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## SOIL PHYSICS

# Composition and Structure of Aggregates from Compacted Soil Horizons in the Southern Steppe Zone of European Russia

**A. S. Sorokin[a], K. N. Abrosimov[b], M. P. Lebedeva[b], and G. S. Kust[a]**
[a] *Moscow State University, Moscow, 119991 Russia*
[b] *Dokuchaev Soil Science Institute, Pyzhevskii per. 7, Moscow, 119017 Russia*
*e-mail: leshasorokin@gmail.com*

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**Abstract**—The composition and structure of aggregates from different agrogenic soils in the southern steppe zone of European Russia have been studied. It is shown that the multi-level study (from the macro- to microlevel) of these horizons makes it possible to identify soil compaction caused by different elementary soil processes: solonetz-forming, vertisol-forming, and mechanical (wheel) compaction in the rainfed and irrigated soils. The understanding of the genesis of the compaction of soil horizons (natural or anthropogenic) is important for the economic evaluation of soil degradation. It should enable us to make more exact predictions of the rates of degradation processes and undertake adequate mitigation measures. The combined tomographic and micromorphological studies of aggregates of 1–2 and 3–5 mm in diameter from compacted horizons of different soils have been performed for the first time. Additional diagnostic features of negative solonetz-forming processes (low open porosity of aggregates seen on tomograms and filling of a considerable part of the intraped pores with mobile substance) and the vertisol-forming processes (large amount of fine intra-aggregate pores seen on tomograms and a virtual absence of humus–clay plasma in the intraped zone)—have been identified. It is shown that the combination of microtomographic and micromorphological methods is helpful for studying the pore space of compacted horizons in cultivated soils.

*Keywords:* chernozems, compaction, computer microtomography, economics of soil degradation, kastanozems, solonetzization, vertic features

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## INTRODUCTION

Steppes, meadows, and their anthropogenic analogues on chernozems and kastanozems, including fallow lands and pastures, occupy more than 220 million hectares in Russia. This area is almost completely plowed (80–95%) [28]. Large areas of plowed soils (about 40%) and pastures are overcompacted [16]. Soil compaction under the impact of field machines (wheel compaction) in the steppe zone is discussed in many works [1, 3, 5, 15, 24, 25, 32, 40, 42]. It is also known that the compaction of steppe soils under natural conditions may also be related to vertisol- and solonetz-forming processes [2, 10, 19, 20, 22, 23, 35, 39, 43, 44]. However, it is often difficult to identify the genesis of compacted horizons in the agrogenic soils. In many of them, not all the diagnostic features of vertisol- and solonetz-forming processes are present, and the factors of compaction of soil horizons cannot be clearly determined. In these cases, it is reasonable to take into account separate features of these macroprocesses (vertic and solonetzic properties) as seen in soils. The attention should be paid to the potential risks of soil compaction and to its actual features. The potential risks of soil compaction depends on their texture, chemical and mineralogical composition, the organic matter content, and the water resistance of the soil structure. The actual features are the real properties of compacted horizons under the particular physiographic conditions [20]. To prevent soil compaction, i.e., to implement sustainable management of soil resources, we should take into account that some natural processes leading to soil compaction cannot be eliminated via simple exclusion of "unsustainable" soil management. The soils subjected to these processes require special reclamation measures. In this context, knowledge of the mechanisms of soil compaction and their diagnosis at the early stage are necessary to predict the rates of soil degradation and to apply adequate measures for their control. Note that soil compaction leads to adverse agrochemical and economic effects. It reduces the efficiency of fertilizers by more than 40%, decreases crop yields by 25–50%, and increases fuel consumption by about 15% [11].

Soil structure and pore space are important factors of soil fertility, the activity of soil organisms, and the migration and accumulation of substances. The soil structure is traditionally assessed with the use of characteristics of the soil bulk density, porosity, particle-

**Table 1.** Investigation objects

| Location | GPS | Classification | | |
|---|---|---|---|---|
| | | 1977 | 2004 | WRB, 2014 |
| Korenovsk district, Krasnodar region | N 45.31814°<br>E 39.62117° | Typical vertic very deep heavy loamy chernozem on loesslike loam | Mycelial-carbonate very deep heavy loamy agrochernozem on loesslike loams | Calcic Vertic Chernozem (Densic) |
| Marx district, Saratov oblast | N 51.71992°<br>E 47.19115° | Light clayey meadow-kastanozem on Khvalyn deposits | Quasi-gley light clayey agrokastanozem on Khvalyn deposits | Calcic Kastanozem (Densic, Sodic) |
| Engels district, Saratov oblast | N 51.38377°<br>E 46.05525° | Medium-deep silt loamy southern chernozem on loesslike loam | Texture-carbonate medium-deep silt loamy agrochernozem on loesslike loam | Haplic Chernozem (Vermic) |
| | N 51.35928°<br>E 46.06412° | Medium-deep silt loamy dark kastanozem on loesslike loam | Texture-carbonate medium-deep silt loamy agrochernozem on loesslike loam | Haplic Kastanozem (Densic) |

size distribution, and aggregate-size distribution [7]. However, these traditional characteristics do not provide adequate information on the shape, orientation, and mutual disposition of pores and aggregates [36], which is often necessary for the specification of the genesis of soil processes. The morphometric study of soil sections enables to evaluate the type of pores and the shape of aggregates by quantitative parameters [37]. The soil structure at different levels is diagnosed by geometric characteristics of the soil pore space and the type of boundaries between the aggregates. The study of soil thin sections under optical and electron microscopes provides the missing morphological data and data on the specific features of the composition and interaction of the main components of the soil solid phase (organic matter, particles of different sizes, and others) [12, 27, 29]. In addition to the micromorphological analysis, tomographic studies provide 3D images of aggregates and internal pores and qualitative and quantitative data on their shape. The tomographic study based on physical principles is a helpful approach for the diagnostics, evaluation, and monitoring of the physical soil status [14]. At present, this approach is used in soil science in order to solve various applied and theoretical problems [6, 7, 10, 33, 46, 48–53, 56].

