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COMPARISON OF MOISTURE PROPERTIES OF SOILS IN THE CONTEXT OF THEIR SUSCEPTIBILITY TO COMPACTION WITH WHEELS OF FARM VEHICLES*

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Abstract. The objective of the studies was to compare optimum moisture content determined with Proctor's method with other moisture properties of the selected soils from the region of Szczecin Lowland (Poland). Soils of the 1st and 2nd complex of agricultural usefulness were investigated by measurements conducted on soil samples collected outside of headlands and technological routes. In the subsoil the following soil properties were determined: current field moisture content, soil moisture at water potentials pF0 and pF2, granulometric composition, density of solid phase, humus content, reaction, limits of plasticity and liquidity, maximum dry density of solid particles and optimal moisture content determined with Proctor's apparatus. It was proved that variability of optimal moisture value increases along with the increase of loamy fractions. It was also found out that for soils of the sandy loam or sandy clay loam granulometric composition the optimal moisture content of soil, determined with Proctor's apparatus is similar to the value of its optimum water content for tillage.

Key words: soil, subsoil, moisture properties

Introduction and objective of the paper

A modern approach to plant production is characterised by trends towards maximizing of economic effects at maintaining requirements of environmental protection. In these preconditions, information concerning moisture properties of soil on account of their direct relation with crop production results or the risk of disadvantageous phenomena is of special significance (Błażejczak, 2010; Nidzgorska-Lencewicz, 2006; Rab et al., 2005).
Knowledge of moisture properties of soil allows, among other, to plan dates of performing cultivation treatments in conditions which support obtaining the most advantageous cultivation effects and preventing various unfavourable phenomena, including excessive soil compaction by wheels of agricultural vehicles. Obtaining the most advantageous agrotechnical effect of tillage is possible, when the treatment is performed at the so-called optimum

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water content for tillage, defined as moisture, at which proportionally the highest number of small soil aggregates is obtained (Dexter, Bird 2001). In case of soil susceptibility to compaction, knowledge of moisture, at which maximum compaction of soil may occur, is significant. This moisture, called optimal compaction moisture, is determined in the established (standard) conditions with the use of Proctor's apparatus. Since both, determination of optimal cultivation moisture, e.g. through analysis of aggregate composition of soil after performing cultivation treatment in various conditions, as well as optimal moisture of compaction is labour consuming, other indirect methods of their determination are searched for.
Previous works concerned, most frequently, comparison of optimal cultivation moisture of soils with values of their consistency limits (Mueller et al., 2003). From the point of view of description of relations between soil strength properties involved in tillage and soil water content, knowledge of the consistency limits of soil is important. It may be proved that these properties reach the maximum values at the plasticity range (Larson et al., 1994). Particularly, knowledge of the plasticity limit of soil is very important (P_L), because in combination with the knowledge of field water capacity (W_{pF2}), which is identified with water potential equal to 100 hPa (*pF*2), allows to assess whether soil is able to obtain optimal cultivation moisture (optimum water content for tillage), which acc. to Dexter and Bird (2001) takes place when W_{pF2}/P_L <1. According to the same authors, in conditions when W_{pF2}/PL >1, soil gets susceptible to destruction of structure during its cultivation.
Studies on optimal moisture of compaction were carried out to a smaller extent. A need for such type of research results however, among other, from the effects obtained in laboratory conditions by Mosaddeghi et al. (2009). They found out that optimal moisture of compaction is similar to the optimal value of cultivation moisture, understood as the water content at which strength of capillary connections between aggregates is minimal. It would in practice mean that when conducting field cultivation works, on one hand, we obtain a maximum tillage effect, on the other hand, a risk of maximum soil compaction by wheel of cultivation units occurs. Moreover, soil moisture, at which the best cultivation efficiency is obtained, may differ in relation to the applied tools and the working depth (Larson et al., 1994). In field conditions, relation between optimal moisture of soil compaction and for example its plasticity limit may be modified by various factors (Mosaddeghi et al., 2000). Therefore, especially in the time of precise farming, formation of individual data bases on moisture properties of soils with reference to regions or particular farm or fields can be justified.
The objective of the presented work was to compare optimal moisture determined with Proctor's apparatus with other moisture properties of the selected soils from the region of Szczecin Lowland (Poland). On account of relation between the long termination of effects of excessive soil compaction in the subsoil layer and its moisture (Szeptycki, 2003), the plough layer was omitted in the research, where soil compaction may be maintained at the determined level by suitable tillage.

