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Original Research

Quality of Structure and Water-Air Properties of Eroded Haplic Luvisol Treated with Gel-Forming Polymer

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Abstract

The effects of the gel-forming polymer AgroAquaGel 500, added at doses of 1 and 2 g·kg^{-1}, on aggregation, aggregate water stability, and water and air properties of eroded Haplic Luvisol developed from loess, were investigated in a field trial. In the first year after the application of AgroAquaGel 500, a significant reduction of the unfavourable content of clods >10 mm was noted compared to the control, while air-dry aggregates of 0.25-5 mm and water-stable aggregates of 0.25-10 mm increased within the 0-5 cm layer of the eroded soil. The addition of the hydrogel to the soil significantly decreased its bulk density and increased its maximum water capacity, saturated hydraulic conductivity, total porosity, the content of macropores with diameters >20 μm, and air permeability. Whereas the beneficial after-effect of the hydrogel applied at the rate of 2 g·kg^{-1} on aggregate size distribution and aggregate water stability was also seen in the second year, no significant influence was observed in the third year after its application. Values of Dexter's index *S* for soil treated with AgroAquaGel 500 indicate the high quality of its water and air properties.

Keywords: eroded Luvisol, AgroAquaGel 500, soil structure, water properties, air properties

Introduction

Soil erosion is the principal process responsible for physical degradation of soil cover in agricultural areas having diversified relief [1-3]. During the degradative process, cultivated horizons located on upper convex segments of slopes become gradually shorter, and soil material is accumulated in hollows. As a consequence, more or less truncated pedons are formed within eroded soils and overbuilt pedons occur within colluvial soils [4-6]. Destruction of soil genetic horizons is accompanied by depletion of humus substances and nutrients in the soil. Ap horizons of eroded soils developed from illuvial horizons or parent material have poorer aeration, aggregate water stability, and less favourable water-air properties compared to non-eroded soils [7-9]. Being responsible for washing away crop plants and their colmatation, as well as leaching of mineral fertilizers and plant protection chemicals, erosion processes pose a threat to the environment, particularly to surface and underground water. Affecting crops and soil fertility, erosion contributes to great losses of crop productivity and its lower quality [10]. In water management, erosion processes cause increased river sedimentation as well as colmatation of water reservoirs and drainage ditches.

As a result of poor aggregate water stability, eroded soils are prone to surface crusting and further water erosion during heavy runoff. Since the soils are potentially rich in plant nutrients, their water-stable aggregate structure should be restored. The conventional methods employed to

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increase soil organic matter and improve soil structure and water-air properties are based on multi-year applications of natural or organic fertilizers at high rates, combined with NPK fertilization and liming [11, 12]. However, such practices are insufficient, due to the necessity of their long-term use and the shortage of adequate quantities of natural and organic fertilizers. Besides, microbial and plant polysaccharides occurring in soil that fix aggregates are decomposed rapidly by soil microorganisms. For this reason, studies on the use of high-molecular weight synthetic polymers for improvement of soil properties have been conducted for a few decades [13].

Hydrophilic gel-forming polymers are recommended as highly effective soil amendment agents. Hydrogels are composed of polymer chains having three-dimensional cross-linked structures. Their dried, tightly coiled macronets in the form of crystal grains or granules are capable of swelling many times their volume in the presence of water, and becoming gel [14-16]. Thanks to their highly deionized water absorption of 10-1,000 $cm^3 \cdot g^{-1}$, small rates of hydrogels, i.e. from 0.03 to 10 $g \cdot kg^{-1}$ to soil mass ratio, may be applied.

The purpose of the study was to estimate the effect of gel-forming polymer AgroAquaGel 500 added in low doses on aggregate structure and water-air properties of eroded Haplic Luvisol developed from loess.

Materials and Methods

This study was carried out from 2005 to 2007 in a small loess catchment basin located in the village of Bogucin (51°19'56"N and 22°23'18"E) on the Nałęczów Plateau (Lublin Upland). The catchment basin, typical of loess regions of Poland, is an experimental research site run by the Institute of Agrophysics, Polish Academy of Sciences in Lublin, for studies on processes of soil erosion [17]. The experiment was performed on a slope with the inclination ranging from 11 to 15%, and the tillage was carried out transversely to the slope. The study was comprised of nine plots in total, including plots treated with two doses of AgroAquaGel 500 and control plots in three replications, established on Haplic Luvisols with different classes of erosion, i.e. the slightly eroded soil with the sequence of genetic horizons Ap-Blt-B2t-BC-Ck, the moderately eroded soil with the sequence of horizons Ap-B2t-BC-Ck, and the strongly eroded soil with the sequence of horizons Ap-BC-Ck. The plot size (5×3 m) was limited by a distinctive mosaic pattern of the soil cover on the loess slopes, formed by patches of non-eroded soil, pedons with different classes of erosion, and colluvial soil.

