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Physical quality of eroded soil amended with gel-forming polymer*

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A b s t r a c t. The aim of this study was to assess the effect of a gel-forming polymer (Aquanika) added at the doses of 1 and 2 g kg^{-1} on structure, water and air properties of eroded soil developed from loess. The addition of the hydrogel resulted in a significant reduction in content of clods >10 mm and a significant increase in the content of air-dry aggregates in the 0.25-10 mm range size in the soil surface layer. At the same time, the content of water-stable aggregates in the 0.25-10 mm range size also increased significantly. In the second year after Aquanika application, more of these water-stable aggregates of 0.25 to 10 mm were found only in the plots treated at the dose of 2 g kg^{-1} as compared to the control plots. The addition of the hydrogel significantly decreased soil bulk density, while increasing actual soil moisture, its maximum water capacity, saturated hydraulic conductivity, total porosity, the content of macropores with diameter >20 μm and air permeability in the soil surface layer. Values of Dexter index, *S*, for the soil from the plots treated with Aquanika were similar to those obtained for the control plots and are indicative of a very high physical quality of the soil.

K e y w o r d s: eroded soil, gel-forming polymer, soil structure, water-air properties

INTRODUCTION

The Ap horizons of eroded soils, developed from illuvial horizons or parent material, have more clods in their aggregate size distribution, lower aggregate water stability, higher bulk density, lower retention of water useful to plants, air capacity and air permeability than those of non-eroded soils (Jankauskas *et al.,* 2008; Paluszek and Żembrowski, 2008; Papiernik *et al.,* 2009; Shukla and Lal, 2005). Weak water stability of soil aggregates leads to their breakdown under rainfall and surface crust formation, making the soil more susceptible to further water erosion (Le Bissonnais, 2006). Also, erosion affects crops by washing off of applied mineral fertilizers and plant protection chemicals from fields. This, in turn, results in reduced crop yields, which contributes to great losses in agriculture and harm to the environment, while erosion protection involves considerable financial costs (Bakker *et al.,* 2007; Den Biggelaar, 2001; Papiernik *et al.,* 2009).

Restoration of aggregate stability to water in eroded soil requires multi-year application of natural and organic fertilizers at high rates, combined with NPK fertilization, liming, and crop rotation with greater use of papilionaceous plants and grasses (Annabi *et al.,* 2007; Arriaga and Lowery, 2003; Becher, 2005; Cox *et al.,* 2001). Natural soil aggregation processes may be stimulated by treatment with high-molecular weight synthetic polymers which are more effective and resistant to microbiological degradation. The polymers include hydrogels, composed of polymer chains having three-dimensional cross-linked structures. In the presence of water, their dried, tightly coiled macronets in the form of crystal grains or granules are capable of swelling many times their volume and becoming gel (Bhardwaj *et al.,* 2007; Hua and Qian, 2001; Martyn and Szot, 2001; Sivapalan, 2006).

The aim of the study was to assess both direct and after effects of gel-forming polymer (Aquanika) on the quality of structure and water-air properties of eroded Haplic Luvisol developed from loess.

MATERIALS AND METHODS

The study was carried out from 2005 to 2007 in a small catchment typical for loess regions of Poland (Bogucin, 51°19'56"N and 22°23'18"E) at the Nałęczów Plateau (Lublin Upland). A field experiment was performed on a slope with the inclination ranging from 11 to 15%, transversely to

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the direction of tillage. The experiment was conducted in plots on Haplic Luvisol with three erosion classes (severely, moderately, and slightly eroded), each treated with two doses of Aquanika (6 plots in total). In order to evaluate the effect of the polymer on the soil studied, the soil properties were compared with those of soil in control plots (in three replications). 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 class of erosion, and colluvial soil.

Spring wheat (cv. Nawra) was grown in 2005, having replaced sugar beet. Cultivation management included winter ploughing, followed by cultivatoring and harrowing in spring. The mineral fertilization per hectare included 40 kg N, 23 kg P, and 75 kg K. As a supplementary agricultural treatment, Aquanika was mixed into the 0-5 cm layer of soil after spring wheat sowing at the beginning of April, at the doses recommended by the manufacturer *ie* 1 and 2 g kg^{-1} (55 and 110 g m^{-2}).

Aquanika (produced by Unika S.J., Cracow), is a cream-coloured cross-linked potassium polyacrylate in the form of crystal grains having a size in the range of 1-2 mm and pH values ranging between 6.0 to 6.8. According to the information given by the manufacturer, its absorptiveness of deionized water is up to 500 cm^3 g^{-1} (Unika, 2005). However, its water storage properties were significantly reduced when water with dissolved salts was used (168.1 cm^3 g^{-1} in the case of tap water).

