Pol. J. Environ. Stud. Vol. 25, No. 1 (2016), 259-271
DOI: *10.15244/pjoes/60161*

Original Research

Comparing the Physical Quality of Polish Chernozems Classified in Various Complexes of Agricultural Suitability

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Received: 27 August 2015
Accepted: 12 October 2015

Abstract

The objective of this study was the estimation of water and air properties of Polish Chernozems developed from loess, classified in various complexes of agricultural suitability. Twelve Chernozems situated in various physical geographic mesoregions of Poland were selected for the study. Chernozems classified in the very good wheat complex were characterised by significantly lower soil density, but greater field water capacity (expressed in $kg \cdot kg^{-1}$ and $m^3 \cdot m^{-3}$), water capacity at permanent wilting point, and content of micropores with equivalent diameter <0.2 μm compared to Chernozems from good and deficient wheat complexes. Chernozems classified in the particular complexes of agricultural suitability did not differ significantly in terms of their maximum water capacity, retention of water usable for plants, hydraulic conductivity in the saturated zone, total porosity, content of macropores >20 μm, content of mesopores with equivalent diameter of 0.2-20 μm, relative field capacity, air permeability at the state of field water capacity, and the index of physical quality *S* according to Dexter. Based on the absolute values of the calculated index *S* the physical quality of all Chernozems under study was estimated as very good. Among the particular properties the most favourable were the following: soil density, total porosity, field water capacity, and retention of water usable for plants, whereas the air capacity and permeability at the state of field water capacity and the saturated hydraulic conductivity were most frequently estimated as good or medium.

Keywords: Chernozems developed from loess, complexes of agricultural suitability, soil physical quality, water-air properties

Introduction

The quality of soil is defined as its ability to function within natural or agriculturally transformed ecosystems, to maintain high plant and animal productivity, with simultaneous preservation of good quality of water and air while ensuring good health status of humans and the natural environment [1, 2]. Soil quality cannot be measured directly, but it can be estimated on the basis of the properties of the soil itself, or of the features of the ecosystem of which it is a part. The indicators of soil quality and health status include numerous morphological features as well as physical, physicochemical, chemical, and biological properties related with the conditions prevailing in soil and with its functions [3-5].

The concept of physical quality of soil is used for quantitative estimation of the physical properties of soils through the comparison of their values with the optimum range and critical limits [6, 7]. The indices for

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the estimation of the physical quality of soils include particle size distribution, soil structure, water resistance of soil aggregates, soil density, field water capacity, retention of water usable for plants, hydraulic conductivity, air capacity, and other physical parameters [2, 8, 9]. Arable soils with good physical quality ensure a balance between the ability of retention and transport of water with dissolved nutrients and the ability of retaining air for the maximum productivity of cultivations and minimum degradation of the environment. Such soils are sufficiently coherent to keep plants upright, resistant to compaction and erosion, and at the same time permit unrestricted growth of plant roots and migration of microorganisms and soil mesofauna [6].

In field conditions the particular physical properties interact with one another and affect the biological properties and plant growth conditions. Stable aggregate structure prevents excessive compaction of soil and ensures that the soil has a favourable content of capillary pores (with equivalent diameter of 0.2-20 μm) for the retention of water usable for plants, and a suitable content of macropores with diameters >20 μm, which determine the hydraulic conductivity and air capacity and permeability [10-12]. Thanks to this, plant roots have unconstrained access both to water and to oxygen contained in soil air. The stability of aggregates has a beneficial effect on the growth of soil microorganisms; enhances the biological activity of soil; creates suitable conditions for germination, emergence, and growth of plants; has a favourable effect on plant root length and canopy density; protects the soil from surface crusting; and increases the infiltration of precipitation. The water properties of soils, especially retention of water usable for plants and hydraulic conductivity, determine the water balance of soils, the accessibility of water with dissolved nutrients for plant roots, and its migration to the deeper genetic horizons [13-14]. The retention capacity of soil must alleviate water deficits in periods of drought. Soil moisture conditions also determine the effects of mechanical treatments applied to the soil during tillage and cultivation operations.

The quality of the physical status of soils can be determined on the basis of estimation of their particular properties, e.g. soil density, retention of usable water, pore size distribution [6, 15, 16], or by means of synthetic indices. Dexter [8, 17-19], on the basis of long-term studies, proposed the adoption of the index of soil physical quality S as a universal method of estimation of the physical status of all soils. That index, defined as the tangent of slope of water retention curve of a soil at its point of inflexion, is closely correlated with soil structure and soil pore size distribution.

Soils developed from loess formations – Chernozems included – are among those that are characterised by favourable physical properties [16]. Chernozems originated in the continental climate, with relative balance of precipitations and evapotranspiration, under grasses or forest-steppe vegetation. They are characterised by a deep black mollic humus horizon, developed as a result of the turf-forming processes consisting of biological accumulation of considerable amounts of organic matter in the soil substrate, with participation of soil fauna [20, 21]. As a result of intensive humification, organic-mineral complexes of humic acids with clay minerals formed in Chernozems, fixed with calcium compounds, and humus content may even reach the level of 4-8% [22]. Chernozems in Central Europe are considered to be relic soils and differ from the East European Chernozems by lesser thickness of humus horizon and lower humus content (2-3%) [21, 23, 24].

As a result of intensive agricultural use Chernozems situated on inclined loess slopes undergo water and tillage erosion [25-27]. The erosion causes a reduction of the thickness of the humus horizon of Chernozems and of humus content, and a change of some other properties. The intensity of the processes of erosion on inclined slopes causes soils to be classified in various soil quality classes and complexes of agricultural suitability [28, 29].

The classification of agricultural suitability of soils is based mainly on their morphological structure, certain properties, and situation in land relief. According to that classification, soils classified in the very good wheat complex are characterised by medium or heavy particle size distribution, good water permeability, water retention capacity, and air permeability [29]. In soils from the good wheat complex the reason for reduced fertility can be lesser thickness of humus horizon, low intensity of erosion properties, and low water permeability. In soils from the deficient wheat complex the reduction of fertility is related to their situation on slopes, causing the threat of surface runoff, soil erosion, and insufficient moisture.

The objective of the study was the comparison of the water-air relations of Polish Chernozems developed from loess, classified in different complexes of agricultural suitability: very good wheat complex, good wheat complex, deficient wheat complex, and the estimation of their physical quality.

