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OPEN

DOI: 10.1515/ssa-2015-0036

SOIL SCIENCE ANNUAL
Vol. 66 No. 4/2015: 191–197

ZBIGNIEW KACZMAREK*, PIOTR GAJEWSKI, ANDRZEJ MOCEK,
WOJCIECH OWCZARZAK, BARTŁOMIEJ GLINA

*Poznań University of Life Sciences, Department of Soil Science and Land Protection,
Szydłowska 50 Str., 60-656 Poznań, Poland*

Physical and water properties of selected Polish heavy soils of various origins

Abstract: The paper presents the characteristics of selected physical, chemical, and water properties of four mineral arable soils characterized with heavy and very heavy texture. Soil samples from genetic horizons of black earths from areas near Kętrzyn, Gniew and Kujawy, and alluvial soils from Żuławy were used. The following properties were determined in the samples of undisturbed and disturbed structure: texture, particle density, bulk density, porosity, natural and hygroscopic moistures, maximal hygroscopic capacity, saturated hydraulic conductivity, potential of water bonding in soil, total and readily available water, total retention in the horizon of 0–50 cm, drainage porosity, content of organic carbon and total nitrogen Parent rocks of these soils were clays, silts and loams of various origin. High content of clay fraction strongly influenced the values of all the analyzed properties. All the examined soils had high content of organic carbon and total nitrogen and reaction close to neutral or alkaline. High content of mineral and organic colloids and, what follows, beneficial state of top horizons' structure, determined – apart from heavy texture – low soil bulk density and high porosity. The investigated soils were characterized by high field water capacity and wide scopes of total and readily available water. The saturated hydraulic conductivity was low and characteristic to heavy mineral arable soils. The parameter which influenced the variability of analyzed parameters most was texture.

Key words: heavy soils, texture, density, retention

INTRODUCTION

Soils of the heaviest texture are characterized by significant (up to several dozens of percent) content of clay which, usually apart from high content of organic matter, determines the scopes of values which may be reached both by physical and most of chemical properties (Habel et al. 2007a). High content of clay minerals causes that, along with the growth or drop of moisturization, their capacity undergoes significant changes. When they swell, they show excessive adhesiveness, which is a result of the decrease of water conduction abilities, and infiltration and rise proceed very slowly. In the period without precipitation, such soils dry quickly and shrink. They become intersected by numerous crevices which destroy the roots of plants; bulk density grows, porosity drops (Habel et al. 2007b). Colloquially, such soils are called *minute soils*. Their tillage at too high moisture causes greasing and sticking of a soil to farm tools, which subsequently affects their structure. However, tillage at too little moisturization is also very hard as the emerging blocks do not crack and fractions of small dimensions become dust. The optimal tillage moisture for these soils is very limited, therefore the time for proper tillage is short (Kaczmarek and Gajewski 2009).

Most of the heavy soils were formed from loams, clays and silt deposits. As far in Poland, the least attention was given to black earths formed from clays and heavy loams. They occupy a relatively small areas – mostly, minor areas of black earths are located throughout Poland. It is possible, however, to encounter larger complexes of black earths, whose names (sometimes mistaken for their types), come from geographical regions or the neighbouring sites. The aim of the study was to investigate the properties of these soils through detailed characteristic of the basic physical and water properties, as well as selected chemical properties, of four mineral tillage soils characterized by medium and heavy texture.

OBJECT AND METHODOLOGY

Soil profiles were prepared in the area of allotments representing complexes of mineral tillage soils considered the heaviest in Poland. They were: black earths of Kętrzyn, Gniew and the Kujawy and alluvial soils of the Żuławy. Research points were located in representative spots of the complexes,