Material and methods

Selected plastic soils of the 1st and 2nd complex of agricultural suitability, located within the following countries: Nowy Przylep, Obojno, Ostoja and Skarbimierzyce, were the research object. These soils possibly enable obtaining high crops and are threatened by excessive compaction as a result of their intense use. Field investigations were carried out in layers which are at the depth of: 25-30, 35-40, 45-50 and 55-60 cm, in periods when spring and winter cultivation treatments are performed. Measurements were carried out in repeats (Nowy Przylep – 4, Obojno – 2, Ostoja – 3, Skarbimierzyce – 3), in points (pits) located approximately 2-3 m from each other, outside of headlands and technological routes. Undisturbed soil samples were collected with the use of the so-called Kopecky's rings (100 cm^{-3}). They were used for determination of current soil moisture and at pF 0 and pF 2 water potentials. Weight moisture at pF 0 water potential was determined in conditions of full saturation of soil with water. Whereas, for determination of soil moisture at pF 2 water potential, a gypsum board was used. In this case, a weekly drying cycle of soil from the state of its full saturation with water was applied.

In order to determine other tested properties of soil, a material in the form of loose soil mass was collected from examined layers. Granulometric composition was determined with Bouyoucos-Casagrande's method in Prószyński's modification (sand fractions were washed on the sieve with 0.1 mm meshes dimension). A pycnometer method was used for determination of the solid phase density. Humus content was determined with Tiurin's method and soil reaction with electrometric method. Limits of plasticity and liquidity and determination of the maximum dry density of solid particles and optimal moisture of compaction in the Proctor's apparatus were carried out according to PN-88/B-04481 (Polish standard). Indispensable calculations were carried out with the use of Microsoft Excel and Statistica StatSoft, Inc. programmes.

Results and a discussion

Table 1 presents results of determination of tested properties of the investigated soils. It may be noticed that the investigated soils differ mainly on account of granulometric composition and humus content, which was reflected in the values of plasticity and liquidity limits (tab. 2), the values of which were respectively within 14.1-31.4% w/w and 17.0-73.0% w/w. Lower diversity was reported in investigations carried out with Proctor's method in the values of optimal moisture (W_{op}), which was within 10.8-18.7 % of weight. Based on the results of determination of optimal moisture values (W_{op}) and the plasticity limit (P_L) one may state that W_{op} was within 0.39-0.87P_L and the average value was W_{op} = 0.64P_L. The smallest values of the quotient W_{op}/P_L were obtained for Obojno object in 45-60 cm layer that is for soil of granulometric composition (see table 1) silty clay loam (*gpyi/SiCL*) and silty clay (*ipy/SiC*). While the maximum values W_{op}/P_L were reported for objects Ostoja and Skarbimierzyce, respectively in 25-30 and 35-40 cm layers, where sandy loam (*gl/SL*) and sandy clay loam (gpi/SCL) were reported. Values of this quotient were similar to those, which were obtained in previous investigations for sandy loam with reference to the value of optimal cultivation moisture i.e. W_{ou}=0.9P_L (Dexter, Bird 2001). It may prove the fact that for this type of soil, optimal cultivation moisture is equal to the optimal value of compaction in the Proctor's apparatus (W_{ou}=W_{op}).