Soil samples for analyses of the direct effect of Aquanika on the aggregate size distribution and aggregate water stability were collected at the depth of 0-5 cm of Ap horizon on four dates in 2005 (May 23, June 14, July 11, August 8). The depth at which the samples were collected in all the plots (0-5 cm) was the same as the depth at which the hydrogel was mixed with soil after its application. Soil samples of undisturbed structure were collected twice (on June 14 and August 8, 2005) using metal cylinders of 100 cm^3 in volume. The samples were taken in 8 replications from all the plots and each sampling date (4 cylinders to determine water capacity and air permeability, and 4 cylinders to determine saturated hydraulic conductivity).

After effects of Aquanika on the aggregate size distribution and aggregate water stability were examined in 2006 and 2007 *ie* in the second and third year after its application. 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. The polymer was mixed with the eroded soil to mean depth of 20 cm during subsequent cultivation practices after spring wheat harvest. In order to study after effects of Aquanika on soil properties, samples were collected from all the plots from the depth of 0-20 cm in 2006 (June 20) and 2007 (June 15). The difference in sampling depth (*ie* from the entire layer of 0-20 cm) was caused by the fact that the aggregates fixed with the hydrogel were mixed into the soil within the entire arable layer as a result of the use of agricultural machinery. Since ploughing on an eroded slop often brings subsoil material up to the surface, the comparison of the effect of Aquanika on aggregate stability between the 2nd and 3rd year of the study for the 0-5 cm soil layer was found to be less appropriate than that for the 0-20 cm layer. Additionally, the macronets of hydrogel that remain several months on the soil surface without plant cover are more easily decomposed by ultraviolet rays than those occurring deeper.

In order to determine aggregate size distribution of air-dried soil were passed through a nest of sieves with the mesh sizes of 10, 7, 5, 3, 1, 0.5, and 0.25 mm. Each soil sample was sieved using 500 g weighed portions in two replications. By multiplying the number of the weighed portions (2) by the number of the plots (3), the results of aggregate size distribution were obtained for each polymer dose and each sampling date in 6 replications.

The basic properties and distribution of water-stable aggregates of investigated soil were determined using standard methods. The mean weight diameter (MWD) of both air-dry and water-stable aggregates according to the procedure of Youker and McGuinness.

Water capacities in the range of soil water potential from -0.1 kPa to -1554 kPa (kg kg^{-1}) to soil water retention curves were determined in pressure chambers (SoilMoisture Equip. Corp., Santa Barbara, CA, USA (Witkowska-Walczak *et al.,* 2004). Retention of water useful to plants (within the range of potential from -15.5 to -1554 kPa) was calculated using water capacity values. Saturated hydraulic conductivity was determined with the use of Wit apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands). Total porosity was calculated using particle density and bulk density values. Content of soil pores with equivalent diameters of >20 μm was calculated on the basis of water capacity values. Air permeability at field water capacity of -15.5 kPa was measured using LPiR-2 apparatus (Polish Foundry Research Institute, Cracow, Poland) for air permeability measurements in the moulding masses.

The examined soil was a 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). Total organic content content ranged from 8.04 to 9.20 g kg^{-1} and tended to decrease with an increasing erosion class. The soil reaction was slightly acid (pH 5.8-6.1), and the particle density was 2.65 Mg m^{-3}.

Dexter (2004) index, *S*, of soil physical quality was calculated on the basis of water retention curves established with the computer program RETC (Retention Curve Program for describing the hydraulic properties of unsaturated soils). RETC may be used to fit several analytical models to observed water retention and unsaturated hydraulic conductivity data. The index *S* is defined as the slope value of the soil water retention curve at its inflection point and should be calculated using the van Genuchten modified equation:

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

where: θ_{sat} – the volumetric water content at saturation, θ_{res} – the residual water content, n – the dimensionless parameter controlling the shape of the curve, m – the dimensionless parameter with Mualem restriction: 1–1/n.

Analysis of variance (ANOVA) involving two-way classification was applied to the data pertaining to 2005, while the data for 2006 and 2007 were analyzed using ANOVA with one-way classification at α = 0.05. A completely randomized design was used for all the data obtained. Significant differences were verified by Tukey test.

RESULTS AND DISCUSION

The addition of Aquanika improved aggregate size distribution in the 0-5 cm layer of the eroded soil. Beneficial changes were found in May 2005 (at the first sampling) and they were also observed for all subsequent sampling dates (Table 1). The content of clods >10 mm decreased significantly (0.183 kg kg^{-1} in the plots treated with 1 and 2 g kg^{-1}). At the same time, compared with the control plots, there was a significant increase in fractions of air-dry macroaggregates:

– 0.25-10 mm size range (0.160-0.155 kg kg^{-1}), including 1-5 mm aggregates (0.094-0.080 kg kg^{-1}),
– 0.25-1 mm aggregates (0.053-0.064 kg kg^{-1}).