AgroAquaGel 500 (produced by Artagro in Kraków) is an acrylic-acrylamide copolymer in the form of crystal grains with the size ranging from 0.2 to 2 mm. According to the producer's information, the capacity of deionized water absorption is of ca. 500 $cm^3 \cdot g^{-1}$ while tap water absorption obtained by the author of the present study was 215.0 $cm^3 \cdot g^{-1}$.

Spring wheat (*Triticum aestivum* L. cv. Nawra) was grown in 2005, replacing sugar beet (*Beta saccharifera*). Cultivation management included winter ploughing, cultivatoring and harrowing in spring. The mineral fertilization per hectare was as follows: 40 kg of N (on a one-off basis, a full dose before sowing, applied in the form of nitrochalk and ammonium phosphate), 23 kg of P, and 75 kg of K (as sixty per cent potassium salt). As a supplementary agricultural treatment, AgroAquaGel 500 was mixed into the soil to the depth of 5 cm at the rates of 1 and 2 $g \cdot kg^{-1}$ (0.5 and 1 $Mg \cdot ha^{-1}$). Since the macronets may stick to the seed drill coulter in wet soil, the soil conditioner was introduced, according to the recommendations, after sowing (at the beginning of April 2005). For crop protection, 'Chwastox Turbo 340 SL' was used (2 $dm^3 \cdot ha^{-1}$).

Soil samples for analyses of the direct effect of AgroAquaGel were collected from the surface layer of Ap horizons (at the depth of 0-5 cm). In order to determine aggregate size distribution and aggregate water stability, soil material was sampled on four dates during 2005 (May 23, June 14, July 11, August 8). Soil samples of undisturbed structure were collected on June 14 and August 8, 2005, in 8 replications to metal cylinders of 100 cm^3 in volume (4 cylinders to determine water capacity and air permeability, and 4 cylinders to determine saturated hydraulic conductivity). Both the total carbon (TC) content and pH were determined in the soil material taken in June.

After effects of AgroAquaGel 500 on aggregate size distribution and aggregate water stability were examined in 2006 and 2007, i.e. in the second and third year after its application. The focus of that part of the analyses was on aggregate structure, which needs most improvement so as to protect soil from accelerated surface erosion by water. Cultivation management included annual skim ploughing, winter ploughing, spring cultivatoring, and harrowing. Spring barley (cv. 'Stratus') was grown twice, and mineral fertilization per hectare was the same as in 2005, viz. 40 kg of N, 23 kg of P, and 75 kg of K. Soil material was sampled on June 20, 2006 and June 15, 2007, from 0-20 cm depth.

Soil texture was determined according to the Casagrande method modified by Prószyński. Organic carbon content (TC) was measured by Tiurin's method in Simakov's modification. Soil reaction in 1 $mol \cdot dm^{-3}$ KCl was determined potentiometrically using a combined electrode.

In order to determine aggregate size distribution ($kg \cdot kg^{-1}$), 500-representative air-dried samples in two replications were passed through a nest of sieves with the mesh sizes of 10, 7, 5, 3, 1, 0.5, and 0.25 mm. The distribution of water-stable aggregates (WSA) ($kg \cdot kg^{-1}$) was determined in four replications through wet sieving with the use of the modified Baksheyev's apparatus made by The Institute of Agrophysics, Polish Academy of Sciences in Lublin [18]. 25-g test portions, corresponding to the size distribution of air-dry aggregates, were placed in a nest of sieves with mesh sizes of 7, 5, 3, 1, 0.5, and 0.25 mm. The soil samples were subjected to capillary saturation and then immersed in water. The analyzed material was kept in Baksheyev's apparatus for 12 minutes. Subsequently, each water-stable

Table 1. Air-dry soil aggregate distribution in Ap horizon (mean values in 3 plots).