Table 1
Results of determinations of tested properties of soils for the selected soil pits and examined layers

Object	Layer	Granulometric group (PTG 2009/USDA)	Sand 2-0.05	Silt 0.05-0.002	Clay <0.002	Specific density	Reaction (in KCl)	Humus content
	(cm)			(%)		($g \cdot cm^{-3}$)	(pH)	(%)
Nowy Przylep	25-30	*pyg/SiL*	36.1	53.9	10.0	2.45	6.32	3.10
	35-40	*pyg/SiL*	36.0	53.0	11.0	2.46	6.34	2.02
	45-50	*pyg/SiL*	34.1	56.9	9.0	2.45	6.29	2.30
	55-60	*gz/L*	36.9	48.4	14.7	2.47	6.21	1.09
Obojno	25-30	*gz/L*	27.0	46.0	27.0	2.45	6.86	4.17
	35-40	*gz/L*	25.0	48.0	27.0	2.49	6.84	3.77
	45-50	*gpyi/SiCL*	14.0	48.0	38.0	2.52	6.78	2.34
	55-60	*ipy/SiC*	12.0	46.0	42.0	2.40	6.52	1.70
Ostoja	25-30	*gl/SL*	60.5	30.6	8.9	2.52	5.08	1.03
	35-40	*gz/L*	45.0	40.3	14.7	2.66	5.13	0.61
	45-50	*gz/L*	50.0	29.4	20.6	2.67	5.23	0.69
	55-60	*gz/L*	48.3	31.2	20.5	2.55	5.63	0.57
Skarbimie-rzyce	25-30	*gpi/SCL*	54.0	24.5	21.5	2.50	6.23	1.78
	35-40	*gpi/SCL*	48.2	27.8	24.0	2.64	6.25	1.05
	45-50	*gi/CL*	35.5	36.2	28.4	2.60	6.21	0.75
	55-60	*pyi/SiL*	28.3	52.1	19.7	2.53	6.22	0.68

Symbols of granulometric groups (PTG/USDA): pyg/SiL – silt loam, gz/L – loam, gpyi/SiCL – silty clay loam, ipy/SiC – silty clay, gl/SL – sandy loam, gpi/SCL – sandy clay loam, gi/CL – clay loam, pyi/SiL – silt loam

Table 2
Determined moisture properties of the soil material for particular objects and examined layers

Object	Layer	Plasticity limit (P_L)	Liquidity limit (L_L)	Optimal moisture (W_{op})	W_{op}/P_L	W_{op}/L_L	W_{op}/I_p
	(cm)	(% w/w)	(% w/w)	(% w/w)	(-)	(-)	(-)
Nowy Przylep	25-30	22.0	29.5	15.4	0.70	0.20	2.05
	35-40	21.3	31.2	15.0	0.70	0.40	1.52
	45-50	23.7	32.0	14.1	0.59	0.45	1.70
	55-60	20.3	31.3	14.5	0.71	0.13	1.32
Obojno	25-30	25.9	44.2	18.7	0.72	0.42	1.02
	35-40	28.0	47.9	13.3	0.48	0.28	0.67
	45-50	30.4	58.7	12.0	0.39	0.20	0.42
	55-60	31.4	73.0	12.1	0.39	0.17	0.29
Ostoja	25-30	14.1	17.0	12.3	0.87	0.72	4.24
	35-40	18.4	27.6	10.8	0.59	0.39	1.17
	45-50	19.8	30.3	11.3	0.57	0.37	1.08
	55-60	18.0	28.8	11.2	0.62	0.39	1.04
Skarbimierzyce	25-30	21.8	39.2	16.0	0.73	0.41	0.92
	35-40	17.9	27.5	15.5	0.87	0.56	1.61
	45-50	24.9	61.0	14.0	0.56	0.23	0.39
	55-60	27.4	52.5	12.8	0.47	0.24	0.51

Symbols: I_p – plasticity index

Higher diversity, in relation to the quotient $W_{op}/P_{L,}$ was obtained for optimal moisture (W_{op}) and liquidity limit (L_L), since W_{op} was within 0.17-0.72L_L. The highest range of change of this quotient was found for optimal moisture (W_{op}) and plasticity index (I_p), where W_{op} was within 0.29 do 4.24I_p. General character of quotient changes W_{op}/L_L i W_{op}/I_p, for particular objects and layers, was close to the direction of changes of W_{op}/P_L. In majority of cases, their values showed a decreasing trend along with the increase of depth. Increase of the content of clay fractions is soil could be the cause, which resulted in the increase of the value of consistency limits (L_L and P_L).