The aim of this work is to reveal specific features of the formation of compacted horizons in agrogenic soils of the steppe zone in European Russia.

The particular goals of the study were to (1) describe morphological, physical, chemical, and physicochemical properties of compacted horizons in the studied soils; (2) identify similarities and differences of these horizons with respect to the studied parameters; (3) investigate specific features of the composition and structure of particular aggregates from compacted soil horizons with the use of morphometric, micromorphological, and tomographic methods; and (4) diagnose the processes leading to the formation of compacted horizons.

## OBJECTS AND METHODS

Plowed soils with compacted horizons were studied in the Krasnodar region and Saratov oblast. According to [18], these soils were classified as Vertic Chernozem (Korenovsk district of Krasnodar region), Calcic Kastanozem (Marx district of Saratov oblast), and Haplic Chernozem and Haplic Kastanozem (Engels district of Saratov oblast). Full soil names according to different classification systems [17, 18, 45] are given in Table 1.

The studies were performed in four pits (one for each object). They were studied in a dry period in order to exclude the effect of moistening on the morphological soil features, in the topsoil in particular.

The soils were described according to the scheme suggested by Rozanov [30]. The upper part of all the studied soil profiles included the plow layer and the underlying compacted layer (compacted horizon). The subsurface part was represented by the humus horizon in the Vertic Chernozem and Haplic Chernozem and in the Calcic Kastanozem and by the middle-profile (B) horizon in the Calcic Kastanozem (according to [17]).

The samples from compacted horizons were analyzed. We determined the main properties important for the soil genesis: the soil bulk density (with cutting rings), the soil solid phase density (by pycnometry), the aggregate porosity (by the method of paraffining), the particle-size distribution (by the pipette method with pyrophosphate pretreatment), the content of water-peptizable clay (by the method of Gorbunov), the humus content (by the method of Tyurin), the soil pH (in water suspension), and the exchangeable sodium content (by the method of Pfeffer) [4].

**Table 2.** Physical, physicochemical, and chemical properties of the investigated compacted horizons

| Soil | Depth (thickness), cm | *D*, g/cm$^3$ | <0.01 mm | <0.001 mm | WPC/clay | *Ea* | *E* | *Eia* | Humus | Na | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % | | | | | | | | |
| Vertic Chernozem | 21–40 (19) | 1.5 | 58 | 35 | 73 | 31 | 42 | 16 | 3 | 0 | 7.2 |
| Calcic Kastanozem | 10–29 (19) | 1.4 | 45 | 35 | 64 | 33 | 46 | 20 | 2.1 | 9.8 | 8.2 |
| Haplic Chernozem | 10–23 (13) | 1.4 | 36 | 24 | 14 | 41 | 46 | 8 | 3.5 | 0 | 6.9 |
| Haplic Kastanozem | 14–26 (12) | 1.5 | 36 | 22 | 13 | 33 | 39 | 10 | 2.8 | 2.1 | 7.5 |

Depth (thickness) column shows the depths of the upper and lower boundaries of compacted horizons and their thickness; *D* is the soil bulk density; <0.01 mm is the content of physical clay fraction; <0.001 mm is the content of clay fraction; WPC/clay is the portion of water-peptizable clay in the total clay; *Ea* is the aggregate porosity; *E* is porosity; *Eia* is the interaggregate porosity. Humus is the humus content; Na is the content of exchangeable sodium; pH is the soil reaction.

Mesomorphometric, micromorphological, and tomographic studies of the samples were performed in order to reveal the specific features of the composition and structure of some aggregates from the compacted horizons. Samples were sieved through screens with different mesh sizes. Aggregates of 1–2 mm were taken for all the analyses; additional tomographic studies were performed for aggregates of 3–5 mm in size. The aggregates of 1–2 mm were studied as an example of small structural units with micropores of 7–30 μm in diameter that could not be seen in thin sections. The aggregates of 3–5 mm were examined in a tomograph as an example of agronomically valuable structural units.

During the mesomorphometric analysis, we examined the shape of the aggregates of 1–2 mm in size. For this purpose, about a hundred aggregates from compacted horizons were scanned on an Epson perfection 2450 scanner with a resolution of 1200 dpi. The obtained images were processed with ImageJ program [54]. Several indices were calculated for the aggregates: the index inverse to roundedness ($1/R$), where $R = 4\pi S/P^2$; the index characterizing the degree of isometry of the aggregates $I = D/L$; and the index of their general form factor $F = (4\pi S/P^2 + D/L)/2$, where $S$ is the area, $P$ is the perimeter, and $D$ and $L$ are the transverse and lengthwise linear dimensions of aggregate projection on the plane [37, 38]. The cluster analysis [29] was applied to the calculated index of isometry ($I$); as a result, the aggregates from compacted horizons were grouped into five classes.

The micromorphological study was performed with the use of an Olympus BX51 polarizing microscope equipped with a digital camera Olympus DP26; international guidelines for the description of thin sections were applied [55]. Thin sections for the micromorphological analysis were prepared by M.A. Lebedev in the Laboratory of Soil Mineralogy and Micromorphology of the Dokuchaev Soil Science Institute. The components of microstructure were visualized and measured with the use of computer programs supplied with the microscope.