Month, Year (M)	Dose of polymer (g·kg^{-1}) (D)	Air-dry aggregate content of diameter in mm (kg·kg^{-1})						MWD (mm)
		>10	5-10	1-5	0.25-1	<0.25	Σ0.25-10	
May 2005	0	0.293	0.145	0.296	0.186	0.080	0.627	9.3
	1	0.119	0.146	0.352	0.247	0.136	0.745	4.9
	2	0.165	0.176	0.354	0.187	0.118	0.717	6.1
June 2005	0	0.336	0.154	0.286	0.158	0.066	0.598	10.1
	1	0.141	0.160	0.371	0.215	0.113	0.746	5.1
	2	0.183	0.144	0.334	0.212	0.127	0.690	6.0
July 2005	0	0.352	0.101	0.209	0.177	0.161	0.487	15.1
	1	0.164	0.131	0.310	0.226	0.169	0.667	5.8
	2	0.148	0.120	0.306	0.239	0.187	0.665	5.5
August 2005	0	0.462	0.125	0.235	0.110	0.068	0.470	16.4
	1	0.213	0.124	0.333	0.198	0.132	0.655	7.3
	2	0.160	0.123	0.313	0.235	0.169	0.671	5.6
Mean	0	0.361	0.131	0.256	0.158	0.094	0.545	12.7
	1	0.159	0.140	0.342	0.221	0.138	0.703	5.8
	2	0.164	0.141	0.326	0.218	0.150	0.686	5.8
LSD (α=0.05):	doses D	0.054	n. s.	0.027	0.027	0.031	0.047	1.6
	interaction D×M	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
June 2006	0	0.299	0.157	0.289	0.159	0.096	0.605	9.0
	1	0.284	0.137	0.272	0.172	0.135	0.581	7.4
	2	0.187	0.140	0.292	0.207	0.174	0.639	5.2
LSD (α=0.05):	doses D	0.106	n. s.	n. s.	n. s.	0.073	n. s.	3.4
June 2007	0	0.369	0.138	0.239	0.136	0.118	0.513	10.1
	1	0.366	0.137	0.252	0.139	0.106	0.528	10.1
	2	0.349	0.144	0.273	0.134	0.100	0.551	9.8
LSD (α=0.05):	doses D	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.

n. s. – non significant differences

aggregate fraction was transferred from the sieves to filter paper, dried, and weighed. The sieving data were used to calculate the mean weight diameter (MWD) of both air-dry and water-stable aggregates according to the procedure of Youker and McGuinness [19]. The determination of the stability of the aggregates in water was assessed following the method described by Le Bissonnais [20].

Specific soil density (Mg·m^{-3}) was measured pycnometrically. Soil bulk density (Mg·m^{-3}) was calculated from the ratio of the mass of the soil dried at 105ºC to its volume. Actual soil moisture during sampling (kg·kg^{-1}) was measured by the gravimetric method. Water capacity in the range of soil water potential from -0.1 kPa to -1,554 kPa (kg·kg^{-1}) was determined in pressure chambers, on porous ceramic plates manufactured by Eijkelkamp Agrisearch Equipment, and Soil Moisture Equipment Corporation. Retention of water useful to plants (within the range of potential from -15.5 to -1,554 kPa) was calculated using water capacity values expressed in kg·kg^{-1}. Saturated hydraulic conductivity was determined with the use of Wit's apparatus (manufactured by Eijkelkamp Agrisearch Equipment) by calculating the water filtration coefficient (m·d^{-1}). Total porosity (m^3·m^{-3}) was calculated on the basis of the values of specific and bulk density. Distribution of pores with equivalent diameters of >20 μm, 0.2-20 μm, and <0.2 μm was calculated on the basis of water capacity values expressed in m^3·m^{-3}.

Air permeability at field water saturation of -15.5 kPa (·10^{-8}·m^2·Pa^{-1}·s^{-1}) was measured using LPiR-2 apparatus for measurement of air permeability in the moulding masses manufactured by the Polish Foundry Research Institute in Kraków.

Table 2. Water-stable soil aggregate content in Ap horizon (mean values in 3 soils).

Month, Year (M)	Dose of polymer ($g \cdot kg^{-1}$) (D)	Water-stable aggregate content of diameter in mm ($kg \cdot kg^{-1}$)				MWD (mm)
		5-10	1-5	0.25-1	Σ0.25-10	
May 2005	0	0.004	0.037	0.265	0.306	0.33
	1	0.071	0.207	0.329	0.607	1.28
	2	0.115	0.211	0.336	0.661	1.64
June 2005	0	0.008	0.044	0.273	0.325	0.37
	1	0.090	0.177	0.333	0.600	1.39
	2	0.160	0.256	0.300	0.716	2.13
July 2005	0	0.018	0.066	0.364	0.448	0.53
	1	0.117	0.212	0.299	0.629	1.66
	2	0.139	0.278	0.329	0.746	1.99
August 2005	0	0.032	0.071	0.312	0.415	0.64
	1	0.111	0.149	0.314	0.574	1.48
	2	0.132	0.246	0.317	0.694	1.85
Mean	0	0.016	0.054	0.303	0.373	0.47
	1	0.097	0.186	0.319	0.602	1.45
	2	0.136	0.248	0.320	0.704	1.90
LSD (α=0.05):	doses D	0.026	0.026	n. s.	0.040	0.25
	interaction D×M	n. s.	0.053	0.041	0.079	n. s.
June 2006	0	0.004	0.043	0.219	0.266	0.32
	1	0.014	0.048	0.246	0.307	0.42
	2	0.019	0.061	0.231	0.310	0.49
LSD (α=0.05)	doses D	0.013	0.018	n. s.	n. s.	0.14
June 2007	0	0.006	0.041	0.242	0.289	0.35
	1	0.011	0.047	0.234	0.292	0.39
	2	0.011	0.046	0.257	0.314	0.40
LSD (α=0.05)	doses D	n. s.	n. s.	n. s.	n. s.	n. s.

n. s. – non significant differences

Analysis of variance (ANOVA) involving two-way classification in the completely randomized design was applied to the data pertaining to direct effects of AgroAquaGel 500 in 2005. After-effects of the hydrogel in 2006 and 2007 were analyzed using ANOVA with one-way classification. The significance of differences was verified by Tukey's test.