* Dr hab. Z. Kaczmarek, kazbig42@up.poznan.pl

within wide typological allotments, which represented each systematic unit. The research was conducted in November 2014. Profile 1 was located nearby Kętrzyn town, in Radole village (black earths of Kętrzyn). Profile 2 was set in Pręgowo village, within Vistula's proglacial stream valley (alluvial soils of the Żuławy region); profile 3 – in Gniew town (black earths of Gniew), within the area of Vistula's proglacial stream valley and the moraine of Pleistocene clay extrusion; profile 4 – in Oporowo village, the Kujawy region (black earths of the Kujawy) (Kondracki 2009). Research points were chosen on the basis of cartographic materials and control drilling network. Four excavations were completed and soil morphology was described. Soils were classified in accordance with the Polish soil classification (PSC 2011), their classes and complexes of arable soils were determined (Mocek and Drzymała 2010). Samples of disturbed and undisturbed structure (V=100 cm^3) were collected from each genetic horizon and submitted to laboratory research. The following properties were determined: texture – with the aerometric-sieve method (PKN 1998), particle density – with the pycnometric method (Soil Conservation Service 1992), bulk density – with Nitzsh's vessels, total porosity – calculated on the basis of density, shrinkage – on the basis of calculations with a micrometric screw, moisture – with the dryer-gravimetric method, maximal hygroscopic capacity – in a vacuum chamber at the vacuum of 0.8 atm and with K_2SO_4 saturated solution (Mocek and Drzymała 2010), the content of carbon and total nitrogen – with Vario Max CNS analyser, pH – potentiometrically (1:2.5) in 1M KCl, saturated hydraulic conductivity – with the method of constant pressure drop (Klute and Dirksen 1986), water bond potential – with Richard's method of pressure chambers (Klute 1986), total (TAW) and readily (RAW) available water – calculated on the basis of pF markings, effective (drainage) porosity (the sum of soil macro- and mesopores, called drainage porosity further in the text) was defined as a difference between total porosity and moisture corresponding with field water capacity (marked at the potential –10 kPa, which corresponds with the value at pF=2.0) and partial capacity of pores of >30 μm diameter. The correlation coefficient was calculated in Microsoft Excel. All the published results are average values from five replications.

RESULTS AND DISCUSSION

The examined soils were classified to the following subtypes: typical black earths (Gleyic Phaeozem; profile 1, 3, 4), proper alluvial soil (Mollic Fluvisol; profile 2). They were used as arable lands (winter wheat and sugar beet tillage). In respect of natural values, the investigated soils were classified to the II class and the 2nd complex of arable soils (profiles 1 and 2), and to the IIIa class and the 3rd complex of arable soils (profiles 3 and 4).

Texture of arable-humus horizons in the investigated soils was characteristic to heavy deposits. The content of clay (<0.002 mm) oscillated between 14 (profile 4) and 44% (profile 3) (Table 1). The lightest texture was observed in profile 4. It was formed completely of sandy loam (SL). A bit heavier composition was found in profile 1 – loam (L). Much heavier texture (S and L) was observed in profile 2. The heaviest texture was found in the black earth of Gniew (profile 3). It was clay (C), both in Ap horizon and in the parent rock (Table 1) (FAO 2006).

In the top horizons of investigated soils, the obtained values of the particle density oscillated within the scope from 2.58 (profile 2) to 2.63 $Mg\cdot m^{-3}$ (profile 4). In the horizons of parent rocks the corresponding values of this property were higher of about 0.02–0.05 $Mg\cdot m^{-3}$, which resulted from the lower content of carbon (Table 2). Low values of this

TABLE 1. Texture of the soils studied

Profile No.	Horizon	Depth (cm)	Percentage content of fraction (in mm)									Texture acc. FAO
			2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.005	0.005–0.002	<0.002	
1	Ap	15–20	0.88	2.03	9.36	16.73	14	10	22	9	16	L
	C	50–60	0.52	1.67	7.77	12.04	16	14	21	8	19	L
2	Ap	15–20	0.58	0.83	3.50	7.09	8	14	22	22	22	Sil
	C	60–70	0.27	0.65	2.23	8.85	8	12	19	28	21	Sil
3	Ap	20–30	0.06	1.75	6.30	13.89	8	4	10	12	44	C
	C	60–70	0.02	1.26	4.18	7.54	7	7	8	17	48	C
4	Ap	15–20	0.63	2.80	13.82	26.75	14	6	14	8	14	SL
	Ckg	70–80	1.17	1.89	9.07	22.87	14	9	13	13	16	SL

Symbols of textures: L – loam, SL – Sandy loam, Sil – Silt, C – Clay.