Materials and Methods

Twelve Haplic Chernozems developed from loess were selected for the study, including four pedons each from the particular complexes of agricultural suitability under winter wheat cultivation. The soils were situated in localities from various physical-geographic mesoregions of Poland [30]:

a) Chernozems classified in the very good wheat complex (1) and soil quality classes I-II, situated on loess hilltops and not undergoing erosion [29]: 1 – Bidziny, 2 – Grochocice (Sandomierz Upland), 3 – Żulice, 4 – Łykoszyn (Sokal Ridge)
b) Chernozems classified in the good wheat complex (2) and soil quality class IIIa, situated on gently loess slopes with inclination of 2-3º and weak erosion intensity: 5 – Zajączkowice, 6 – Prusinowice (Sandomierz Upland), 7 – Kryszyn, 8 – Telatyn (Sokal Ridge)
c) Chernozems developed from loess, classified in the deficient wheat complex (3) and soil quality class IVa,

situated on loess slopes >5º and subject to considerable erosion [28]: 9 – Franusin, 10 – Wasylów, 11 – Radostów (Sokal Ridge), 12 – Kułakowice (Horodło Ridge). Chernozems of this type have formerly been erroneously classified as brown soil proper.

The Chernozems selected for the study were situated in private farms, where the share of cereals in crop rotation was most often 75%. The Chernozems were characterised by low levels of organic fertilisation, consisting mainly in ploughing-over of straw. The level of mineral fertilisation varied, with predominance of nitrogen fertilisers, while liming was performed rarely.

As the physical properties of arable soils change during the vegetation season due to the tillage and cultivation treatments performed, field studies were conducted in August, when wheat was at the phase of full maturity or soon after its harvest. That is a sampling time suitable for the comparison of the water-air properties of various soils, as the effect of soil-loosening tools is then limited and the properties are fairly stabilised. Soil samples were collected from four layers of the pedons, with depths of 0-25 cm (from Ap horizon), 25-50 cm (from horizons A or ABw), 50-75 cm (from horizons A, Bw or Ck), and 75-100 cm (from horizons ABw, Bw, or Ck). Apart from standard samples for the determination of particle size distribution and chemical properties, samples with undisturbed structure were taken into metal 100 cm^3 cylinders [31]. The latter samples were collected in a total of eight replications (four for the determination of water capacity and air permeability and four for the determination of saturated hydraulic conductivity).

The particle size distribution was determined with the Casagrande areometric method as modified by Prószyński, with sand sub-fraction separation on sieves with mesh size of 1, 0.5, 0.25, and 0.1 mm. The particle size groups were determined in accordance with the classification of the Polish Society of Soil Science of 2008 [32]. The content of organic carbon was assayed with a Vario Max CNS Elementar analyser at the Central Laboratory of Chemical Analyses IUNG, Puławy. The content of $CaCO_3$ was assayed by means of a Scheibler apparatus. Soil reaction in 1 $mol \cdot dm^{-3}$ KCl was measured potentiometrically using a combined electrode.

Solid phase density ($Mg \cdot m^{-3}$) was assayed with the pycnometric method. Soil density ($Mg \cdot m^{-3}$) was determined with the thermogravimetric method, calculating the values on the basis of the ratio of the mass of soil dried at 105°C to its initial volume of 100 cm^3. Total porosity ($m^3 \cdot m^{-3}$) was calculated on the basis of solid phase density and soil density [33].

Water capacity ($kg \cdot kg^{-1}$ and $m^3 \cdot m^{-3}$) within the soil water potential from -0.1 kPa (pF 0) to -49.03 kPa (pF 2.7) was determined in 4 replications in low-pressure chambers, and in the range from -155 kPa (pF 3.2) to -1554 kPa (pF 4.2) in high-pressure chambers, on porous ceramic plates made by Eijkelkamp Agrisearch Equipment and Soil Moisture Equipment Corporation [34]. The content of water at soil water potential value of -0.1 kPa (pF 0) was adopted as maximum water capacity. The content of water at potential of -15.5 kPa (pF 2.2) was adopted as field water capacity, and the capacity at permanent wilting point at the potential of -1554 kPa (pF 4.2).

The retention of water usable for plants ($kg \cdot kg^{-1}$) was calculated as the difference between the value of field water capacity (-15.5 kPa) and the water capacity at the permanent wilting point (-1554 kPa). The effect of hysteresis was omitted from the calculations of water retention of the soils [34].

The relative field water capacity (ability to retain water in relation to the total volume of pores) was calculated on the basis of the value of total porosity and the field water capacity (at potential of 15.5 kPa), expressed in $m^3 \cdot m^{-3}$ [6].

Soil pore size distribution (>20 μm, 0.2-20 μm, and <0.2 μm) was calculated on the basis of corresponding values of water capacity, expressed in $m^3 \cdot m^{-3}$ [33]. The content of macropores with equivalent diameter >20 μm was calculated from the difference between total porosity and field water capacity at potential of -15.5 kPa (pF 2.2). The content of mesopores with equivalent diameter of 0.2-20 μm was calculated on the basis of field water capacity at potential of -15.5 kPa (pF 2.2) and water capacity at permanent wilting point at potential of -1554 kPa (pF 4.2). The content of micropores with equivalent diameter <0.2 μm was obtained from the value of water capacity at permanent wilting point at potential of -1554 kPa (pF 4.2).

Hydraulic conductivity in the saturated zone was measured with a Wit apparatus made by Eijkelkamp Agrisearch Equipment, with the method of constant and dropping water level [35]. The measurements were made after 24 hours from the moment of soil saturation with water in cylinders, and then coefficients of water filtration were calculated in metres per day ($m \cdot d^{-1}$).

Air permeability at field water capacity (-15.5 kPa) was measured by means of an LPiR-2e apparatus for the determination of air permeability of moulding sand. The measurements were made at pressure head of 0.981 kPa in the measurement chamber, at constant ambient temperature (20±1.0ºC) and constant relative air humidity (4±5%), so that the dynamic air viscosity could be omitted [16]. The results of measurements were obtained in units $m^2 \cdot Pa^{-1} \cdot s^{-1} \times 10^{-8}$.

Based on the water retention curves the indexes of physical status of soils *S* according to Dexter were calculated [17]. Index *S* was defined by the author as the tangent of slope of the water retention curve at its inflexion point to the axis of soil water potential and is calculated by means of the transformed van Genuchten equation:

$$S = -n\,(\theta_{sat} - \theta_{res})\,[1 + 1/m]^{-(1+m)} \quad (1)$$

…where the particular symbols denote:

θ_{sat} – water content in soil at full saturation ($kg \cdot kg^{-1}$),

θ_{res} – so-called “residual” (>pF 4.2) water content ($kg \cdot kg^{-1}$),

n – empirical parameter controlling the form of the retention curve, and

m – empirical parameter with Mualem constraint: $1–1/n$.