The microtomographic analysis of the aggregates was performed at the Laboratory of Soil Physics and Hydrology of the Dokuchaev Soil Science Institute on a Bruker SkyScan 1172 microtomograph providing X-ray images with resolutions from 0.6 to 26 μm/pixel. The beam energy was 100 keV; the resolutions of 0.88 μm (for the aggregates 1–2 mm in size) and 2.4 μm (for the aggregates 3–5 mm) were applied. The obtained data were processed using special Bruker software. We made the layer analysis of the microtomographic data, calculated soil porosity (open and closed) seen in the tomograms, and made 3D modeling of the pore space using the CTan computer program. The specificity of the morphological structure of soil aggregates and pore space was evaluated with the help of CTvox and DataViewer programs. A Despeckle filter with a threshold of more than 25 voxels for 3D images was used. The binarization was performed using similar criteria for all the samples.

The following notions and definitions were applied for the interpretation of microtomographic data: (1) pore opening or the mean diameter of pores (as initially used in geology) signifies the largest distance between the walls of a pore [13, 31]; (2) total porosity seen in the tomograms (or porosity) is a part of the volume of a solid body seen in the tomograms, which is not filled with its material [34]; (3) open pores is a term that is not definitely determined in soil science. In our study, open pores were considered the pores crossed by the sides of a cube inscribed in the 3D image of the analyzed sample [9].

## RESULTS AND DISCUSSION

*Physical, physicochemical, and chemical properties of the studied soils.* Let us consider soil properties specifying the soil capacity for strong compaction. The obtained data are given in Table 2.

The compacted horizons of the studied soils had some common properties, i.e., the high bulk density (1.4–1.5 g/cm$^3$) as determined by the drilling method and a relatively low humus content (2.1 to 3.5%) as evaluated according to Orlov [25].

**Table 3.** Mesomorphological properties of the studied soils

| Parameter | Vertic Chernozem | Calcic Kastanozem | Haplic Chernozem | Haplic Kastanozem |
|---|---|---|---|---|
| Structure of plow horizon | Blocky | Angular blocky | Blocky | |
| Depth (thickness) of CH, cm | 21–40 (19) | 10–29 (19) | 10–23 (13) | 14–26 (12) |
| Structure of CH | Massive, coarse angular blocky | Prismatic to angular blocky | Angular blocky | |
| Density of CH | Very dense | Dense | Rather dense | Dense |
| Hardness of CH | Very hard | Hard | Soft | Hard |
| Aggregate pores in CH | Single pores | Small amount of fine pores | Medium amount of fine pores | |
| Vertical cracking | Large (4–5, up to 7 cm) open cracks from the surface; deep (down to 80 cm) | Narrow (1–1.5 cm) cracks to the depth of 10 cm with a polygonal (20(70) × 15(80) cm) pattern | To the depth of 10 cm | Narrow to the depth of 40 cm and very narrow to the depth of 70 cm |
| Horizontal fissuring of CH | Parting to “plates” of 3–4 cm in thickness | Finely fissured | Finely fissured | Thin fissures spaced at 3–10 cm |
| Impact of CH on root development (visual description) | Prevents root penetration deep into the soil profile | The amount of roots sharply decreases in comparison with that in the overlying horizon | Does not prevent root penetration deep into the soil profile | Hampers root penetration deep into the soil profile |

CH is the compacted horizon.

The studied soils differed in their (1) *particle-size distribution* with the maximum contents of physical clay (<0.01 mm) and clay (<0.001 mm) in the Vertic Chernozem (58 and 35%, respectively) and the minimum contents of these fractions (36 and 22%, respectively) in the Haplic Kastanozem; (2) *aggregate porosity* with the minimum value (31%) in the compacted horizon of the Vertic Chernozem and the maximum value (41%) in the compacted horizon of the Haplic Chernozem; (3) *total porosity* with the lowest values in the Vertic Chernozem and Haplic Kastanozem (41 and 39%, respectively) and the highest value (46%) in the Calcic Kastanozem; (4) *interaggregate porosity* with the highest values in the Calcic Kastanozem and Vertic Chernozem (20 and 16%, respectively) and the lowest values in the Haplic Chernozem and Haplic Kastanozem (8 and 10%, respectively); (5) *the content of water-peptizable clay* (WPC) and its portion in the total clay content with the highest values in the Vertic Chernozem (26 and 73%, respectively) and the lowest values in the Haplic Kastanozem (3 and 13%, respectively); (6) *pH* with the highest value (8.2) in the Calcic Kastanozem and the lowest value (6.9) in the Haplic Chernozem; and (7) *the content of exchangeable sodium,* which was determined in the compacted horizon of the Calcic Kastanozem and reached 9.8% of the exchange capacity.

*Mesomorphological study* showed the following specific features of compacted horizons (Table 3): (1) the well-pronounced nutlike (angular blocky) shape of aggregates; (2) the increased bulk density and penetration resistance; (3) the prevention of free root penetration deep into the soil profile; and (4) the lowered amount and small size of pores. These features are typical of all the studied soils, though they are best pronounced in the compacted horizons of the Vertic Chernozem and Calcic Kastanozem.