Dexter's index of soil physical quality S [21] was calculated on the basis of water retention curves using the computer programme RETC. The index S is defined by the author as the slope value of the soil water retention curve at its inflection point and should be calculated using the van Genuchten modified equation [22]:

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

...where:

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

θ_{res} – residual water content ($kg \cdot kg^{-1}$),

n – dimensionless parameter controlling the shape of the curve,

m – dimensionless parameter with Mualem restriction [23]: $1–1/n$.

Results

In terms of soil texture, the examined Haplic Luvisol developed from loess was silt loam comprising (depending upon the erosion class) 12-15% of sand (2-0.05 mm), 68-74% of silt (0.05-0.002 mm), and 14-17% of clay (<0.002 mm). TC content in the soil ranged from 8.04 to 9.20 $g \cdot kg^{-1}$

Table 3. Bulk density and water properties in Ap horizon (mean values in 3 plots).

Month, Year (M)	Dose of polymer (g·kg^{-1}) (D)	Bulk density (Mg·m^{-3})	Actual moisture (kg·kg^{-1})	Water capacity (kg·kg^{-1}) at			Retention of water useful for plants (kg·kg^{-1})	Saturated hydraulic conductivity (m·d^{-1})
				-0.1 kPa	-15.5 kPa	-1,554 kPa		
June 2005	0	1.31	0.184	0.389	0.262	0.069	0.193	2.00
	1	1.20	0.179	0.455	0.274	0.074	0.200	4.78
	2	1.13	0.179	0.511	0.279	0.078	0.201	6.09
August 2005	0	1.31	0.134	0.388	0.273	0.069	0.204	1.40
	1	1.16	0.142	0.487	0.282	0.072	0.210	5.17
	2	1.20	0.144	0.458	0.282	0.078	0.204	4.33
Mean	0	1.31	0.159	0.389	0.267	0.069	0.198	1.70
	1	1.18	0.161	0.471	0.278	0.073	0.205	4.97
	2	1.16	0.162	0.485	0.280	0.078	0.203	5.21
LSD (α=0.05):	doses D	0.04	n. s.	0.028	0.012	0.003	n. s.	1.65
	interaction D×M	0.06	n. s.	0.040	n. s.	n. s.	n. s.	n. s.

n. s. – non-significant differences

and tended to decrease with increasing erosion classes. The soil reaction was slightly acid (pH 5.8-6.1). The specific soil density was 2.65 Mg·m^{-3}.

The application of AgroAquaGel 500 improved size aggregate distribution in the surface layer of the eroded Haplic Luvisol. Beneficial changes were found in May 2005 (at the first sampling) and they were also observed for all subsequent sampling times (Table 1). The content of clods >10 mm decreased significantly (by 0.201 kg·kg^{-1} in the plots treated with 1 g·kg^{-1}, and by 0.197 kg·kg^{-1} in the plots treated with 2 g·kg^{-1} on average). At the same time, compared with the control plots, there were significant increases in fractions of air-dry macroaggregates in the 0.25-10 mm size range (by 0.158-0.141 kg·kg^{-1} on average), including 1-5 mm aggregates (by 0.086-0.070 kg·kg^{-1}), 0.25-1 mm aggregates (by 0.063-0.060 kg·kg^{-1}), and microaggregates <0.25 mm (by 0.044-0.056 kg·kg^{-1}). As a result, the mean weight diameter of air-dry aggregates decreased significantly (by 6.9 mm for both rates).

In the second year after application of AgroAquaGel 500, there were significantly fewer clods >10 mm (by 0.112 kg·kg^{-1}), and significantly more air-dry aggregates with sizes of 0.25-1 mm and microaggregates <0.25 mm (by 0.048 kg·kg^{-1} and 0.078 kg·kg^{-1}, respectively), and the mean weight diameter was significantly lower (by 3.8 mm) in the plots treated with doses of 2 g·kg^{-1} than in the control plots. The differences in the proportion of air-dry aggregates in the soil amended with 1 g·kg^{-1} of AgroAquaGel 500 were negligible (Table 1). In the third year after hydrogel application, there were no significant differences in the proportions of air-dry aggregates in the Ap horizon of the treated plots relative to the control plots.

