those ions are chemically immobile. Our investigations showed that the inner part of the ped contains the anaerobe association of microorganisms, but the external – the aerobe one. This microbiological composition favours Fe-ions migration to the surface, transformation to Fe-oxide films on the ped surface, and the formation of columnar rigid blocks. Results of the study indicate that the preferential flows create favourable conditions for the soil gleyzation inside the ped, anaerobic microbiota formation, but during subsequent dry periods aerobic microbiota on the surface ped layers transform Fe^{2+} to Fe^{3+} and lead to aggregate transformation from granular structure to the columnar blocks.

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