Table 3 presents results of measurements of the properties of soil determined in Kopecky's rings. It may be observed that the reported variability in determined soil moisture at water potentials $pF0$ and $pF2$ was related to current moisture properties (W_a) and dry density of solid particles (ρ_d) of collected soil samples. Table 3 presents also a real index of soil compaction determined with quotient of the dry density of solid particles (ρ_d) and maximum density determined with Proctor's method (ρ_{ds}). Generally, this index was within 0.73-0.96, that is soils did not achieve a maximum level of compaction produced in the Proctor's apparatus in none of the layers.

Table 3

The scope of changes of average values of soil properties of objects and layers determined in Kopecky's rings

Object	Layer	Current moisture content (W_a)	Dry density of solid particles (ρ_d)	Moisture at $pF0$ (W_{pF0})	Moisture at $pF2$ (W_{pF2})	ρ_d/ρ_{ds*}
	(cm)	(% w/w)	(g·cm^{-3})	(% w/w)		(-)
Nowy Przylep	25-30	17.4-22.4	1.32-1.54	30.9-38.8	21.7-26.3	0.80-0.93
	35-40	16.8-21.8	1.40-1.55	27.4-31.6	20.7-25.2	0.80-0.89
	45-50	16.9-21.2	1.40-1.58	26.9-31.8	20.7-24.9	0.79-0.89
	55-60	15.8-19.7	1.52-1.65	24.8-29.6	19.7-20.9	0.85-0.93
Obojno	25-30	21.2-21.7	1.52-1.54	28.1-28.3	22.5-22.5	0.94-0.96
	35-40	21.9-22.3	1.48-1.53	27.8-29.0	23.2-23.3	0.80-0.82
	45-50	23.3-25.3	1.44-1.54	27.5-33.1	23.3-27.7	0.76-0.81
	55-60	27.5-29.1	1.41-1.42	35.3-36.1	29.0-31.3	0.73-0.74
Ostoja	25-30	13.3-15.0	1.69-1.80	17.4-21.3	12.5-15.0	0.89-0.95
	35-40	14.0-16.4	1.65-1.69	21.2-22.9	13.1-16.5	0.86-0.89
	45-50	16.5-21.5	1.56-1.67	22.6-28.0	16.9-22.7	0.80-0.86
	55-60	16.6-19.6	1.60-1.70	21.3-24.7	17.4-20.4	0.84-0.89
Skarbimierzyce	25-30	16.2-18.6	1.60-1.70	22.2-23.0	17.2-19.0	0.90-0.96
	35-40	16.7-17.3	1.62-1.67	22.7-25.5	17.6-19.4	0.90-0.93
	45-50	17.7-33.4	1.36-1.62	26.2-36.7	18.6-34.2	0.74-0.88
	55-60	15.5-42.4	1.27-1.66	21.1-47.8	16.2-43.8	0.68-0.89

* – maximum density of soil determined with Proctor's method

Variability in moisture values at water potentials $pF0$ and $pF2$ (tab. 3) affected the scope of quotient changes W_{pF2}/P_L, W_{pF0}/P_L, W_{op}/W_{pF2} i W_{op}/W_{pF0} (tab. 4). Based on the analysis of these data, one may state that moisture of the investigated soils at the water potential equal to $pF2$ is close to their plasticity limits because average value of quotient W_{pF2}/P_L was 0.97. The only one, considerably different that the remaining quotient was the result determined for a layer 55-60 cm of Skarbimierzyce object, where the minimum and maximum value W_{pF2}/P_L were respectively 0.59 and 1.60. Maximum results of the quotient W_{pF2}/P_L in majority of cases were higher than 1, which means that these soils are acc. to Dexter and Bird (2001) susceptible to destruction of structure during their deep cultivation.