The application of AgroAquaGel 500 increased significantly the content of water-stable aggregates with sizes of 0.25-10 mm (by 0.229 kg·kg^{-1} in the plots with the dose of 1 g·kg^{-1} and by 0.331 kg·kg^{-1} in the plots with the dose of 2 g·kg^{-1} on average) (Table 2). In particular, increases in the number of stable aggregates with sizes of 5-10 mm (by 0.081-0.120 kg·kg^{-1}) and of 1-5 mm (by 0.194 kg·kg^{-1}) as well as in their MWD values (by 0.92-1.43 mm) were found.

In 2006, the after effect of the AgroAquaGel on aggregate water stability was considerably lower than the direct effect noted in 2005. Nonetheless, it was significant for the plots treated with the dose of 2 g·kg^{-1}. When compared with the control plots, significantly more aggregates with sizes of 5-10 mm and 1-5 mm (by 0.015 kg·kg^{-1} and 0.018 kg·kg^{-1} respectively) having a greater MWD (by 0.17 mm) were observed there (Table 2). In the third year after application of the gel-forming polymer, only insignificant differences were noted in the proportions of water-stable aggregates in all the plots.

The decrease in clods in the soil aggregate distribution and the increase in the aggregate water stability in the first year after polymer treatment substantially influenced some water and air properties of the soil. After the addition of AgroAquaGel 500, bulk density in the layer of 0-10 cm decreased significantly (on average by 0.13 Mg·m^{-3} in the plots with the dose of 1 g·kg^{-1}, and by 0.15 Mg·m^{-3} in the plots with the rate of 2 g·kg^{-1}) in comparison with bulk density in the control plots. At the same time, actual soil moisture during sampling showed no significant differences among the plots (Table 3).

A significant increase (by 0.082-0.096 kg·kg^{-1} on average) in maximum water capacity of the soil (at the soil water potential of -0.1 kPa) attributable to the application of AgroAquaGel was detected, while significantly higher field water capacity (at the potential of -15.5 kPa) was found

Table 4. Porosity and air permeability in Ap horizon (mean values in 3 plots).

Month, Year (M)	Dose of polymer ($g \cdot kg^{-1}$) (D)	Total porosity ($m^3 \cdot m^{-3}$)	Pore-size content ($m^3 \cdot m^{-3}$)			Air permeability at –15.5 kPa ($\cdot 10^{-8} \cdot m^2 \cdot Pa^{-1} \cdot s^{-1}$)
			>20 μm	0.2-20 μm	<0.2 μm	
June 2005	0	0.506	0.165	0.252	0.089	23.8
	1	0.545	0.215	0.240	0.090	46.2
	2	0.574	0.260	0.227	0.087	119.2
August 2005	0	0.505	0.148	0.267	0.090	18.9
	1	0.561	0.234	0.244	0.083	104.6
	2	0.546	0.209	0.243	0.094	50.6
Mean	0	0.506	0.157	0.259	0.090	21.3
	1	0.553	0.225	0.242	0.086	75.4
	2	0.560	0.235	0.235	0.091	84.9
LSD (α=0.05):	doses D	0.016	0.026	0.016	0.004	50.8
	interaction D×M	0.022	0.037	n. s.	0.005	71.8

n. s. – non-significant differences

only in the plots where the rate of 2 $g \cdot kg^{-1}$ was added (by 0.013 $kg \cdot kg^{-1}$). Both hydrogel doses contributed to significant increases in permanent wilting point moisture contents (at the potential of -1,554 kPa), by 0.004 $kg \cdot kg^{-1}$ and by 0.009 $kg \cdot kg^{-1}$, respectively (Table 3). In consequence, retention of water useful to plants (within the range of the potential from -15.5 kPa to -1,554 kPa) increased only slightly (by 0.007-0.005 $kg \cdot kg^{-1}$) under the hydrogel treatment.

Saturated hydraulic conductivity in the surface layer of the soil treated with AgroAquaGel increased significantly (by 3.27-3.51 $m \cdot d^{-1}$ on average) compared with the control plots (Table 3).

Total porosity in the soil with the addition of AgroAquaGel 500 was significantly higher (by 0.047 $m^3 \cdot m^{-3}$ and by 0.054 $m^3 \cdot m^{-3}$on average, depending on the dose) than in the control plots (Table 4). The application of the gel-forming polymer led to significant increases (by 0.068 $m^3 \cdot m^{-3}$ and by 0.078 $m^3 \cdot m^{-3}$) in the proportion of macropores with effective diameters >20 μm, which determine air capacity of the soil at field water saturation. By contrast, the content of mesopores with diameters ranging from 0.2 to 20 μm, which retain water available to plants, decreased significantly (by 0.017-0.024 $m^3 \cdot m^{-3}$) in the soil where the hydrogel was added. At the same time, there were no significant differences in the content of micropores with diameters <0.2 μm (which retain water unavailable to plants).