The graph of the water retention curve presents the relationship of the natural logarithm of soil-water potential to the gravimetric water content ($kg \cdot kg^{-1}$). The point of inflexion of the water retention curve means the boundary between the so-called "structural porosity" (determined by slots, biogenic ducts, and inter-aggregate pores dependent on soil use) and the "mother porosity" (intra-aggregate and inter-grain) determined by the particle size distribution of the soil. The fitting of the water retention curve to the van Genuchten equation is to ensure a standard and objective procedure for determining the inflexion point and calculation of the index of physical quality [36]. The calculation of index *S* was performed by means of a retention curve computer program (RETC) for the description of water properties of unsaturated soils.

The results were subjected to the analysis of variance with the use of double classification in a completely random system using the Statistica 7 PL program [37]. The significance of differences was verified with the Tukey test. In addition, the coefficients of simple correlation (r) between the water-air properties under study and the content of particle size fractions, C org. and $CaCO_3$ were calculated.

Results

The Chernozems developed from loess included in the study were characterised by a notable similarity of particle size distribution. Horizons Ap (0-25 cm) of soils classified in the very good wheat complex contained 12-14% of sand fraction (2-0.05 mm), 74-78% of silt (0.05-0.002 mm), and 8-12% of clay <0.002 mm (Table 1). Horizons Ap of soils from the deficient wheat complex contained slightly more clay fraction (13-17%), similarly to horizons A, ABw, Bw, and Ck in the layer of 25-100 cm (12-19%). In terms of their particle size distribution, the soils studied were most often clayey silt or loamy silt.

In horizons Ap of Chernozems classified in the very good wheat complex the content of C org. was 11.2-18.3 $g \cdot kg^{-1}$, which – when converted to organic matter – is 1.9-3.2%. In soils from the good wheat complex the content of C org. was slightly lower, and in soils from the deficient wheat complex the lowest (7.0-9.7 $g \cdot kg^{-1}$) (Table 1). With the depth of the pedons, the content of C org. decreased to 0.6-2.5 $g \cdot kg^{-1}$ in horizons Bw and Ck.

The Chernozems classified in the very good wheat complex contained $CaCO_3$ at a depth of 75-100 cm or deeper (in horizons Bw and Ck), while certain Chernozems from the good and the deficient wheat complexes situated on slopes contained calcium carbonate also in horizons Ap and A (Table 1). Reaction in horizons Ap of soils classified in the very good wheat complex was acidic (pH 4.7-5.4), and in horizons A and ABw weakly acidic (pH 5.7-6.4). In the soils from the good and the deficient wheat complexes the reaction varied from acidic to alkaline (pH 5.1-7.9), depending on the occurrence or absence of calcium carbonate.

Solid phase density in horizons Ap of the Chernozems under study was 2.61-2.64 $Mg \cdot m^{-3}$, and in deeper horizons it increases significantly to 2.63-2.69 $Mg \cdot m^{-3}$ (Table 2). On average, soil density in horizons Ap (in the layer of 0-25 cm) was 1.34 $Mg \cdot m^{-3}$, and it was significantly lower (by 0.04-0.13 $Mg \cdot m^{-3}$) than soil density in the sub-surface horizons A, ABw, Bw, and Ck (in the layer of 25-100 cm). Chernozems classified in the very good wheat complex were characterised by significantly lower compaction (on average by 0.04 $Mg \cdot m^{-3}$) compared to the soils from the good and the deficient wheat complexes.

Table 1. Soil texture and some properties of Chernozems (range of values from four pedons).

Complex	Layer – depth (cm)	Horizons	% fraction with diameter in mm			C org. ($g \cdot kg^{-1}$)	$CaCO_3$ ($g \cdot kg^{-1}$)	pH KCl
			2-0.05	0.05-0.002	<0.002			
1	0-25	Ap	12-14	74-78	8-12	11.2-18.3	0.0	4.7-5.4
	25-50	A	12-15	71-73	12-17	7.6-13.8	0.0	5.7-6.1
	50-75	A, Bw	12-14	70-73	14-17	1.6-12.0	0.0	6.2-6.4
	75-100	ABw, Bw	12-14	70-72	14-18	1.7-6.9	0.0-16.9	6.3-7.4
2	0-25	Ap	11-14	74-79	7-14	9.8-14.1	0.0-16.9	5.1-7.4
	25-50	A	11-15	66-74	15-19	5.2-7.9	0.0-65.5	6.0-7.6
	50-75	Bw, Ck	12-14	69-74	14-17	1.4-1.9	0.0-103.5	6.1-7.8
	75-100	Bw, Ck	12-15	71-74	14-15	0.6-1.7	0.0-128.9	6.8-7.9
3	0-25	Ap	11-16	71-76	13-17	7.0-9.7	0.0-31.7	6.6-7.5
	25-50	ABw	11-19	66-75	14-17	3.1-5.2	0.0-80.4	6.3-7.8
	50-75	Bw, Ck	12-20	67-73	13-16	1.2-2.5	1.3-90.8	7.3-7.8
	75-100	Ck	12-16	72-74	12-15	0.8-2.5	35.9-93.0	7.7-7.9

Table 2. Bulk density and water-air properties (mean values from four pedons).

Complex (C)	Layer – depth (cm) (L)	Particle density ($Mg·m^{-3}$)	Bulk density ($Mg·m^{-3}$)	Water capacity ($kg·kg^{-1}$) at			Retention of useful water ($kg·kg^{-1}$)	Saturated hydraulic conductivity ($m·d^{-1}$)
				-0.1 kPa	-15.5 kPa	-1554 kPa		
1	0-25	2.61	1.33	0.369	0.272	0.077	0.195	0.41
	25-50	2.63	1.37	0.350	0.258	0.079	0.179	0.28
	50-75	2.64	1.40	0.335	0.251	0.076	0.175	1.26
	75-100	2.67	1.44	0.320	0.246	0.072	0.174	1.05
2	0-25	2.63	1.34	0.366	0.251	0.078	0.173	1.45
	25-50	2.65	1.40	0.337	0.247	0.077	0.170	1.03
	50-75	2.68	1.44	0.321	0.244	0.063	0.181	1.14
	75-100	2.68	1.48	0.303	0.238	0.060	0.178	0.34
3	0-25	2.64	1.34	0.367	0.260	0.076	0.184	0.91
	25-50	2.67	1.38	0.350	0.259	0.069	0.190	0.13
	50-75	2.69	1.46	0.313	0.237	0.061	0.176	0.96
	75-100	2.68	1.49	0.298	0,226	0.063	0.163	0.81
Mean	0-25	2.63	1.34	0.367	0.261	0.077	0.184	0.92
	25-50	2.65	1.38	0.346	0.255	0.075	0.180	0.48
	50-75	2.67	1.43	0.323	0.244	0.067	0.177	1.12
	75-100	2.68	1.47	0.307	0,237	0.065	0.172	0.74
1	mean	2.64	1.38	0.344	0.257	0.076	0.181	0.75
2		2.66	1.42	0.332	0.245	0.070	0.175	0.99
3		2.67	1.42	0.332	0.246	0.067	0.179	0.70
LSD ($\alpha = 0.05$):	layers L	0.01	0.03	0.017	0.010	0.003	0.010	0.62
	complexes C	0.01	0.03	n. s.	0.008	0.003	n. s.	n. s.
	interaction L×C	0.02	n. s.	n. s.	n. s.	0.005	0.016	1.03

n. s. – non significant differences

Maximum water capacity (at soil water potential of -0.1 kPa) in horizons Ap (0-25 cm) was, on average, 0.367 $kg·kg^{-1}$, and it was significantly higher (on average by 0.021-0.060 $kg·kg^{-1}$) than in the sub-surface horizons (25-100 cm), whereas the differences of maximum water capacity of soils from the particular complexes of agricultural suitability were statistically insignificant (Table 2).