The following distinctive features of the studied compacted horizons should be noted. (1) In the Vertic Chernozem, this horizon has a considerable thickness (19 cm on the average), and its lower boundary may descend down to 40 cm. The average thickness of the plow layer is 21 cm, i.e., the compacted horizon is considerably thicker than the usually described thickness of the plowpan. It has a blocky structure, pitch glance on the cut of knife (spade), and deep cracks from the surface to the depth of 70 cm (Table 3, column 2). (2) In the Calcic Kastanozem, the compacted horizon has a prismatic structure with clay–humus coatings on ped faces; gypsum and carbonates are present in the deeper horizon (Table 3, column 3). (3) In the Haplic Chernozem and Haplic Kastanozem, the lower boundary of the compacted horizon is found at the depth of 23 (26) cm, and the bulk density and penetration resistance in this horizon in the Haplic Chernozem are the lowest among all the studied compacted horizons, though the features of its structural transformation are clearly seen.

**Table 4.** Morphometric parameters of aggregates from compacted horizons

| Soil | Isometry class, *I*, % | | | | | Parameter | | | Features of shape |
|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | 1/*R* | *I* | *F* | |
| Vertic Chernozem | 0 | 0 | 7.5 | 52.3 | 40.2 | 0.82 (0.06) | 0.77 (0.11) | 0.79 (0.07) | Rounded, slightly dissected |
| Calcic Kastanozem | 0 | 1.3 | 16.0 | 49.4 | 33.3 | 0.72 (0.08) | 0.72 (0.13) | 0.72 (0.09) | Most elongated |
| Haplic Chernozem | 0 | 0 | 4.7 | 58.5 | 36.8 | 0.74 (0.07) | 0.77 (0.09) | 0.76 (0.07) | Most isometric |
| Haplic Kastanozem | 0 | 0 | 9.8 | 44.6 | 45.6 | 0.77 (0.06) | 0.78 (0.11) | 0.77 (0.07) | Isometric, slightly dissected |

Isometry (*I*) classes: I—fissurelike; II—elongated dissected; III—isometric strongly dissected and elongated oval-shaped; IV—isometric slightly dissected; V—rounded. Mean values of the parameters with standard deviation (in parentheses): 1/*R*—inverse ratio of rotundity, *F*—generalized form factor.

The bulk density of the described compacted horizons is higher than the range of the optimum bulk density of the soils according to Bondarev [3]. This means that the soils may be subjected to temporal overmoistening with an insufficient amount of air necessary for the normal functioning of plant roots. Thus, the productivity of these soils should greatly depend on the particular weather conditions and on the rational land use. As shown by Manucharov and Abrukova [8], the content of WPC is usually less than 10% in the well-structured soils and may be as high as 30% and more in the structureless soils. Thus, the horizons with well-pronounced compaction (the compacted horizons of the Vertic Chernozem and Calcic Kastanozem) are also characterized by the high content of WPC.

The specific features of the described compacted horizons allow us to suggest the following genetic hypotheses.

(1) In the Vertic Chernozem, the compacted horizon is characterized by definite vertic properties (in terms of the World Reference Base for Soil Resources) [41], as it has the high content of the physical clay and clay fractions, the low aggregate and high interaggregate porosities, and the high content of WPC against the background of its considerable thickness, deep lower boundary, “monolithic” structure, the presence of deep vertical cracks, and the absence of exchangeable sodium.

(2) In the Calcic Kastanozem, the compacted horizon has solonetzic properties [21] as it has the high content of physical clay and clay fractions, the low aggregate and high interaggregate porosities, the high WPC content, the prismatic structure with clay–humus coatings on ped faces, and the presence of exchangeable sodium in this horizon, together with the presence of gypsum and carbonates in the deeper layer. However, the solonetz-forming processes are not well-developed in this horizon, because the exchangeable sodium percentage is less than 10% (this is a low-sodium soil according to [17]), and the pH is 8.2, which is typical of the soil solutions of the carbonate–calcium composition.

(3) The Haplic Chernozem and Haplic Kastanozem differ from the two above-described soils in their characteristic features; their compacted horizons contain less physical clay and clay, have a higher aggregate porosity and a lower interaggregate porosity, the WPC content is less than 14%, and the exchangeable sodium is absent or present in small amounts (2%), which points to the absence of actual solonetzic or vertic properties in the compacted horizons of these soils and to the development of agrogenic (wheel) compaction in them.

The subsequent studies made it possible to refine the initial diagnostics of the processes taking place in the soils and to determine specific features of the morphology of aggregates in the compacted horizons.

*The morphometric analysis of aggregates* 1–2 mm (Table 4 and Fig. 1) proved that the studied soil samples differ in the shape of their aggregates. Thus, the Calcic Kastanozem is characterized by the most elongated aggregates, whose portion reaches 17.3%. In the other soils, the portion of these aggregates varies from 4.7 to 9.8%. The isometric and rounded shape is typical of the aggregates from the compacted horizon of the Haplic Chernozem; the portion of these aggregates in this soil reaches 45.6%. Aggregates from the compacted horizon of this soil are relatively weak and are easily disintegrated into smaller aggregates, even under slight mechanical impacts.

*Micromorphological analysis* of the studied samples made it possible to identify several common and specific features related to different pedogenetic processes. The major elements of the microfabric of aggregates from different soil types are shown in Fig. 2.

*Vertic Chernozem*. The aggregates from the compacted horizon are characterized by the irregular shape with somewhat “stretched” angles and by the nonuniform color related to their uneven impregnation with clay–humus and clay–humus–iron substances (Fig. 2a-I-*a*). The content of humus–clay plasma inside the peds is low, while fragmentary clay–iron–humus coatings and numerous concentrations, coagulates, and strands (humified and ferruginated small plant debris) are abundant near ped faces (Fig. 2a-II-*b*). Very thin fragmentary clay coatings attest to some clay mobility, which may appear upon the agrogenic compaction of the soils. The specific shape of aggregates (with "duckbills") and thin clay coatings were described for the soils with vertic properties; they can be referred to as microslickensides [47].