TABLE 2. Basic physical and chemical properties of the soils studied

Profile No.	Horizon	Depth (cm)	Particle density ($Mg \cdot m^{-3}$)	Bulk density ($Mg \cdot m^{-3}$)	Total porosity (%v/v)	pH in 1M KCl	Total carbon ($g \cdot kg^{-1}$)	Total nitrogen ($g \cdot kg^{-1}$)	C:N
1	Ap	15–20	2.60	1.22	53.08	6.81	21.0	3.45	6.1
	C	50–60	2.64	1.47	44.32	7.07	12.4	1.96	6.3
2	Ap	15–20	2.58	1.18	54.46	6.20	26.7	3.92	6.8
	C	60–70	2.63	1.35	48.67	6.36	12.2	1.54	7.9
3	Ap	20–30	2.59	1.16	55.08	6.80	23.6	2.84	8.3
	C	60–70	2.64	1.26	52.27	6.33	10.5	0.97	10.8
4	Ap	15–20	2.63	1.55	41.06	7.60	14.7	2.20	6.7
	Ckg	70–80	2.65	1.60	39.62	7.38	8.7	1.05	8.3

property in the examined soils were also surely determined their richness in clay materials, the particle density of which oscillates within 2.60–2.63 $Mg \cdot m^{-3}$ at a relatively low content of quartz (Mocek and Drzymała 2010).

Bulk density in the epipedones remained at the level from 1.18 $Mg \cdot m^{-3}$ (profile 2) to 1.55 $Mg \cdot m^{-3}$ (profile 4), and in endopedones – from 1.26 $Mg \cdot m^{-3}$ (profile 3) to 1.60 $Mg \cdot m^{-3}$ (profile 4). From an agro-technical point of view, these values were usually beneficially low, and at the same time – characteristic to heavy soils remaining under tillage and in high culture (Kaczmarek and Gajewski 2009) (Table 2). Low density determined high total porosity. The lowest values of porosity (41.06 and 39.62%) were observed in the black earth of Kujawy (profile 4). The highest total porosity was found in the black earth of Gniew (profile 3), despite its heaviest texture (Table 1 and 2). High total porosity was also found in the alluvial soils of Żuławy (54.46 and 48.67%) and the black earth of Kętrzyn (53.08 and 44.32%) (Table 2).

Clay deposits undergo the process of shrinkage when drying. The result of this process is a change of their physical properties. The phenomenon of shrinkage is proportionally high to the content of mineral and organic colloids in the soil – clay minerals and organic matter. At very low natural moisturization, shrinkage may be irreversible and cause constant changes in the quality of solid phase (Habel et al. 2007a). Shrinkage of the discussed soils was marked on the samples of undisturbed structure ($V = 100\ cm^3$). All the samples shrank after drying (air-dry state). Epipedones of soils with the highest content of carbon underwent the most visible shrinkage. In profile 1 containing 21.0 $g \cdot kg^{-1}$ of Ctot the shrinkage was 22.04%, and in soil 3, of Ctot 23.5–36.12%. In accordance with the presented rules, the smallest shrinkage was observed in profile 4, of the lowest content of carbon (Table 2 and 3). The influence of mineral colloids on the size of shrinkage was well visible in case of profile 3 (clays of Gniew) of the heaviest texture and the domination of smectites in their mineral composition (Mocek et al. 2009). In epipedones at much lower content of organic matter, the values of shrinkage were several or even over a dozen times lower than in top horizons (Table 2 and 3). As an effect of shrinkage, soil bulk density and total porosity also changes. In the topsoils, increase of bulk density oscillated around 0.3 $Mg \cdot m^{-3}$ at a subsequent drop of total porosity by about 12–19%. In C horizons, at smaller shrinkage, changes of these properties were lower, but still visible (Table 3). In the soils under study the correlation coefficient between the ratio of current to the maximum moisture

TABLE 3. Physical properties of investigated soils after shrinkage process

Profile No.	Horizon	Depth (cm)	Particle density ($Mg \cdot m^{-3}$)	Bulk density ($Mg \cdot m^{-3}$)	Bulk density after shrinkage ($Mg \cdot m^{-3}$)	Total porosity (%)	Porosity after shrinkage (%)	Percent of shrinkage (% v/v)
1	Ap	15–20	2.60	1.22	1.56	53.08	40.00	22.04
	C	50–60	2.64	1.47	1.68	44.32	36.36	12.69
2	Ap	15–20	2.58	1.18	1.62	54.46	37.21	27.47
	C	60–70	2.63	1.35	1.67	48.67	36.50	19.38
3	Ap	20–30	2.59	1.16	1.82	55.08	29.73	36.12
	C	60–70	2.64	1.26	1.81	52.27	31.44	30.36
4	Ap	15–20	2.63	1.55	1.86	41.06	29.28	16.70
	Ckg	70–80	2.65	1.55	1.64	39.62	38.11	5.38

and shrinkage ratio was 0.55373; between total carbon content and the shrinkage ratio was 0.63295, and between content of clay fractions and shrinkage ratio was 0.77658.