Table 4
The scope of changes of a verage values of quotient of soil properties for particular objects and examined layers

Object	Layer (cm)	W_{pF2}/P_L (-)	W_{pF0}/P_L (-)	W_{op}/W_{pF2} (-)	W_{op}/W_{pF0} (-)
Nowy Przylep	25-30	0.99-1.20	1.41-1.76	0.59-0.71	0.40-0.50
	35-40	0.97-1.18	1.29-1.48	0.60-0.72	0.47-0.55
	45-50	0.87-1.05	1.14-1.34	0.57-0.68	0.44-0.52
	55-60	0.97-1.03	1.22-1.46	0.69-0.73	0.49-0.58
Obojno	25-30	0.87-0.87	1.08-1.09	0.83-0.83	0.66-0.67
	35-40	0.83-0.83	0.99-1.03	0.57-0.57	0.46-0.48
	45-50	0.77-0.91	0.90-0.91	0.43-0.51	0.36-0.44
	55-60	0.92-1.00	0.92-1.00	0.39-0.42	0.34-0.34
Ostoja	25-30	0.89-1.06	1.24-1.51	0.82-0.98	0.58-0.71
	35-40	0.71-0.90	1.15-1.25	0.65-0.82	0.47-0.51
	45-50	0.85-1.15	1.14-1.41	0.50-0.67	0.40-0.50
	55-60	0.97-1.13	1.18-1.37	0.55-0.64	0.45-0.53
Skarbimierzyce	25-30	0.79-0.87	1.02-1.06	0.84-0.93	0.70-0.72
	35-40	0.98-1.08	1.27-1.42	0.80-0.88	0.61-0.68
	45-50	0.75-1.37	1.05-1.47	0.41-0.75	0.38-0.54
	55-60	0.59-1.60	0.77-1.74	0.29-0.79	0.27-0.61

From the point of view of speed and costs of obtaining information on the value of optimal moisture of compaction, it is justifiable to predict its properties based on the commonly performed basic characteristic of soil. Complexity of the soil environment causes that searching for this type of relations takes place by selection of regression equations (Canarache, 2001; Błażejczak, 2010). Based on the results obtained during the studies discussed in this paper, satisfactory results concerning the relation between W_{op} and basic parameters of soil, as humus content (Z_{pr}), sand content ($Z_{2\text{-}0.05}$), silt content ($Z_{0.05\text{-}0.002}$) and clay content ($Z_{<0.002}$) and values P_L and L_L were not obtained. Thus, an attempt was made to determine relation between the above-mentioned parameters of soil and optimal moisture of compaction, presented in the complex form with the use of quotient of moisture properties listed in table 2 and 4. Regression equations, for which the highest values of determination coefficient R^2 were reported and obtained based on the results of determination of basic parameters of the investigated soils, were presented in table 5. It may be noticed that the sand content ($Z_{2\text{-}0.05}$), was the best predictor of optimal moisture of compaction quotients and other selected moisture propertes of soil (P_L, L_L and W_{pF2}), because in each obtained equations it was significant. Including of other independent variables to equations brought a slight change to their statistical assessment. Equations were subjected to validations with the use of data obtained at the additional object (Reńsko). Values of tested properties of soils of Reńsko object were within the limits of variability of parameters of objects described in table 1. Validation was based on comparison of the measured optimal moisture of compaction (W_{op}) with the predicted, calculated with the use of converted equations (tab. 5), and then on calculation of the relative error of prediction (δ_p). In this paper it was obtained that $W_{pF2} \approx P_L$. Thus, it was assumed that the result of equations validation $R1_{PL}$ and $R1_{pF2}$ will be similar. However, it was found that although these equations are almost identical, for estimation of W_{op} it is better to use information on the value of plasticity limit of soil, because a mean relative error was 9.6% for equation $R1_{PL}$ in comparison to 18.4% for equation $R1_{pF2}$. Comparison of results of equations validations leads to similar conclusions $R2_{PL}$ and $R2_{pF2}$. It was also found that the use of independent variables in the form of humus content (Z_{pr}) or clay fractions $Z_{<0.002}$, despite the increase of the value of determination coefficient did not improve the quality of prediction.