The intraped mass contains large amounts of small coal-like tissues and particles (Fig. 2a-III-*c*), whose origin may be related to decomposition of plant tissues in the reducing medium upon temporary water stagnation.

Minerals of coarse fractions are concentrated in nests and have sharp-angled shapes, which may be related to fracturing and disintegration of sand particles into smaller silt-size grains.

*Calcic Kastanozem*. The aggregates are characterized by anisometric shape and "stretched" angles. They have a nonuniform color pattern and microstructure with irregular distribution pattern of skeletal grains, humus–clay plasma, and iron–humus and clayey pedofeatures (Fig. 2b). The aggregates are characterized by smooth surfaces and a rather high content of small coal-like particles and fine-dispersed organic matter bound with fine-dispersed silicate material. The enrichment with humus and clay is clearly seen in the reflected light (Fig. 2b-III-*b*). The amount of plant debris is small.

Humus–clay pedofeatures are represented by thin coatings on ped faces and on coarse mineral grains, infillings in fine intraped pores, and fragments of coatings (papules) assimilated in the intraped mass (Fig. 2b-II-*a*). These features are indicative of the solonetz-forming process with mobilization of clay and humus–clay material and the formation of coatings that are gradually destroyed in the course of shrink–swell processes and become assimilated by the intraped mass in the form of papules.

Fine coal-like particles, iron–humus–clay coatings, and small humus–iron concretions are the diagnostic features of periodical changes in the redox conditions under the impact of surface water stagnation.

The skeletal grains are represented by quartz, potassium feldspars, plagioclases, glauconite, micas, epidote-zoisite, and fragments of metamorphic quartzite rocks. Minerals of rounded shapes predominate. Plagioclases are the most altered minerals; they display the microfeatures of corrosion and fissuring (Fig. 2b-III-*c*); pseudomorphs of humus–clay matter are seen in some of the fissures.

In general, aggregates from the compacted horizon of the Calcic Kastanozem are enriched with organic, organic–clay, and iron–clay plasma (Fig. 2b-I-*d*). It can be concluded that these aggregates are formed in a relatively humified soil (Table 2) subjected to the modern solonetz-forming process and periodical surface hydromorphism.

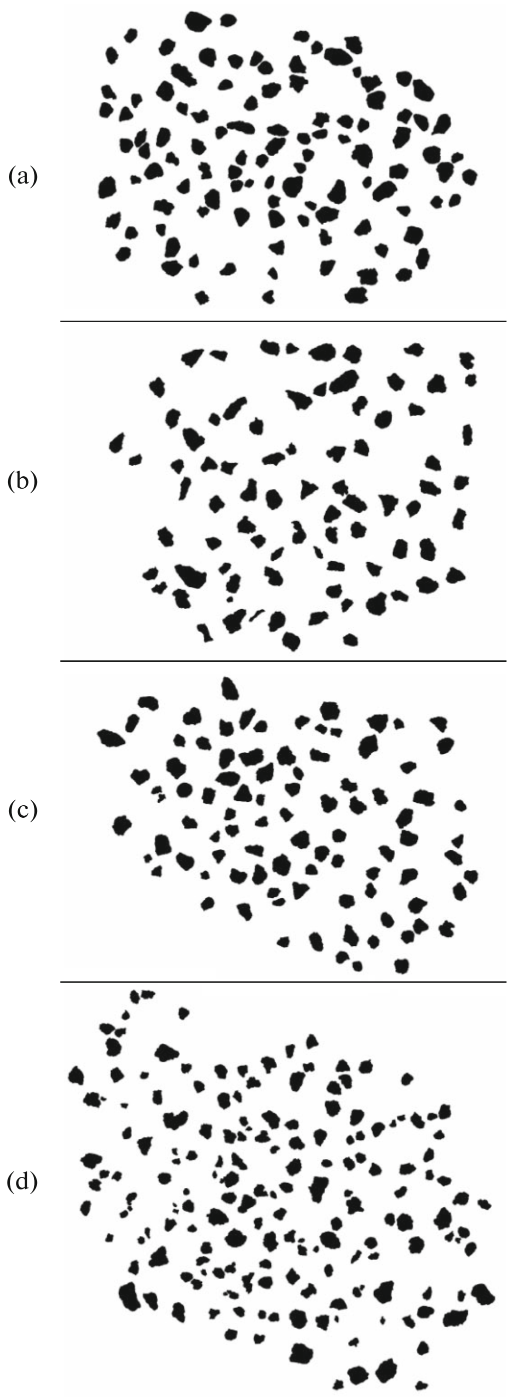

**Fig. 1.** Images of soil aggregates 1–2 mm in size from the compacted horizons. Soils here and in the following figures: (a) typical chernozem, (b) meadow-chestnut soil, (c) dark chestnut soil, and (d) southern chernozem.