Field water capacity (at soil water potential of -15.5 kPa), measured in relation to soil mass in the 0-50 cm layer of the Chernozems, was 0.261-0.255 $kg·kg^{-1}$, and it was significantly higher (by 0.011-0.024 $kg·kg^{-1}$) than in the layer of 50-100 cm. In soils of the very good wheat complex that capacity was significantly higher (by an average of 0.011-0.012 $kg·kg^{-1}$) than in soils from the good and the deficient wheat complexes (Table 2).

Water capacity at the permanent wilting point of plants (at soil water potential of -1554 kPa) was the highest (the least favourable) in horizons Ap and A (0.076-0.079 $kg·kg^{-1}$). In the layer of 0-50 cm that property was significantly higher (on average by 0.008-0.012 $kg·kg^{-1}$) than in the layer of 50-100 cm. In the Chernozems from the very good wheat complex it was significantly greater (on average by 0.006-0.009 $kg·kg^{-1}$) than in soils classified in the good and the deficient wheat complexes (Table 2).

Retention of water usable for plants (in the range of water potential from -15.5 kPa to -1554 kPa) in horizons Ap of the Chernozems studied was, on average, 0.184 $kg·kg^{-1}$, and it was significantly higher (by 0.012 $kg·kg^{-1}$) than in the 75-100 cm layer, whereas no significant differences were noted in the retention of usable water among soils classified in the particular complexes of agricultural suitability (Table 2). Significant differences appeared only in the interaction of the complexes of agricultural suitability with the layers in the pedons.

Table 3. Water-air properties – continued (mean values from four pedons).

Complex (C)	Layer – depth (cm) (L)	Total porosity ($m^3·m^{-3}$)	Water capacity at –15,5 kPa ($m^3·m^{-3}$)	Pore-size content ($m^3·m^{-3}$)			Relative field capacity	Air permeability at –15.5 kPa (×10^{-8} $m^2·Pa^{-1}·s^{-1}$)	Index *S*
				>20 µm	0.2-20 µm	<0.2 µm			
1	0-25	0.491	0.362	0.129	0.259	0.103	0.74	14.8	0.066
	25-50	0.480	0.353	0.127	0.245	0.108	0.74	47.5	0.060
	50-75	0.470	0.351	0.119	0.245	0.106	0.75	69.5	0.060
	75-100	0.461	0.354	0.107	0.251	0.103	0.77	95.7	0.059
2	0-25	0.490	0.335	0.155	0.230	0.105	0.68	60.1	0.058
	25-50	0.471	0.346	0.125	0.239	0.107	0.74	40.2	0.058
	50-75	0.462	0.351	0.111	0.260	0.091	0.76	57.4	0.062
	75-100	0.447	0.352	0.095	0.263	0.089	0.79	48.0	0.061
3	0-25	0.491	0.347	0.144	0.245	0.102	0.70	29.6	0.064
	25-50	0.483	0.357	0.126	0.261	0.096	0.74	31.1	0.068
	50-75	0.457	0.345	0.112	0.255	0.090	0.76	84.8	0.062
	75-100	0.444	0.337	0.107	0.243	0.094	0.76	55.6	0.057
Mean	0-25	0.491	0.348	0.143	0.245	0.103	0.71	34.8	0.063
	25-50	0.478	0.352	0.126	0.248	0.104	0.74	39.6	0.062
	50-75	0.463	0.349	0.114	0.253	0.096	0.76	70.6	0.061
	75-100	0.451	0.347	0.104	0.252	0.095	0.77	66.4	0.059
1	mean	0.475	0.355	0.120	0.250	0.105	0.75	56.9	0.061
2		0.468	0.346	0.122	0.248	0.098	0.74	51.5	0.060
3		0.469	0.346	0.123	0.251	0.095	0.74	50.3	0.063
LSD (**α** = 0,05):	layers L	0.013	n.s.	0.015	n. s.	0.005	0.03	35.7	n. s.
	complexes C	n. s.	0.007	n. s.	n. s.	0.004	n. s.	n. s.	n. s.
	interaction L×C	n. s.	0.015	n. s.	0.018	0.008	0.04	n. s.	0.007

n. s. – non significant differences

Hydraulic conductivity in the saturated zone of the Chernozems under study displayed a notable variation of measurement results obtained in the particular pedons. In the layer of 50-75 cm hydraulic conductivity was, on average, 1.12 $m·d^{-1}$, and it was significantly higher (by 0.64 $m·d^{-1}$) than in the layer of 25-50 cm. Due to the large variation of values, the differences among Chernozems classified in the particular complexes of agricultural suitability were not significant, whereas a few significant differences in the interaction of the complexes of agricultural suitability with the layers appeared (Table 2).

Total porosity in horizons Ap of the soils under study was, on average, 0.491 $m^3·m^{-3}$, and it was significantly higher (by 0.013-0.040 $m^3·m^{-3}$) than in the deeper horizons. No significant differences were noted among the soils classified in the particular complexes of agricultural suitability (Table 3).

Field water capacity (at soil water potential of -15.5 kPa), measured in relation to soil volume in the particular layers of the Chernozems, varied only slightly (0.352-0.347 $m^3·m^{-3}$). In soils of the very good wheat complex that capacity was significantly higher (on average by 0.009 $m^3·m^{-3}$) than in soils from the good and the deficient wheat complexes (Table 3).

Content of macropores with equivalent diameter >20 µm determines the air capacity of soil at field water capacity, and in periods of intensive precipitations it determines the ability of gravitational water retention in the soil. Horizons Ap of the Chernozems under study contained, on average, 0.143 $m^3·m^{-3}$ of air pores – significantly more (by 0.017-0.039 $m^3·m^{-3}$) than the deeper horizons (Table 3). The volume of macropores >20 µm did not display any significant differences among soils classified in different complexes of agricultural suitability.