Results of natural moisture show the dependence of water content in soil on texture and the content of total carbon. In all of the cases, higher natural moisture was found in Ap horizons than in endopedones and it oscillated between 32.25%v/v in profile 4 (of the texture of sandy loam and the low content of total C) and 54.09% v/v in profile 3 (the texture of clay and very high content of total C). In subsurface horizons natural moisture was by about 3–7%v/v lower than in the topsoils (Table 4). The obtained values of natural moisturization cannot be the subject of a detailed analysis as they characterize only the state of temporary (current) moisture of each genetic horizon of the investigated soils and these parameter undergoes dynamic changes, mainly as a result of precipitation, tillage, vegetation etc. The only objective ones are – discusses below – the so-called water-soil constants.

In soils of defined texture and mineralogical composition, hygroscopic moisture (H) and maximal hygroscopic capacity (MH) are constant values which change in an only very narrow range. Their minor fluctuations may be caused only by the changes of the content of mineral or organic colloids fraction in a soil (Mocek and Drzymała 2010).

In the examined soils, the values of H and MH were characteristic to mineral soils of heavy texture and high content of organic matter. Their size depended strictly on the above mentioned factors. Therefore, the lowest H and MH was observed in case of the black earth of Kujawy (profile 4) – H of 2.7156 (Ap horizon) and 1.8722%v/v (C horizon), at MH – respectively 5.9754 (Ap) and 4.2732%v/v (C). The highest values of both parameters were found in arable-humus horizons in soils of the heaviest composition (clay and silt). The results for H and MH are as follows: in profile 3 H = 7.7731 (Ap) and 3.6652%v/v (C), at MH = 16.1937 (Ap) and 10.4121%v/v (C), and in profile 2 H = 7.2026 (Ap) and 5.0898%v/v (C), at MH = 12.3644 (Ap) and 8.0712%v/v (C) (Table 4).

TABLE 4. Basic water properties of the soils studied

Profile No.	Horizon	Depth (cm)	Natural moisture (%v/v)	Hygroscopic water	Maximum hygroscopic capacity
1	Ap	15–20	48.88	4.3835	16.2431
	C	50–60	45.58	7.2121	11.0049
2	Ap	15–20	48.51	7.2026	12.3644
	C	60–70	42.54	5.0898	8.0712
3	Ap	20–30	54.09	7.7731	16.1937
	C	60–70	47.61	3.6652	10.4121
4	Ap	15–20	32.25	2.7156	5.9754
	Ckg	70–80	27.06	1.8722	4.2732

Maximal water capacity oscillated at the level close to total porosity and its values were a bit (of about 1–3%) lower. Each moistures was high at field water capacity. Almost always in top horizons, the values significantly exceeded 40%. Only in Ap horizon in profile 4 (of the lightest texture and the highest content of total carbon), this moisture was 38.76 (Ap) and 38.18% (Ckg), which is a very profitable value in a mineral soil. In endopedons the corresponding values of field water capacity (pF 2.0) were lower (of about 1–8%). At balanced texture in both (Ap and C) horizons, the factor that determined such a state was the content of organic matter which has been dropping along with the depth. At pF 2.2 the indicated values of moisture were slightly (of about 1.5–2%) lower. Such a state is a proof of good and effective possibilities of the provision of water for arable plants at the upper limit of its availability. The content of water at the point of production water (pF = 3.7) and at the lower limit of its availability (pF = 4.2) was also high. It oscillated within the range between 16.85 for pF 3.7 and 9.27% for pF 4.2 (profile 4; horizon C) and: 41.73 for pF 3.7 and 25.25% for pF 4.2 (profile 3; Ap) (Table 5). Unlike the case of FWC such composition of values of moisture at such capacities had a positive influence on the availability of soil water as high level of these parameters limits the scopes for both potential and effective useful retention (Table 5).