*Haplic Chernozem*. The non typical microfeatures for the above-described samples were revealed in the compacted aggregates of this soil. The macroaggregates are characterized by the multiordered structure with the high intraped porosity and microaggregation (Fig. 2d-II-*d*). Clay–humus rounded microaggregates

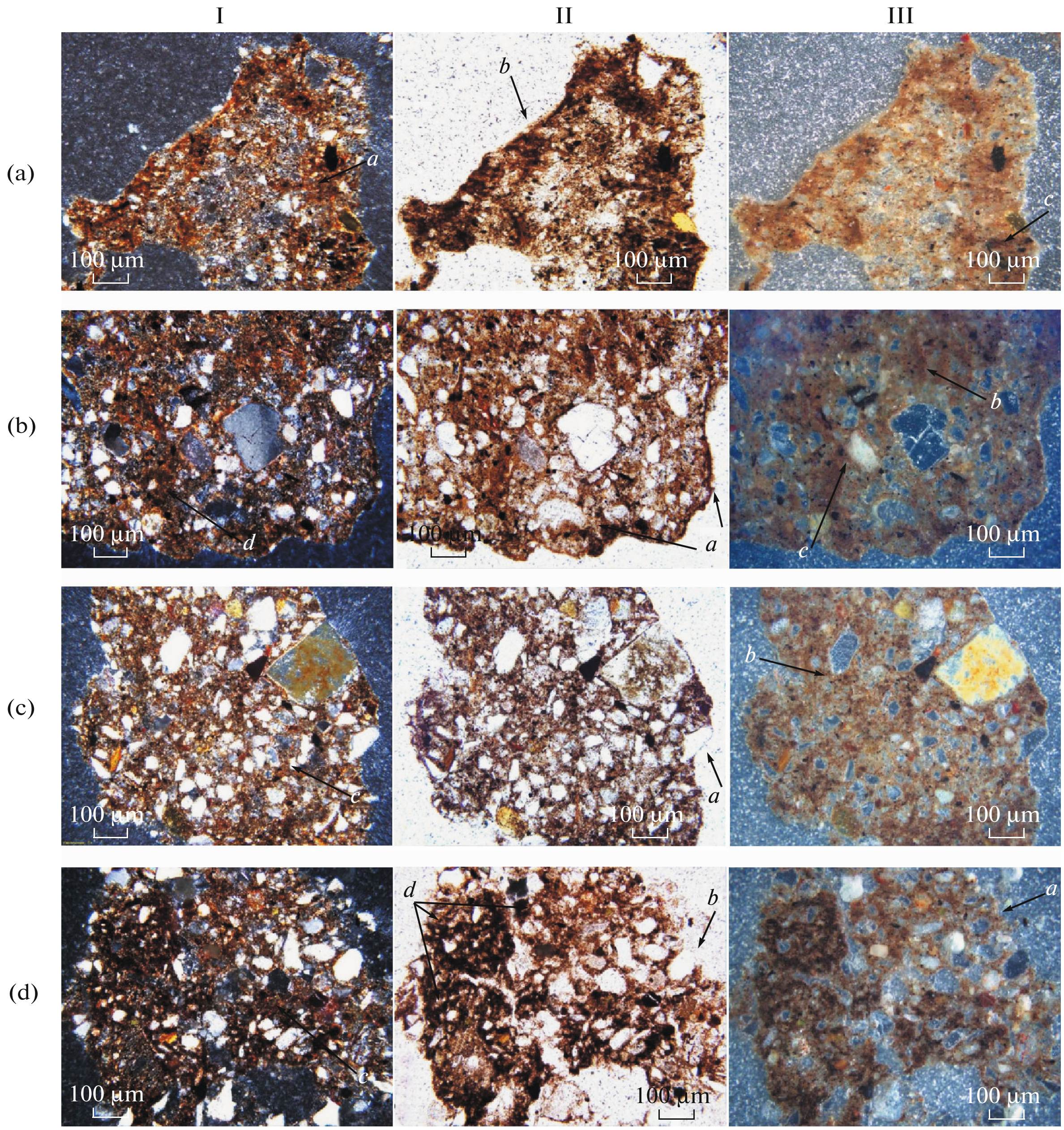

**Fig. 2.** Micromorphological structure of aggregates 1–2 mm from the compacted horizons: I—crossed nicols; II—parallel nicols; III—reflected light. Lowercase letters (a, b, c, d) indicate the features explained in the text.

and coagulates presumably represent assimilated coprolites. The humus-rich plasma is evenly distributed (Fig. 2d-I-*c*). Coal-like particles are absent, but roots of various sizes and decomposition degrees are present (they are absent in the other soils). The surface of skeletal grains is covered by clay–humus coatings inside the aggregates, whereas on the surface of aggregates these grains are covered by thin and fragmentary coatings (Fig. 2d-II-*b*); in some cases, such coatings are absent (Fig. 2d-II-*a*).

The mineralogical composition differs from that of the other soils by the higher content of micas, very small amount of ore and heavy minerals, and the absence of glauconite.

*Haplic Kastanozem.* This soil is characterized by the even impregnation of the clay material with humus. The clay–humus plasma is virtually isotropic (the flaky orientation is only seen at high magnification) and serves as a cement for sandy and silty skeleton grains (Fig. 2c-I-*c*). Dark collomorphic impregnating and fine-dispersed microforms of humus predominate (Fig. 2c-III-*b*). Coal-like particles are very small and single. Films on ped surfaces are thin (Fig. 2c-II-*a*).

Minerals of coarse fractions are mainly rounded. They are altered more strongly than those in the other soils and display iron and humus–iron pseudomorphs. Grains with old colonies of iron bacteria are present. Quartz and feldspar grains predominate; the amount of the grains of glauconite and epidote is somewhat smaller, whereas the content of ore minerals is higher.