As a result, the mean weight diameter of air-dry aggregates (MWD-dry) decreased significantly (6.0-6.4 mm). In the second year of the study, negligible differences were noted in proportions of air-dry aggregates in the plots amended with Aquanika compared to the control plots. Similarly, differences in aggregate size distribution among the plots were statistically non-significant in the third year.

During wet-sieving, air-dry aggregates, particularly those >1 mm, disintegrated into smaller fractions, including microaggregates smaller than 0.25 mm and macroaggregates 0.25-1 mm. After the sieving, more water-stable aggregates of 0.25-1 mm were stated when compared to air-dry aggregates in the same range size (Tables 1, 2). By contrast, there were far less waterstable aggregates of 1-10 mm than air-dry aggregates in the same range size.

The application of Aquanika the polymer increased significantly the content of stable aggregates in the ranges of 0.25-10 mm (0.090 kg kg^{-1} in the plots with the dose of 1 and 0.171 kg kg^{-1} in the plots with the dose of 2 g kg^{-1}). Significant increases were found in the quantities of stable aggregates with sizes of 5-10 mm (0.020-0.033 kg kg^{-1}), of 1-5 mm (0.041-0.088 kg kg^{-1}), and of 0.25-1 mm (0.029-0.050 kg kg^{-1}) as well as in their MWD-wet values (0.27-0.49 mm). In 2006, the after effect of Aquanika on aggregate water stability was considerably lower than the direct effect noted in 2005. Nonetheless, it was still significant for the plots treated with the dose of 2 g kg^{-1} (Table 2). The content of 0.25-10 mm aggregates was significantly higher there (0.044 kg kg^{-1}), including those of 5-10 mm (0.012 kg kg^{-1}), and they had greater MWD-wet (0.15 mm) when compared to the control plots. In the third year after application of Aquanika, there were only insignificant differences observed in the proportions of water-stable aggregates between the plots treated with the hydrogel and the control plots.

The Aquanika addition had a positive effect on some water and air properties of the soil. Bulk density in the layer of 0-5 cm decreased significantly (0.008 Mg m^{-3} in the plots with the dose of 1 g kg^{-1}, and by 0.012 Mg m^{-3} in the plots with the dose of 2 g kg^{-1}) in comparison with bulk density in the control plots.

Actual soil moisture during sampling showed significant non differences among the plots (Table 3). A significant increase (by 0.049-0.075 kg kg^{-1}) in maximum water capacity of the soil (at the soil water potential of -0.1 kPa) was detected as a result of the treatment with Aquanika. No significant differences were found in field water capacity (at the potential of -15.5 kPa) (Table 3). Wilting point moisture (at the potential of -1554 kPa) increased significantly (by 0.005 kg kg^{-1}) only in the plots with the dose of 2 g kg^{-1}. In consequence, the application of Aquanika had no effect on retention of water useful to plants (within the range of the potential from 15.5 kPa to -1554 kPa). Saturated hydraulic conductivity increased significantly under the hydrogel treatment by 2.07 m day^{-1} (122%) in the plots with the dose of 1 g kg^{-1} and 3.51 m day^{-1} (236%) in the plots with the dose of 2 g kg^{-1}.

Total porosity in the soil with the addition of Aquanika was significantly higher (0.030-0.044 m^3 m^{-3}) than in the control plots (Table 4). The application of the gel-forming polymer led to significant increases (0.052-0.64 m^3 m^{-3}) in the content of macropores with equivalent diameters >20 μm, determining air capacity of the soil at field water capacity. Also air permeability at field water capacity (-15.5 kPa) increased significantly in the soil amended with Aquanika (85.9 10^{-8} m^2 Pa^{-1} s^{-1} in the plots with 1 g kg^{-1} and 162.7 10^{-8} m^2 Pa^{-1} s^{-1} in the plots with 2 g kg^{-1}).