The average content of mesopores with equivalent diameter of 0.2-20 µm, retaining water usable for plants, was 0.245-0.253 $m^3·m^{-3}$ and did not display any significant differences between the particular layers of the

Table 4. Correlation coefficients (r) between granulometric fractions, C org., and $CaCO_3$ content and water-air properties (n = 48).

Variable	% fraction with diameter in mm			C org.	$CaCO_3$	pH
	2-0.05	0.05-0.002	<0.002			
Bulk density ($Mg \cdot m^{-3}$)	0.03	-0.25	0.27	-0.65**	0.41**	0.61**
Maximum water capacity ($kg \cdot kg^{-1}$)	-0.03	0.26	-0.27	0.60**	-0.37**	-0.55**
Field water capacity ($kg \cdot kg^{-1}$)	0.50**	0.23	-0.32	0.45**	-0.26	-0.37**
Wilting point ($kg \cdot kg^{-1}$)	-0.40**	0.21	0.10	0.80**	-0.34*	-0.54**
Retention of useful water ($kg \cdot kg^{-1}$)	0.24	0.15	-0.38**	0.10	-0.11	-0.09
Hydraulic conductivity ($m \cdot d^{-1}$)	0.02	-0.08	0.08	0.06	-0.17	-0.17
Total porosity ($m^3 \cdot m^{-3}$)	-0.05	0.24	-0.24	0.56**	-0.33*	-0.51**
Field water capacity ($m^3 \cdot m^{-3}$)	0.10	0.09	-0.19	0.02	0.02	0.07
Macropores >20 µm ($m^3 \cdot m^{-3}$)	-0.11	0.17	-0.11	0.51**	-0.33*	-0.46**
Mesopores 20-0.2 µm ($m^3 \cdot m^{-3}$)	-0.30*	0.02	-0.28	-0.29*	0.12	0.23
Micropores <0.2 µm ($m^3 \cdot m^{-3}$)	-0.45**	0.10	0.27	0.62**	-0.21	-0.35*
Relative field capacity	0.12	-0.14	0.06	-0.47**	0.31*	0.42**
Air permeability at –15.5 kPa	-0.20	-0.14	0.34*	0.09	-0.04	-0.17
Index S	0.23	0.09	-0.31*	-0.20	0.12	0.20

* significance level α = 0.05, ** significance level α = 0.01

Chernozems (Table 3). Also, the differences between the complexes of agricultural suitability were not significant, but there were sporadic significant differences in the interaction of the complexes with the layers in the pedons.

In the layer of 0-50 cm the content of soil micropores with equivalent diameter <0.2 µm, retaining water very strongly bound with molecular forces and unavailable for plants, was 0.103-0.104 $m^3 \cdot m^{-3}$ and it was significantly higher (by 0.007-0.009 $m^3 \cdot m^{-3}$) in comparison with the layer of 50-100 cm (Table 3). The average content of micropores in Chernozems from the very good wheat complex was significantly higher (by 0.007-0.010 $m^3 \cdot m^{-3}$) compared to the soils from the good and the deficient wheat complexes.

Relative field water capacity characterises the soil ability of water retention in relation to the total pore volume. In horizons Ap of the soils studied that property had a mean value of 0.71 and it was significantly lower (by 0.03-0.06) than in the deeper horizons (Table 3). No significant differences were noted among the particular complexes of agricultural suitability, but there were a few significant differences in the interaction of the complexes with the layers of the Chernozems.

Analysis of air permeability of the soils in the state of field water capacity (at water potential of -15.5 kPa) demonstrated a notable variation of results obtained. In the layer of 50-75 cm of the Chernozems air permeability was, on average, 70.6×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$ and it was significantly higher (by 35.8×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$) than in horizons Ap (Table 3), whereas the differences in air permeability between the complexes of agricultural suitability were insignificant.

Values of Dexter's index of physical quality *S*, calculated by means of the computer program RETC, were high for all of the Chernozems studied and varied from 0.060 to 0.063 (Table 3). Index *S* displayed statistically significant differences only in the interaction of the complexes of agricultural suitability and the soil layers.

Statistical analysis did not reveal many significant correlations between the content of the particular particle size fractions and the water-air properties of the Chernozems (Table 4). That was due to the very small variation of the particle size distribution in the soil population under study. The content of clay <0.002 mm showed a weak positive correlation with air permeability (r = 0.34) and a close negative correlation with retention of usable water from plants (r = -0.38), and a weak negative correlation with index *S* (r = -0.31). The content of C org. closely correlated positively with maximum water capacity (r = 0.60), field water capacity expressed in $kg \cdot kg^{-1}$ (r = 0.45), permanent wilting point of plants (r = 0.80), total porosity (r = 0.56), content of macropores >20 µm (r = 0.51), and content of micropores (r = 0.62). In turn, soil density (r = -0.65), relative field capacity (r = -0.47) and content of mesopores (r = -0.29) displayed negative correlation with the content of C org. The content of $CaCO_3$ correlated positively with soil density (r = 0.41) and relative field water capacity (r = 0.31), and negatively with maximum water capacity (r = -0.37), permanent wilting point (r = -0.34), total porosity (r = -0.33), and content of macropores (r = -0.33). Similar correlations with the physical properties under study were shown by pH, the highest absolute values of coefficients of correlation being noted with soil density (r = 0.61) and maximum water capacity (r = -0.55).

Table 5. Correlation coefficients (r) between water-air properties (n = 48).