Thus, the micromorphological analysis has made it possible to diagnose some characteristic genetic features of the compacted horizons in the studied soils. (1) In the Vertic Chernozem, the compacted horizon has some vertic properties diagnosed by the elongated aggregates with sharp angles that are specific to Vertisols according to [32]; the impregnation of the intraped mass is more intense near the surface of the peds with the formation of stress cutans and very thin coatings. These microfeatures attest to clay mobility inside the peds, which is also confirmed by the high content of WPC. Periodical water stagnation in the horizon is indicated by a large amount of small fragments of coal-like tissues and particles in the soil mass. (2) In the Calcic Kastanozem, the low content of exchangeable sodium is combined with definite microfeatures of the mobility of organomineral substances with the formation of thin coatings on the surface of aggregates and on the coarse minerals in the intraped mass; compact clayey infillings are seen in fine pores. The alternation of oxidation–reduction conditions is indicated by numerous iron concentrations. (3) The Haplic Chernozem is characterized by preservation of the spongy microstructure typical of fertile soils and by the active biogenic transformation of the soil material with preservation of coprolites and the high amount of plant residues. The absence of clay–humus coatings on minerals of the coarse fraction located on the surfaces of studied aggregates attests to regular excessive moistening of the soil upon irrigation. (4) Contrary to the other soils, the microfeatures of active intraped migration of substances are absent in the Haplic Kastanozem; the clay–humus plasma evenly impregnates the soil mass, and textural pedofeatures (clay films) are absent, which points to some advantages of the rainfed farming practiced on this soil.

*The tomographic analysis* provides data for quantitative characterization of the pore space in the aggregates of the compared soils and confirms the results of the micromorphological analysis. The results of the tomographic investigation are given as a series of 2D roentgen images and 3D computer models for each sample (Fig. 3) with resolution of 0.88 μm. Table 5 contains the survey data for resolutions of 0.88 and 2.4 μm.

The 3D models of the aggregates differ considerably. Aggregates of the Vertic Chernozem are characterized by the most compact structure with distinct large sharp edges and tiny edges on their surface. Aggregates of the Calcic Kastanozem soil are also characterized by the compact structure, but it is less pronounced because of the microfractures on the aggregate surfaces. Aggregates of the Haplic Chernozem and Haplic Kastanozem qualitatively differ from the compact aggregates of the Vertic Chernozem and Calcic Kastanozem. They are fractured, contain a lot of grains and isolated nodes on the surfaces, and are mainly rounded.

In small aggregates 1–2 mm (the resolution is 0.88 μm), the total porosity seen in the tomograms varies from 35 to 50%. The aggregate of the Calcic Kastanozem has the lowest porosity. It should be noted that the visual total porosity for the chernozems with vertic properties is 50% and is close to that of virgin chernozems. However, in the larger agronomically valuable aggregates of 3–5 mm in size (the resolution is 2.4 μm), the characteristics of the total visual porosity are different. In the Vertic Chernozem, it decreases to 16%. In the other samples, the values of the total visual porosity determined for the coarse aggregates (with a resolution of 2.4 μm) and for the small aggregates (with a resolution of 0.88 μm) are similar (Table 5).

As shown earlier, specific features of the composition and structure of the compacted horizon of the Vertic Chernozem attest to the development of vertic properties in this horizon. At the same time, the total visual porosity of coarse agronomically valuable aggregates (scanned with a resolution of 2.44 μm) from the compacted horizon of the Calcic Chernozem is more than two times lower than that of the other aggregates, which is obviously related to the formation of a large amount of very fine pores with the mean diameter of 7–12 μm. For the small aggregates scanned with a resolution of 0.88 μm, the total visual porosity reaches 50%, and the mean diameter of the pores equal to 7–12 μm is preserved.

The total visual porosity (37%) and the open porosity (9%) seen in the tomograms of small aggregates from the compacted horizon of the Calcic Kastanozem are considerably lower than those in the small aggregates from the other soils, where they exceed 44 and 35%, respectively. According to the micromorphological data, this can be explained by the development of solonetz-forming process in the Calcic Kastanozem with the high content of clay material both in the pores and in the intraped mass. This decreases the volume of the pores and their connectivity inside the aggregates.

## CONCLUSIONS

The formation of compacted horizons in arable soils of the southern part of the steppe zone was studied in four soils of Krasnodar region and Saratov oblast of European Russia. Specific features of the morphology of these horizons, the development of which cannot be eliminated via simple exclusion of