Values of total available water (TAW) remained at a high level and oscillated between 21.04 (profile 4; Ap) and 29.03% (profile 2; Ap). Usually, the differences of this trait between Ap and C horizons were minor. Values of readily available water (RAW) were usually high as well. Only in the black earth of Gniew (profile 3) RAW values were much lower in both horizons, which was caused by high values of moisture at pF 3.7 in this soil (Table 5). The discussed values of TAW and RAW are relative indicators and show only a theoretical amount of retention water. In order to obtain specific retention abilities defined in the millilitres of precipitation it is crucial to take into consideration the thickness of genetic horizons. With the implementation of the above data, retention was calculated in the studied soils and its values in the horizon of 0–50 cm were presented (Table 6). Retention calculated for the horizons of thickness of 0–50 cm at TAW was relatively balanced and oscillated between 105.20 (profile 4) and 136.50 mm (profile 2). Significant differences were visible in case of retention of easily available water. They resulted from the discussed differences in the investigated values

TABLE 5. Soil water potentials and the total and readily available water in the soils studied

Profile No.	Horizon	Depth (cm)	Water capacity at pF: (%v/v)							Total available water (%v/v)	Readily available water (%v/v)
			0.0	2.0	2.2	2.5	3.7	4.2	4.5	2.0–4.2	2.0–3.7
1	Ap	15–20	50.81	43.32	41.78	34.65	24.03	19.44	16.24	23.88	19.29
	C	50–60	43.83	41.74	40.36	30.11	21.84	16.61	11.00	25.13	19.90
2	Ap	15–20	51.70	47.51	45.88	41.93	34.62	18.48	12.36	29.03	12.89
	C	60–70	44.25	39.76	37.15	32.74	24.53	16 50	8.07	23.26	15.23
3	Ap	20–30	53.42	48.37	46.65	44.17	41.73	25.25	16.19	23.12	6.64
	C	60–70	49.99	45.87	46.01	42.79	37.54	18.22	10.41	27.65	8.33
4	Ap	15–20	38.76	34.65	32.25	29.48	23.66	13.61	5.97	21.04	10.99
	C	70–80	38.18	37.82	35.75	27.13	16.85	9.27	4.27	28.55	20.97

TABLE 6. Retention of the investigated soils

Profile No.	RAV (mm)	Retention at RAV in layer 0–50cm (mm)	TAV (mm)	Retention at TAV in layer 0–50 cm (mm)
1	86.80	96.76	107.46	120.03
	9.95		12.57	
2	45.12	67.96	101.61	136.50
	22.85		34.89	
3	31.21	33.71	108.66	116.96
	2.50		8.30	
4	40.66	54.95	77.85	105.20
	14.29		27.35	

of RAW coefficient. In this case, retention abilities of water varied from 33.71 (profile 3) to 96.76 mm (profile 1). On the basis of the data it may be assumed that the examined soils have high water retention abilities. At TAW these soils may store about 20% of annual precipitation at once and at RAW – about 5–17% (Table 6). When compared to the detailed data by Ślusarczyk (1979) for various soils, the soils studied in the present paper are placed at the top of the ranges given by the above mentioned author or slightly exceed them.

Despite high total porosity and relatively low bulk density, the obtained values of the saturated hydraulic conductivity were low. In top horizons the values of this parameter oscillated between 0.0462 in profile 3 (soil of heavy texture) and 2.7384 $\mu m \cdot s^{-1}$ in profile 4 (the lightest texture). A better state of structure, higher content of organic matter and lower bulk density caused a significant drop of the speed of filtration along with the depth in all soils. In C horizons the corresponding values of water conductivity were always lower than in Ap and oscillated between 0.0301 (profile 3) and 1.3752 $\mu m \cdot s^{-1}$ (profile 4) (Table 7). The indicated values oscillated in the ranges given by many authors (Tan 1989, Krogulec 1994, Sivapullaiah et al. 2000). The correlation coefficient between total porosity and filtration coefficient was Pc/Ks = -0.74557, whereas the strength of its bond with drainage porosity was surprisingly low Pd/Ks = 0.512977. It could be explained by a significant share of pores with diameters less than 30 mm, which are not involved in the transport of water in the saturation zone and with increase of their tortuosity with increasing content of clay fraction (Mualem 1976, Kosugi 1999, Vervort and Cattle 2003).