Variable	Bulk density ($Mg \cdot m^{-3}$)	Maximum water capacity ($kg \cdot kg^{-1}$)	Field water capacity ($kg \cdot kg^{-1}$)	Wilting point ($kg \cdot kg^{-1}$)	Retention of useful water ($kg \cdot kg^{-1}$)	Hydraulic conductivity ($m \cdot d^{-1}$)	Total porosity ($m^3 \cdot m^{-3}$)	Field water capacity ($m^3 \cdot m^{-3}$)	Macropores >20 µm ($m^3 \cdot m^{-3}$)	Mesopores 20-0.2 µm ($m^3 \cdot m^{-3}$)	Micropores >0.2 µm ($m^3 \cdot m^{-3}$)	Relative field capacity	Air permeability at –15.5 kPa	Index S
Bulk density ($Mg \cdot m^{-3}$)	1													
Maximum water capacity ($kg \cdot kg^{-1}$)	-0.99**	1												
Field water capacity ($kg \cdot kg^{-1}$)	-0.80**	0.80**	1											
Wilting point ($kg \cdot kg^{-1}$)	-0.56**	0.52**	0.33*	1										
Retention of useful water ($kg \cdot kg^{-1}$)	-0.58**	0.60**	0.89**	-0.12	1									
Hydraulic conductivity ($m \cdot d^{-1}$)	-0.22	0.23	0.01	0.16	-0.06	1								
Total porosity ($m^3 \cdot m^{-3}$)	-0.99**	0.99**	0.80**	0.50**	0.61**	0.22	1							
Field water capacity ($m^3 \cdot m^{-3}$)	-0.21	0.21	0.75**	-0.07	0.82**	-0.21	0.22	1						
Macropores >20 µm ($m^3 \cdot m^{-3}$)	-0.80**	0.81**	0.29*	0.51**	0.06	0.33*	0.80**	0.41**	1					
Mesopores 20-0.2 µm ($m^3 \cdot m^{-3}$)	-0.08	0.11	0.59**	-0.50**	0.86**	-0.20	0.12	0.88**	-0.42**	1				
Micropores <0.2 µm ($m^3 \cdot m^{-3}$)	-0.17	0.12	-0.01	0.91**	-0.44**	0.07	0.10	-0.19	0.21	-0.64**	1			
Relative field capacity	0.69**	-0.69**	-0.12	0.49**	0.10	-0.32*	-0.69**	0.56**	0.98**	0.56**	-0.24	1		
Air permeability at –15.5 kPa	-0.02	0.01	-0.18	0.34*	-0.35*	0.30*	0.03	-0.30*	0.29*	-0.43**	0.39**	-0.25	1	
Index S	-0.03	0.04	0.26	-0.40**	0.47**	0.13	0.07	0.42**	-0.19	0.57**	-0.49**	0.25	-0.02	1

* significance level $\alpha = 0.05$, ** significance level $\alpha = 0.01$

Analysis of correlation revealed many significant relationships among the particular water-air properties of the Chernozems (Table 5). Not all of the relationships obtained are equally important, some of them are obvious, while others are accidental. Maximum water capacity, field water capacity expressed in $kg \cdot kg^{-1}$, and total porosity displayed mainly a close negative correlation with soil density (r = -0.99 to -0.80). Permanent wilting point closely correlated negatively with soil density (r = -0.56) and positively with maximum water capacity (r = 0.52) and field water capacity (r = 0.33). Retention of water usable for plants correlated negatively with soil density (r = -0.58), and closely with field water capacity (r = 0.89) and total porosity (r = 0.61). Content of macropores with diameter >20 μm primarily correlated closely and positively with total porosity (r = 0.80), maximum water capacity (r = 0.81), and field water capacity expressed in $m^3 \cdot m^{-3}$ (r = 0.41). Content of mesopores of 20-0.2 μm correlated closely and positively with field water capacity expressed in $m^3 \cdot m^{-3}$ (r = 0.88) and with retention of usable water (r = 0.86), while it had negative correlations with the content of macropores >20 μm (r = -0.42) and micropores <0.2 μm (r = -0.64). In turn, relative field capacity showed a close positive correlation with the content of macropores >20 μm (r = 0.98) and mesopores (r = 0.56), and a negative correlation with total porosity (r = -0.69). Saturated hydraulic conductivity showed a weak positive correlation with the content of macropores >20 μm (r = 0.33). Air permeability at field water capacity had a weak positive correlation with the content of macropores (r = 0.29) and with saturated hydraulic conductivity (r = 0.30). The index of physical quality S showed a close positive correlation with the retention of water usable for plants (r = 0.47), field water capacity expressed in $m^3 \cdot m^{-3}$ (r = 0.42), and with the content of mesopores 20-0.2 μm (r = 0.57), and a negative correlation with the content of micropores (r = -0.49).

Discussion

The research results presented above demonstrated that Chernozems classified in the very good wheat complex were characterised by significantly lower soil density, but higher field water capacity, water capacity at permanent wilting point of plants, and content of micropores with equivalent diameter <0.2 μm compared to Chernozems from the good and the deficient wheat complexes. Chernozems classified in the particular complexes of agricultural suitability did not differ significantly in terms of their maximum water capacity, retention of water usable for plants, hydraulic conductivity in the saturated zone, total porosity, content of macropores >20 μm, content of mesopores with equivalent diameter of 0.2-20 μm, relative field water capacity, air permeability in the state of field water capacity, and the index of physical quality *S*. These small differences among the soils classified in the particular complexes of agricultural suitability resulted from the relatively slight differences in the particle size distribution of the soils (especially content of clay <0.002 mm), content of C org. and their aggregate composition. An earlier study [27] concluded that among Chernozems classified in particular complexes of agricultural suitability there were small differences in the content of air-dry aggregates with sizes of 0.25-10 mm. The composition of air-dry aggregates in horizons Ap, A, and ABw was estimated as good or medium, while in horizons Bw and Ck as medium or poor. In Chernozems classified in the very good wheat complex and the good wheat complex the content of stable aggregates with sizes of 0.25-10 mm was significantly higher than in soils from the deficient wheat complex. The composition of water-stable aggregates in horizons Ap of soils classified in the very good and good wheat complexes was estimated as good, and in horizons Ap of soils from the deficient wheat complex as medium. In the case of Chernozems the physical properties of loess as the mother rock are of decisive importance. The composition of loess is dominated by silica dust with sizes of 0.05-0.002 mm (66-79%). It was accumulated in subaerial conditions, in which freely deposited dust particles formed a little-compacted porous spatial system [38].

Values of physical properties similar to those presented in this study were obtained by other authors studying Polish Chernozems on Sokal Ridge [16] and Proszowice Plateau [25]. Pranagal [16] observed that soil density in horizon Ap (0-20 cm) of Chernozem under field cultivation was 1.26-1.29 $Mg \cdot m^{-3}$ and in horizon A (35-40 cm) 1.27 $Mg \cdot m^{-3}$. Field water capacity (-15.5 kPa) attained values of 0.293-0.300 $kg \cdot kg^{-1}$ in horizon Ap and 0.290 $kg \cdot kg^{-1}$ in horizon A. According to that author the retention of water usable for plants attained values of 0.210-0.218 $kg \cdot kg^{-1}$ in horizon Ap and 0.210 $kg \cdot kg^{-1}$ in horizon A. Saturated hydraulic conductivity was 0.16-0.37 $m \cdot d^{-1}$ in horizon A and 0.29 $m \cdot d^{-1}$ in horizon Ap. In turn, total porosity was 0.498-0.511 $m^3 \cdot m^{-3}$ in horizon Ap of the Chernozem and 0.507 $m^3 \cdot m^{-3}$ in horizon A. The content of macropores >20 μm was 0.111-0.142 $m^3 \cdot m^{-3}$ in horizon Ap and 0.139 $m^3 \cdot m^{-3}$ in horizon A, whereas the content of mesopores of 0.2-20 μm was 0.264-0.281 $m^3 \cdot m^{-3}$ in horizon Ap and 0.266 $m^3 \cdot m^{-3}$ in horizon A. Air permeability at the state of field water capacity was 49.0-49.2×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$ in horizon Ap and 2.0×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$ in horizon A. Żyła [25] demonstrated that typical Chernozems under agricultural use were characterised by soil density of 1.29-1.40 M $g \cdot m^{-3}$ in horizon Ap and 1.22-1.48 $Mg \cdot m^{-3}$ in deeper horizons, whereas eroded Chernozems were more compacted and attained values of 1.45 $Mg \cdot m^{-3}$ in horizons Ap and 1.24-1.53 $Mg \cdot m^{-3}$ in deeper horizons. Total porosity of typical Chernozems was 0.450-0.514 $m^3 \cdot m^{-3}$ in horizons Ap and 0.433-0.540 $m^3 \cdot m^{-3}$ in subsurface horizons. In turn, total porosity of eroded Chernozems was 0.440-0.445 $m^3 \cdot m^{-3}$ in horizon Ap and 0.412-0.529 $m^3 \cdot m^{-3}$ in deeper horizons.