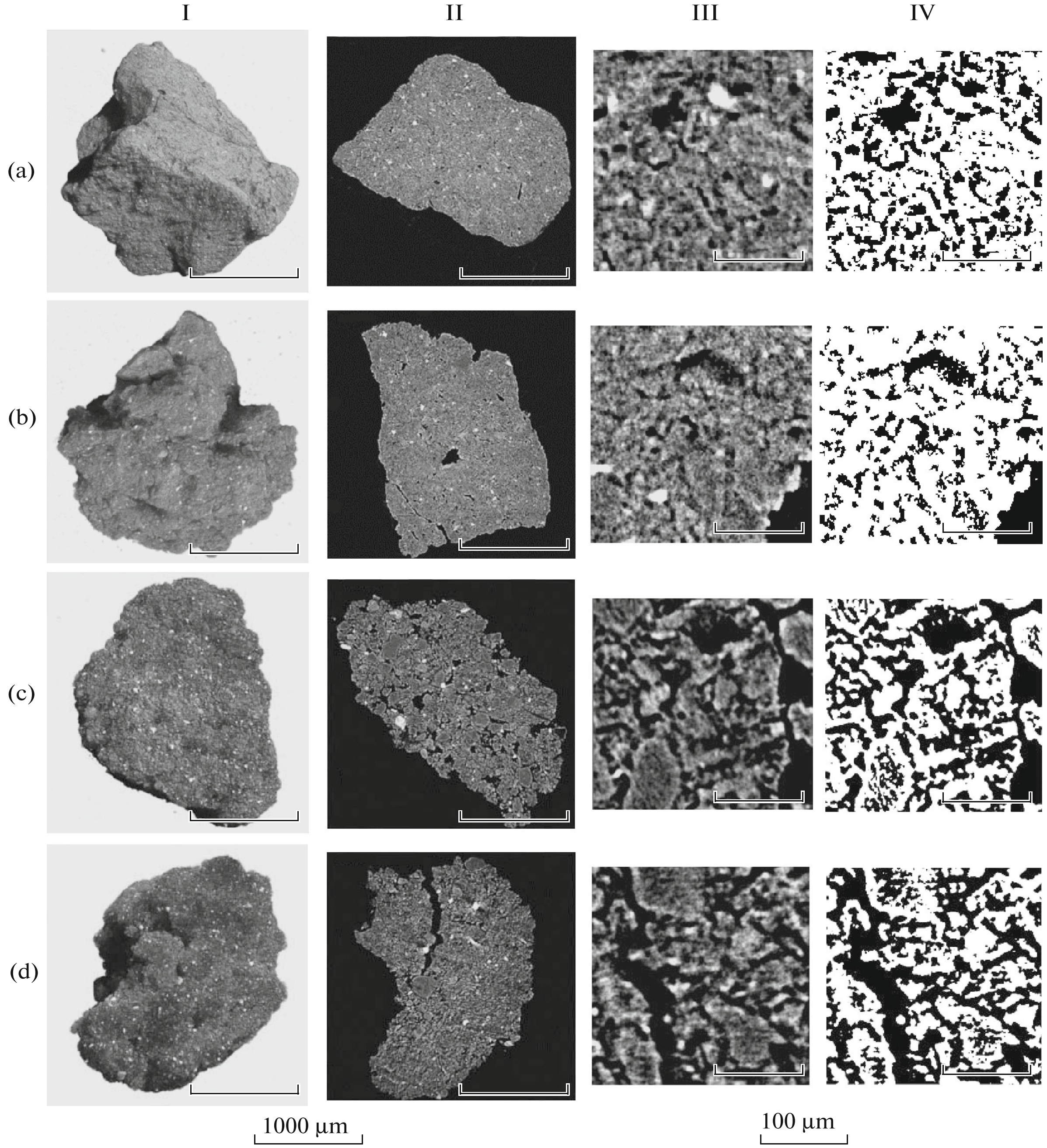

**Fig. 3.** Visualization of aggregates 1–2 mm in size (resolution 0.88 μm) from the compacted horizons: (I) 3D, (II) 2D (layer by layer); (III) and (IV) initial and binarized images.

"unsustainable" soil management, were found in the Calcic Chernozem and Calcic Kastanozem. In the Calcic Chernozem, the compacted horizon displayed some vertic properties. In the Calcic Kastanozem, it had solonetzic features (probably of the relict nature). In the other two soils, the genesis of the compacted horizon was directly related to the agrogenic compaction, which could be prevented via the use of sustainable soil management practices. In the Haplic Chernozem, the physical compaction of this horizon took place under irrigated management conditions; in the Haplic Kastanozem, it took place under rainfed management conditions.

Actual features of soil compaction can be diagnosed with the use of traditional studies of soil macro- and micro-morphology and soil physical properties in the dry period with indication of the soil stratification, bulk density, porosity, shape of the aggregates, the distinctness of aggregate faces and edges, quality and strength of the soil structure, distribution of the roots, etc.

**Table 5.** Microtomographic data. General characterization of aggregates from the compacted soil horizons

| Parameter | Typical chernozem | Meadow-chestnut soil | Southern chernozem | Dark chestnut soil |
|---|---|---|---|---|
| Total porosity, % | 50 (16) | 37 (30) | 45 (42) | 44 (43) |
| Open pores, % | 38 | 9 | 35 | 35 |
| Pore opening, µm | 7–12 | 8–20 | 12–40 | 12–120 |
| Aggregate structure | Compact, uniform, smooth faces with sharp edges | Compact with microfractures; rough faces with sharp edges | Nonuniform, porous; rough faces with blunt edges | Nonuniform, fissured; rough faces with blunt edges |

Porosity of aggregates 1–2 mm (resolution 0.88 µm) is given without parentheses, and porosity of aggregates 3–5 mm (resolution 2.44 µm) is given in parentheses.

Micromorphological features (the presence of coatings on ped faces and pore walls, distribution of humic substances, composition of plasma and its orientation and distribution, corrosion of mineral grains, the abundance of humus microforms, porosity, and shape of the microaggregates) can be applied for a more complete characterization of the processes taking place in the compacted soils.

Morphological and micromorphological data can be used to predict the the risks of soil compaction; additional information is provided by quantitative data on the particle-size distribution, the content of water-peptizable clay, the humus content, the soil acidity, and the exchangeable sodium content.

The key differences between the studied compacted horizons can be estimated from the results of the computer microtomography in combination with the micromorphological study. Although the morphological, physical, and chemical properties of the compacted soil horizons with vertic and solonetzic features are similar, the characteristic feature of the vertic horizons is the high content of fine (7–12 µm) aggregate pores, whereas the solonetzic horizons are specified by abundant clay material in the pores and in the intraped mass and by the lowest content (9%) of open pores visible in the tomograms among the studied compacted horizons.

Aggregates from the compacted horizons of agrogenic nature (wheel compaction) under irrigation and rainfed conditions have their own qualitative and quantitative specificity. They are highly fractured and contain numerous grains and isolated nodes on their surfaces. Their visible total porosity is relatively high (42–45%) in both small and coarse aggregates. In the rainfed soils, the microfeatures of the active intraped migration of substances are absent, the clay–humus plasma evenly impregnates the soil mass, and textural pedofeatures (clay coatings) are absent.

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