Table 5
Regression equations for forecasting values of quotients of optimal moisture of soil compaction and other selected moisture properties and their statistical assessment and results of their validation

Number of equation	Equation	Statistical assessment of equation		Result of equation validation
		p	R^2	δ_p (%)
$R1_{PL}$	$W_{op}/P_L = 0.008 \cdot Z_{2-0.05} + 0.323$	+++	0.57	9.6 (1.6#)
$R1_{LL}$	$W_{op}/L_L = 0.008 \cdot Z_{2-0.05} + 0.106$	0.001	0.53	10.9 (9.0#)
$R1_{pF2}$	$W_{op}/W_{pF2} = 0.008 \cdot Z_{2-0.05} + 0.340$	+++	0.59	18.4 (14.6#)
$R2_{PL}$	$W_{op}/P_L = 0.010 \cdot Z_{2-0.05} + 0.050 \cdot Z_{pr} + 0.181$	+++	0.64	15.7 (14.4#)
$R2_{LL}$	$W_{op}/L_L = 0.010 \cdot Z_{2-0.05} + 0.059 \cdot Z_{pr} - 0.064$	+++	0.63	16.1 (17.8#)
$R2_{pF2}$	$W_{op}/W_{pF2} = 0.010 \cdot Z_{2-0.05} + 0.053 \cdot Z_{pr} + 0.196$	+++	0.59	35.6 (26.4#)
$R3_{LL}$	$W_{op}/L_L = 0.007 \cdot Z_{2-0.05} - 0.006 \cdot Z_{<0.002} + 0.045 \cdot Z_{pr} + 0.191$	+++	0.73	19.6 (17.0#)

Symbols: p – limit probability (+++ – $p < 0.001$), W_{op} – optimal moisture of soil compaction, R^2– determination coefficient, $Z_{2-0.05}$ – sand content, $Z_{<0.002}$ – clay content, Z_{pr} – humus content, δ_p – mean relative error of prediction W_{op}, # – value of standard error deviation, remaining symbols see. tab. 2 and 3

Conclusions

1. For subsoil with the sand and silt content within 12.0-60.5% and 8.9-42% of optimal moisture of soil compaction determined in Proctor's apparatus was from 0.39 to 0.87 of their plasticity. But lesser values were obtained for soils of granulometric composition of silty clay loam or silty clay and higher for those, where occurrence of sandy loam and sandy clay loam was reported.
2. For the investigated forms of the granulomteric composition of sandy loam or sandy clay loam there is a possibility that optimal moisture of compaction is equal to their optimal cultivation moisture.
3. Values of optimal moisture of compaction of the investigated soils were within 0.17 to 0.72 value of their liquidity limit.
4. Moisture of the investigated soils at the water potential equal to $pF2$ is close to their plasticity limit.

5. For estimation of optimal moisture of soil compaction, for soils with granulometric composition similar to soils investigated in this paper, information on the value of their plasticity and sand content may be used.

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PORÓWNANIE WILGOTNOŚCIOWYCH WŁAŚCIWOŚCI GLEB W KONTEKŚCIE ICH PODATNOŚCI NA UGNIATANIE KOŁAMI POJAZDÓW ROLNICZYCH

Streszczenie. Celem niniejszej pracy było porównanie wilgotności optymalnej wyznaczanej metodą Proctora z innymi właściwościami wilgotnościowymi wybranych gleb z rejonu Niziny Szczecińskiej. Badano gleby 1 i 2 kompleksu przydatności rolniczej wykonując pomiary poza uwrociami i ścieżkami technologicznymi. W warstwie podornej gleby oznaczono: wilgotności gleby przy potencjałach wody pF0 i pF2, skład granulometryczny, gęstość fazy stałej, zawartość próchnicy, odczyn, granice plastyczności i płynności oraz maksymalną gęstość objętościową szkieletu gruntowego i wilgotność optymalną aparatem Proctora. Wykazano, że zmienność wartości wilgotności optymalnej gleby zwiększa się wraz ze wzrostem zawartości cząstek ilastych. Stwierdzono, że dla utworów o składzie granulometrycznym gliny lekkiej lub gliny piaszczysto - ilastej wilgotność optymalna gleby, oznaczona aparatem Proctora, jest zbliżona do wartości jej optymalnej wilgotności uprawowej.

Słowa kluczowe: gleba, warstwa podorna, właściwości wilgotnościowe

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