East European Chernozems, which compared to Polish Chernozems have a much higher humus content (3.4-6%), are characterised by lower compaction and higher porosity than the Polish Chernozems. According to Korolev [39], mean soil density in typical and common Chernozems of the Russian Plain under field cultivation was 1.10-1.20 $Mg\cdot m^{-3}$ in the 0-30 cm layer and 1.22-1.42 $Mg\cdot m^{-3}$ in the 40-100 cm layer. Average values of total porosity of those soils were 0.535-0.571 $m^3\cdot m^{-3}$ in the 0-30 cm layer and 0.469-0.529 $m^3\cdot m^{-3}$ in the 40-100 cm layer. Air permeability at the state of field water capacity was 0.135-0.202 $m^3\cdot m^{-3}$ in the 0-30 cm layer and 0.107-0.176 $m^3\cdot m^{-3}$ in the o40-100 cm layer. Medvedev et al. [40] observed that soil density in the 0-30 cm layer of Ukrainian Chernozems was 1.13-1.24 $Mg\cdot m^{-3}$, while the optimum value according to those authors is 1.10-1.35 $Mg\cdot m^{-3}$. Kuznetsova [22] determined the normative values of physical parameters in the arable layer of Chernozems of the Central Russian Upland. According to those determinations the optimum soil density was 1.10-1.25 $Mg\cdot m^{-3}$, allowable density 1.25-1.35 $Mg\cdot m^{-3}$, and critical density >1.35 $Mg\cdot m^{-3}$. As optimum total porosity of Chernozems that author adopted 0.550-0.600 $m^3\cdot m^{-3}$, allowable porosity 0.450-0.550 $m^3\cdot m^{-3}$, and critical porosity <0.450 $m^3\cdot m^{-3}$. Optimum field water capacity according to that author was 0.320-0.360 $m^3\cdot m^{-3}$, allowable was 0.260-0.320 $m^3\cdot m^{-3}$, and critical <0.260 $m^3\cdot m^{-3}$. In turn, the optimum air capacity at field water capacity was 0.150-0.250 $m^3\cdot m^{-3}$, allowable was 0.100-0.150 $m^3\cdot m^{-3}$, and critical <0.100 $m^3\cdot m^{-3}$. The author observed that the use of heavy agricultural machinery and reduced doses of organic and mineral fertilisers for economic reasons caused greater compaction of soil and, as a result, unfavourable changes in the water-air properties of Chernozems. However, the optimum and critical values of physical properties determined for Russian Chernozems are not suitable for the evaluation of quality of other soils, differing considerably in their particle size distribution and organic matter content.

Soil density is a measure of packing of soil particles and it is one of the most important indicators of physical quality of soils. It is dependent on the mineral composition and particle size distribution of soils, their structure, and on the tillage and cultivation treatments applied and factors causing soil compaction [41, 42]. Soil density is the lowest in the surface layer of humus horizon and gradually increases with depth of the pedon. In horizons Ap of arable small-grained soils the optimum value most often adopted for soil density is 1.10-1.40 $Mg\cdot m^{-3}$, and the value of critical density ≥1.50-1.60 $Mg\cdot m^{-3}$ [6, 7, 15, 43]. Based on those determinations, soil density in horizons Ap of the Chernozems studied, 1.33-1.34 $Mg\cdot m^{-3}$, should be estimated as low, and on horizons A, Bw, and C (1.37-1.49 $Mg\cdot m^{-3}$) as low or medium.

Total porosity and pore size distribution are dependent on the same factors that affect soil density [42, 44]. Various authors have adopted values of 0.450-0.500 $m^3\cdot m^{-3}$ as favourable total porosity [15, 16, 45]. Based on this the total porosity in the 0-75 cm layer of the Chernozems studied, amounting to 0.457-0.491 $m^3\cdot m^{-3}$, should be estimated as high, while that in the 75-100 cm and 0.461 $m^3\cdot m^{-3}$ layers as high, and 0.444-0.447 $m^3\cdot m^{-3}$ as medium.

Maximum water capacity at soil-water potential of -0.1 kPa (pF 0) is strictly dependent on soil density and total porosity [34, 41, 46]. Field water capacity at soil water potential of -15.5 kPa (pF 2.2) corresponds to that amount of water that soil can retain after free drainage of gravitational water from a sample fully saturated with water, under conditions of no contact with ground water and elimination of surface evaporation. Field water capacity of soils is determined by their particle size distribution, soil density, and content of meso- and micropores. The literature gives values of 0.300-0.350 $m^3\cdot m^{-3}$ as favourable field water capacity for soils developed from loess [15, 47]. The field water capacity of the Chernozems studied, 0.351-0.362 $m^3\cdot m^{-3}$, was estimated as very high, and 0.337-0.347 $m^3\cdot m^{-3}$ as high.

Water capacity at permanent wilting point (-1554 kPa) is determined by the content of soil micropores <0.2 μm retaining water very strongly bound by intermolecular forces with the solid phase and soil and unavailable for plants. That property is dependent on the content of soil colloids, and especially the fraction of clay <0.002 mm [15, 16, 46]. Low values of that water capacity are favourable for plant growth.