Air permeability at field water saturation (-15.5 kPa) increased significantly (by $54.1 \cdot 10^{-8} \cdot m^2 \cdot Pa^{-1} \cdot s^{-1}$ in the plots with the dose of 1 $g \cdot kg^{-1}$ and by $63.6 \cdot 10^{-8} \cdot m^2 \cdot Pa^{-1} \cdot s^{-1}$ in the plots with the dose of 2 $g \cdot kg^{-1}$) (Table 4).

Dexter's index of soil physical quality *S* for the soil from the control plots, calculated on the basis of water retention curves (Fig. 1), reached the values in the range of 0.064 to 0.078. In the soil treated with AgroAquaGel, the index values were comparable or higher, ranging from 0.062 to 0.083 in the plots with the rate of 1 $g \cdot kg^{-1}$ and from 0.058 to 0.088 in the plots with the dose of 2 $g \cdot kg^{-1}$.

Discussion

The results of the present study clearly show that the addition of AgroAquaGel 500 hydrogel effectively improved the aggregate size distribution and significantly increased the water stability of aggregates in the range size of 0.25-10 mm. When referring to the classes proposed by Le Bissonnais [20], based on the mean weight diameter after wet sieving, the aggregates in the layer of 0-10 cm of the control plots were assessed in May and June 2005 and June 2006 and 2007 as very unstable (MWD <0.4 mm), and in July and August 2005 as unstable (MWD from 0.4 to 0.8 mm). At the same time, the aggregates from the plots treated with the hydrogel were classified mostly as stable (MWD 1.3-2.0 mm), more rarely as moderately stable (MWD 0.8-1.3 mm) or highly stable (MWD >2 mm).

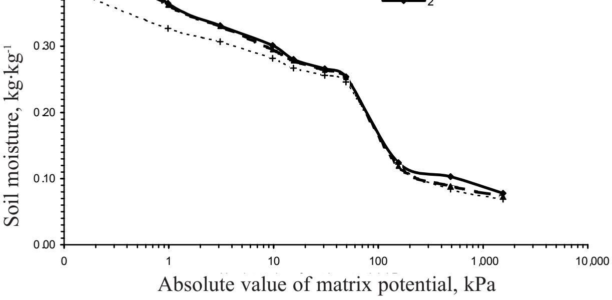

Fig. 1. Water retention curves of soil (mean values).

The values of Dexter's index of soil physical quality, S (0.062-0.083 in the plots with the dose of 1 g·kg^{-1} and 0.058-0.088 in the plots with the dose of 2 g·kg^{-1}) indicate a high quality of water-air properties of the eroded Haplic Luvisol [21].

Lower after effects of AgroAquaGel 500 on the soil structure in the second and third year after its application may be explained by its high dispersion in the soil caused by subsequent tillage treatments. When brought to the soil surface and exposed to ultraviolet radiation, macronets are decomposed into CO_2, H_2O, and NH_3 within several weeks.

Gel-forming polymers have a beneficial effect on improving soil structure, giving rise to the formation of new soil aggregates, which is facilitated by soil moistening. In a gel-forming polymer, water is bound through hydrogen bonds between oxygen atoms of functional groups and water protons. Upon contact with water, amide functional groups in cross-linked chains undergo solvation and dissociate, cations K^+ are released, and the negative charges of a polymer chain repel each other under the influence of Coulomb forces [14, 16]. This results in loosening of the granules that are able to absorb water further and to form gel. Under wet conditions, gel absorbs dispersed clay particles and microaggregates together with water. Water absorption continues until polymer chains forming a space lattice elongate to a maximum. Swelling gel makes soil substantially loosend and areated, and bonds between microaggregates within wetted soil aggregates weaken at the same time.

New soil aggregates are formed as a result of cation bridging ($–Ca^{2+}–$, $–Mg^{2+}–$) between polymer functional groups and negatively charged edge sites on surfaces of minerals. Less stable aggregates are formed by hydrogen bonds between functional groups and free OH groups and oxygen atoms of mineral edges. An effect of aggregate stabilization depends on a polymer rate, its molecular weight, types of functional groups, their numbers and arrangement in cross-linked polymer chains.

While comparing the present results with those obtained in other experiments conducted on eroded Haplic Luvisols developed from loess, the improvement in the structure of eroded soil amended with AgroAquaGel 500 has proven to be less marked than that achieved by the addition of other gel-forming polymers, such as Vittera or sodium polyacrylate applied at lower doses, e.g. 0.5 and 1 g·kg^{-1} [13, 24].