A detailed analysis of chemical properties was not the subject of the paper. This data serves as a supplement to the characteristic of the object. The reaction of all the investigated soils was a bit acid or close to neutral (pH within the range from 6.20 – profile 2, Ap to 7.60 – profile 4, Ap). The content of total carbon and total nitrogen was very high. Total carbon in epipedones oscillated between 14.7 $g \cdot kg^{-1}$ in profile 4 and 26.7 $g \cdot kg^{-1}$ in profile 2, and total nitrogen – between 2.20 $g \cdot kg^{-1}$ and 3.92 $g \cdot kg^{-1}$ – in the same profiles. Due to the high content of nitrogen, the relation of C and N was quite narrow in most of the soils and – apart from the horizon of parent rock in profile 3 – C to N ratios oscillated within the range of 6–8 (Table 2).

TABLE 7. Saturated hydraulic conductivity in the soils studied

Profile No.	Horizon	Depth (cm)	Drainage porosity (%)	Saturated hydraulic conductivity ($\mu m\ s^{-1}$)
1	Ap	15–20	9.76	0.7684
	C	50–60	3.58	0.4891
2	Ap	15–20	9.95	0.0911
	C	60–70	5.91	0.0637
3	Ap	20–30	6.71	0.0462
	C	60–70	6.26	0.0301
4	Ap	15–20	7.41	2.7384
	C	70–80	7.69	1.3752

CONCLUSIONS

1. High content of clay fraction strongly influenced the analysed physical and water properties. Content of clay fraction as well as high content of carbon and, consequently, beneficial state of top horizons structure, caused – despite heavy texture – low bulk density of the soil and high total porosity.
2. The investigated soils were characterized by a very high field water capacity and wide scopes of potential and effective useful retention. Their retention abilities allow for the retention of about 20% of annual precipitation in the horizon of 0–50 cm at once.
3. The investigated physical and water properties, when compared with very beneficial basic chemical properties, suggest that the examined soils of heavy texture are, apart from some difficulties, one of the best arable lands in Poland.

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Received: September 1, 2015
Accepted: April 4, 2016

Właściwości fizyczne i wodne wybranych polskich gleb ciężkich o różnej genezie

Streszczenie: W pracy przedstawiono charakterystykę wybranych właściwości fizycznych, chemicznych i wodnych czterech uprawnych gleb mineralnych, charakteryzujących się ciężkim i bardzo ciężkim uziarnieniem. Wykorzystano próbki glebowe pochodzące z poziomów genetycznych czarnych ziem: kętrzyńskiej, gniewskiej i kujawskiej oraz mady żuławskiej. W próbkach o strukturze naruszonej i nienaruszonej oznaczono takie właściwości, jak: skład granulometryczny, gęstość fazy stałej, gęstość gleby, porowatość, wilgotność naturalną i higroskopową, maksymalną pojemność higroskopową, współczynnik filtracji, potencjały wiązania wody przez glebę, potencjalną (PRU) i efektywną (ERU) retencję użyteczną, retencję całkowitą w warstwie 0–50 cm, porowatość drenażową, zawartość węgla organicznego i azotu ogólnego Skałami macierzystymi badanych gleb były gliny, pyły i iły różnego pochodzenia. Wysoka zawartość frakcji iłu silnie oddziaływała na wartości wszystkich analizowanych właściwości fizycznych. Wszystkie badane gleby cechowały się wysoką zawartością węgla organicznego i azotu ogólnego oraz odczynem zbliżonym do obojętnego lub zasadowym. Wysoka zawartość koloidów mineralnych i organicznych oraz związany z tym korzystny stan struktury warstw powierzchniowych determinował – pomimo ciężkiego składu – niską gęstość objętościową gleby oraz wysoką porowatość. Badane gleby cechowały się wysoką polową pojemnością wodną oraz szerokimi przedziałami potencjalnej i efektywnej retencji użytecznej. Prędkość filtracji była niska, charakterystyczna dla uprawnych mineralnych gleb ciężkich. Parametrem najsilniej wpływającym na zmienność analizowanych właściwości było uziarnienie.

Słowa kluczowe: gleby ciężkie, uziarnienie, gęstość, retencja