In soil pore size distribution sufficiently high content of mesopores with equivalent diameter of 0.2-20 μm, retaining water usable for plants, and macropores >20 μm, ensuring soil aeration, is very important. The content of macropores >20 μm determines the air permeability of soils at the state of field water capacity, after the drainage of gravitational water. The volume of air-filled pores, the content of oxygen in soil air, and its exchange capacity have an enormous effect of the development of plant root systems and on the uptake of nutrients by plants. Macropores make it possible for plant roots to bypass soil zones with excessive mechanical resistance, especially in the deeper genetic horizons [12, 14, 45]. Soil air capacity considered the minimum is 0.100-$m^3\cdot m^{-3}$, 0.140-0.150 $m^3\cdot m^{-3}$ as medium favourable, and 0.160-0.220 $m^3\cdot m^{-3}$ as the optimum [6, 7, 15]. In horizons Ap of the Chernozems studied the air capacity at the state of field water capacity, amounting to 0.144-0.155 $m^3\cdot m^{-3}$, was estimated as high, 0.111-0.129 $m^3\cdot m^{-3}$ as medium, and 0.095-0.107 $m^3\cdot m^{-3}$ as low.

Mesopores with equivalent diameter of 20-0.2 μm retain water usable for plants in the range of soil water potential from -15.5 to -1554 kPa. The best retention properties are characteristic of soils with the particle size distribution of silty formations, rich in humus, with stable aggregate structure, not susceptible to excessive compaction. Exceptionally favourable for the retention capacity of soils is the effect of a high content of silt fraction (0.05-0.002 mm), which guarantees the highest content of intra-aggregate capillary pores [10, 46, 48]. The content of organic matter has an indirect effect on the retention of usable water by improving aggregation and preventing excessive compaction. The value accepted as the optimum retention of usable water is >0.200 $m^3\cdot m^{-3}$, 0.150-0.200 $m^3\cdot m^{-3}$ as good, 0.100-0.150 $m^3\cdot m^{-3}$ as limited, and poor <0.100 $m^3\cdot m^{-3}$ [7]. In the Chernozems studied the content of mesopores with diameter of 0.2-20 μm retaining water usable for plants, amounting to 0.230-0.263 $m^3\cdot m^{-3}$, was estimated as very high.

Good growth and functioning of roots of crop plants require a suitable relationship between the content of mesopores with diameter of 0.2-20 μm, retaining water usable for plants, and the share of macropores >20 μm, ensuring soil aeration. According to Reynolds et al. [6, 7], for rain-fed arable mineral soils the optimum balance between the water capacity of the root zone of soils and air capacity occurs when the relative field water capacity equals 0.6-0.7. At that value the most intensive microbiological nitrification takes place in soil. Values of relative field water capacity below 0.6 decrease the intensity of nitrification due to soil water deficit, while values >0.7 cause reduced production of nitrates as a result of soil air deficit [49]. By adopting those determinations one can estimate that the relative field capacity in horizons Ap of Chernozems classified in the good and the deficient wheat complexes was optimal, and in the other horizons higher than the optimum.

Hydraulic conductivity in the saturated zone determines the rate of water movement in soil at the state of the maximum water capacity at potential of -0.1 kPa (pF 0). Hydraulic conductivity depends on particle size distribution, soil structure, soil density, and content of macropores >20 μm, and especially on the activity of plant roots, soil meso- and macrofauna, and determining the presence of vertical biogenic channels [11, 44, 50, 51]. The diversity of factors affecting the conducting properties of soils causes a large spatial and temporal variation of obtained values. Therefore, various values of saturated hydraulic conductivity have been adopted as favourable for the quality of various soils [6, 15, 16]. In the Chernozems under study, saturated hydraulic conductivity of 0.13-0.41 $m \cdot d^{-1}$ was estimated as low, while that of 0.81-1.45 $m \cdot d^{-1}$ as medium.

Air permeability determines gas exchange ability of soil. Gas exchange between the soil and the atmosphere takes place primarily under the effect of concentration gradient (diffusive flow) and, to a lesser extent, under the effect of pressure gradient [52]. Like hydraulic conductivity, air permeability at the state of field water capacity depends primarily on the volume of soil macropores with diameter >20 μm, and especially on the length, form, and continuity of biogenic channels [53-55]. Air permeability value accepted as favourable for gas exchange is 35.0×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$ [15, 16]. Air permeability at the state of field water capacity of 14.8×10^{-8} $m^2 \cdot Pa^{-1} \cdot s^{-1}$ in the Chernozems under study was estimated as low, $29.6\text{-}48.0 \times 10^{-8}$ $m^2 \cdot Pa^{-1} \cdot s^{-1}$ as medium, and $55.6\text{-}95.7 \times 10^{-8}$ $m^2 \cdot Pa^{-1} \cdot s^{-1}$ as high.

Index *S* can be used in the estimation of the quality of physical properties of soils and in the estimation of their degradation or amendment. According to Dexter [17], other physical properties of soils can be estimated directly from the value of index *S*, e.g., ease of cultivation, clogging, unsaturated hydraulic conductivity, and cohesion. Dexter and Czyż [18] adopted the following categories of physical quality of soil based on calculated absolute values of index *S*: <0.020 – very poor quality, 0.020-0.035 – poor quality, 0.035-0.050 – good quality, and >0.050 – very good quality. Based on this classification, the physical quality of all of the Chernozems under study was estimated as very good (S = 0.057-0.068). However, it should be kept in mind that the index takes into account primarily the hydraulic properties of soil, especially the retention of water usable for plants, while the air properties are taken into account to a lesser extent. In the Chernozems under study the air capacity and the air permeability at the state of field water capacity were less favourable than the water properties, most frequently being estimated as good or medium.

Conclusions

1. Chernozems classified in the very good wheat complex were characterised by significantly lower soil density, but higher field water capacity (expressed in $kg \cdot kg^{-1}$ and $m^3 \cdot m^{-3}$), water capacity at permanent wilting point, and content of micropores with equivalent diameter <0.2 μm than Chernozems from the good and the deficient wheat complexes.
2. Chernozems classified in the particular complexes of agricultural suitability did not differ significantly in terms of their maximum water capacity, retention of water usable for plants, hydraulic conductivity in the saturated zone, total porosity, content of macropores >20 μm, content of mesopores with equivalent diameter of 0.2-20 μm, relative field water capacity, air permeability at the state of field water capacity, and the index of physical quality *S* according to Dexter.
3. Based on the calculated values of index *S* the physical quality of all Chernozems was estimated as very good. Among the particular properties the most favourable were the following (especially in horizons Ap): low soil density, high total porosity, very high field water capacity, very high content of mesopores with equivalent diameter of 0.2-20 μm, and retention of water usable for plants.
4. The content of macropores with diameter >20 μm, determining the air capacity at the state of field water capacity, was most frequently high or medium. As a result, the relative field capacity was optimum only in horizons Ap of Chernozems classified in the good and the deficient wheat complexes, while in the other horizons it was too high.
5. In the Chernozems under study the saturated hydraulic conductivity was estimated as medium or low, and the air permeability at the state of field water capacity as high, medium, or low.

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