The application of Vittera significantly decreased the content of clods >10 mm (by 0.238-0.317 kg·kg^{-1} on average) and significantly increased the proportion of air-dry aggregates in the 0.25-10 mm size range (by 0.193-0.231 kg·kg^{-1}) and the content of water-stable aggregates in the 0.25-10 mm size range (by 0.212-0.325 kg·kg^{-1}) in the soil surface layer [13]. Viterra (manufactured by Schering Agrochemicals, Düsseldorf) is a potassium propenoate-propenamide copolymer [25]. It contains 9.9% of potassium available to plants and nitrogen as amide groups ($–CONH_2$), its granules have a size between 0.1 and 2 mm, the density is 0.70 Mg·m^{-3}, the pH values range from 7.0-8.5, and the capacity of deionized water absorption is 350 cm^3·g^{-1}. The highly beneficial effect of Viterra resulted from its chemical composition and a large number of $–CONH_2$ functional groups in particular. After the detachment of K^+ cations, surfaces of soil particles were attached strongly to amide groups with ionic bonds, via $–Ca^{2+}–$ cation bridges.

In comparison to the control soil, the soil where sodium polyacrylate (marketed under the trade name of Hidroplus) was added at the doses of 0.5 and 1 g·kg^{-1} showed a significant decrease in the content of clods >10 mm (by 0.174-0.214 kg·kg^{-1}) and increases in the proportion of air-dry aggregates with sizes of 0.25-10 mm (by 0.145-0.135 kg·kg^{-1}) and in the content of water-stable aggregates with sizes of 0.25-10 mm (by 0.281-0.351 kg·kg^{-1}) [24]. The sodium polyacrylate, $[–CH_2–CH(COONa)–]_n$, (produced by Emerging Technologies Inc. Greensboro) contains 10% of Na, its granules have a size between 0.1 and 3 mm, and its capacity of deionized water absorption is 400 cm^3·g^{-1} [16]. After the release of Na^+ cations into soil solution, the edges of molecules and soil microaggregates were strongly fixed by ionic bonds formed by numerous carboxyl groups of the polyacrylate.

The lower effect of AgroAquaGel 500 on soil structure as compared to the aforementioned polymers may be ascribed to its different chemical composition and structure of macronets. The molecules of AgroAquaGel contain less potassium (the producer has disclosed no detailed information on the content). Its $–CONH_2$ functional groups are less numerous and have a lower ability to aggregate soil particles. Additionally, polyacrylamide polymers tend to bind silt-sized quartz grains weaker than other hydrogels, irrespective of soil reaction or presence of cations in soil [26]. However, the addition of AgroAquaGel 500 was more effective than the application of Terravest 801 emulsion polymer or compost fertilization.

In soils amended with Terravest 801 at doses of 1 g·kg^{-1} and 2 g·kg^{-1}, there were significantly fewer clods >10 mm (by 0.147-0.210 kg·kg^{-1}), and significantly more air-dry aggregates with sizes of 0.25-10 mm (by 0.117-0.173 kg·kg^{-1}), as well as water-stable aggregates with sizes of 0.25-10 mm (by 0.093-0.195 kg·kg^{-1}) [13]. Terravest 801 (Chemische Werke Hüls AG, Marl, Germany) is a linear emulsion polymer, 1,4-polybutadiene with a chemical formula of $[–CH_2–CH=CH–CH_2–]_n$, containing the addition of emulsifiers and activators, having a density of 0.91 Mg·m^{-3} and viscosity of 790±10% mPa·s [27]. When applied to the soil surface as a diluted aqueous emulsion, it penetrates to a depth of 2-3 cm. Polybutadiene reacts with oxygen and converts into a solid, water-insoluble form, developing a permanent filiform, reticular structure which interconnects three-directionally soil particles and aggregates by chemical bonds. Unlike gel-forming polymers, Terravest, as an emulsion polymer, does not produce new soil aggregates, but only stabilizes the existing ones.

Compost fertilization at doses of 10 and 20 g·kg^{-1} (11 and 22 Mg·ha^{-1}) resulted in the first year of the treatment in a significant reduction of a content of clods >10 mm (by 0.105-0.151 kg·kg^{-1}) within the 0-10 mm layer of the soil, while the proportion of air-dry aggregates with sizes of

0.25-10 mm increased (by 0.094-0.138 kg·kg^{-1}), as compared to the control plots [24]. Whereas no change in the proportion of water-stable aggregates with sizes of 0.25-10 mm was found in the first year, there was a significant increase (by 0.046-0.086 kg·kg^{-1}) observed in the second year after compost application. The compost used in that study (obtained from PUH Botom) was made from solid green waste (grass, leaves, ground-up wood), and had dry matter content of 50.95%. The dry matter included: 19.4% Corg, 1.3% N, 1.0% P_2O_5, and 0.5% K_2O.

Unlike synthetic polymers that improve mainly soil structure and its water-air properties, natural or organic fertilizers increase contents of organic carbon and nutrients in soil and enhance its physicochemical and biological properties. However, they require long-term heavy application. A slow increase in aggregate water stability as resulted from compost addition is due to low abilities of partially decomposed plant remnants and humic and fulvic acids to bind mineral particles together into stable aggregates. Bacterial polysaccharides formed during further microbiological transformations are needed to form persistent bonds between the particles and soil microaggregates. Organic binding agents responsible for soil aggregate stabilization include also plant roots, fungal hyphae, some fungi, and resistant aromatic humic substances strongly bound to polyvalent cations inside aggregates [28].

Apart from various composts, other natural and organic fertilizers are used to improve soil structure and water-air properties, such as animal manure and slurry (at doses of 60 Mg·ha^{-1}), peat, brown coal, straw, green manure, sewage sludge and other organic waste (at doses to 200-300 Mg·ha^{-1}) [11, 12, 29, 30]. In order to amend sandy soils, a variety of organic-mineral and mineral materials may be used, including alluvial sediments, clays, loams, mine wastes, bentonites and zeolites applied at equally high rates.

All the aforementioned ways to improve soil structure are not as effective as synthetic polymers, particularly hydrogels. Among them, cultivation of green manure papilionaceous species (e.g. alfalfa and red clover) or an increased proportion of those plants in plant mixtures with perennial grasses used in crop rotation (2-3 years) is worth mentioning. Roots of legume plants and grasses produce plant polysaccharides which effectively stabilize soil aggregates and enrich soil with nitrogen and organic carbon. Thanks to their deep roots, the plants contribute to translocation of nutrients from deeper layers to the humus horizon [31, 32].

Gel-forming polymers make irreplaceable materials for insulating in mining and geological drilling and for stabilizing grounds in earthworks, roadsides, embankments, escarpments, channel banks, workings, and mine slag heaps [33, 34]. The use of hydrogels in environmental protection includes post-industrial land and mine restoration, recultivation of forest soil destroyed by fire, stabilization of coal ash disposal at power plants, removal of organic contaminants and heavy metals in soil and water treatment. Hydrogels are the polymers that may find wider applications in soil protection against severe water and air erosion, stabilization of migrating dunes in arid and semi-arid areas, and soil fertility restoration of sands [35-37]. Additionally, hydrogels have been successfully used in forestry and horticulture, for the purpose of transplanting shrubs and trees, rooting plant seedlings and their mycorrhizal inoculation, establishing lawns, sport fields and golf courses, manufacturing roll turf lawns, and for container cultivation [38, 39]. However, due to the high costs of gel-forming polymer applications, its widespread use in agriculture does not seem to be economically viable.

Conclusions

1. AgroAquaGel 500 added at doses of 1 and 2 g·kg^{-1} had a direct beneficial effect on aggregate size distribution within the 0-5 cm layer of the eroded Haplic Luvisol developed from loess. As a result of its application a significant reduction of an unfavourable content of clods >10 mm was noted compared to the control, while air-dry aggregates ranging from 0.25 to 10 mm (particularly those with sizes of 1-5 mm and 0.25-1), significantly increased there. The mean weight diameter of air-dry aggregates decreased significantly in comparison with the control.
2. In the second year after application of AgroAquaGel 500, the same trend was noted in the plots with a dose of 2 g·kg^{-1}, where content of clods >10 mm remained significantly lower, the content of air-dry aggregates with sizes of 0.25-1 mm significantly higher, and their mean weight diameter significantly lower compared with the control plots. No significant after effect of the polymer on the aggregate size distribution was observed in the third year.
3. In the first year after its addition, AgroAquaGel 500 increased significantly the content of water-stable aggregates between 0.25 to 10 mm (including those with sizes of 5-10 mm and 1-5 mm), and their mean weight diameter.
4. In the second year after hydrogel treatment, the significant after effect was observed only in the plots amended with the rate of 2 g·kg^{-1}, where more 0.25-10 mm aggregates (including those with sizes of 5-10 mm and 1-5 mm) with a significantly greater mean weight diameter were found. Little effect of the polymer on aggregate stability was noted in the third year after its application.
5. Addition of AgroAquaGel 500 at doses of 1 and 2 g·kg^{-1} contributed to a significant decrease of bulk density and to significant increases of maximum water capacity, water content at the permanent wilting point, saturated hydraulic conductivity, total porosity, the content of macropores >20 μm in diameter, and air permeability at field water saturation in the 0-5 cm layer of the eroded Haplic Luvisol developed from loess. Moreover, the hydrogel dose of 1 g·kg^{-1} significantly increased field water capacity.
6. AgroAquaGel 500 had no significant effect on actual soil moisture during sampling, retention of water useful

to plants and the content of micropores <0.2 μm in diameter. At the same time, its application resulted in a significant decrease in the content of mesopores with diameters of 0.2-20 μm.

7. The values of Dexter's index of soil physical quality *S* in the plots treated with AgroAquaGel 500 were similar or higher compared with those of the control plots, which indicates a high quality of water and air properties of the examined soil.

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