The absolute values of Dexter index of soil physical quality, S, for the soil from the control plots were in the range of 0.064-0.078. In the soil treated with Aquanika, the index values were comparable, ranging from 0.059 to 0.067 in the plots with the dose of 1 g kg^{-1} and from 0.061 to 0.080 in the plots with the dose of 2 g kg^{-1}. When assessed by Dexter index, S, soil physical quality showed no improvement after addition of Aquanika, but remained largely unchanged. The quality of the amended soil was very high, similarly to that of the control soil. The index S is closely connected with the number of mezopores with an equivalent diameter of 0.2-20 μm which retain water useful to plants. All soils

T a b l e 1. Air-dry soil aggregate distribution in Ap horizon (mean values in 3 plots)

Month, Year (M)	Dose of hydrogel (g kg^{-1}) (D)	Air-dry aggregate distribution (dia in mm, kg kg^{-1})						MWD-dry (mm)
		>10	5-10	1-5	0.25-1	<0.25	Σ 0.25-10	
May 2005	0	0.293	0.145	0.296	0.186	0.080	0.627	9.3
	1	0.133	0.155	0.394	0.217	0.101	0.766	5.3
	2	0.184	0.176	0.342	0.206	0.092	0.724	7.0
June 2005	0	0.336	0.154	0.286	0.158	0.066	0.598	10.1
	1	0.139	0.154	0.387	0.224	0.096	0.765	5.3
	2	0.158	0.145	0.367	0.223	0.107	0.735	5.6
July 2005	0	0.352	0.101	0.209	0.177	0.161	0.487	15.1
	1	0.178	0.121	0.298	0.230	0.173	0.649	6.4
	2	0.196	0.123	0.283	0.227	0.171	0.633	6.6
August 2005	0	0.462	0.125	0.235	0.110	0.068	0.470	16.4
	1	0.263	0.148	0.318	0.173	0.098	0.639	9.7
	2	0.174	0.125	0.354	0.228	0.117	0.709	5.8
Mean	0	0.361	0.131	0.256	0.158	0.094	0.545	12.7
	1	0.178	0.144	0.350	0.211	0.117	0.705	6.7
	2	0.178	0.142	0.336	0.222	0.122	0.700	6.3
LSD (α = 0.05):	doses D	0.052	n. s.	0.025	0.028	0.019	0.047	1.7
	interaction D×M	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.	3.3
June 2006	0	0.299	0.157	0.289	0.159	0.096	0.605	8.8
	1	0.245	0.146	0.301	0.185	0.123	0.632	6.3
	2	0.255	0.145	0.304	0.182	0.114	0.631	7.0
LSD (α= 0.05):	doses D	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
June 2007	0	0.369	0.138	0.239	0.136	0.118	0.513	10.1
	1	0.373	0.138	0.226	0.133	0.130	0.497	10.2
	2	0.358	0.117	0.230	0.149	0.146	0.496	9.7
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.

developed from loess are characterized by very high retention of useful water. However, the index *S* does not include aggregate stability or the proportion of aeration pores which are responsible for saturated hydraulic conductivity and air permeability of the soil *ie* the properties which were significantly improved by the hydrogel application.

Of all the physical properties of the eroded Haplic Luvisol studied, saturated hydraulic conductivity and air capacity at field water capacity have proven to be the most useful for evaluating the effectiveness of Aquanika, followed by the proportion of air-dry clods >10 mm and MWD-wet.

T a b l e 2. Water-stable soil aggregate content in Ap horizon (mean values in 3 soils)

Month, Year (M)	Dose of hydrogel ($g\ kg^{-1}$) (D)	Water-stable aggregate distribution (dia in mm, $kg\ kg^{-1}$)				MWD-wet (mm)
		5-10	1-5	0.25-1	Σ 0.25-10	
May 2005	0	0.004	0.037	0.265	0.306	0.33
	1	0.018	0.082	0.310	0.410	0.55
	2	0.046	0.105	0.338	0.489	0.85
June 2005	0	0.008	0.044	0.273	0.325	0.37
	1	0.022	0.091	0.323	0.436	0.61
	2	0.039	0.144	0.331	0.514	0.87
July 2005	0	0.018	0.066	0.364	0.448	0.53
	1	0.045	0.110	0.381	0.536	0.86
	2	0.058	0.177	0.381	0.616	1.13
August 2005	0	0.032	0.071	0.312	0.415	0.64
	1	0.060	0.098	0.314	0.472	0.94
	2	0.054	0.140	0.362	0.556	1.00
Mean	0	0.016	0.054	0.303	0.373	0.47
	1	0.036	0.095	0.332	0.463	0.74
	2	0.049	0.142	0.353	0.544	0.96
LSD (α = 0.05):	doses D	0.015	0.017	0.023	0.038	0.15
	interaction D×M	n. s.	n. s.	n. s.	n. s.	n. s.
June 2006	0	0.004	0.043	0.219	0.266	0.32
	1	0.009	0.044	0.226	0.279	0.37
	2	0.016	0.060	0.234	0.310	0.47
LSD (α= 0.05):	doses D	0.011	n. s.	n. s.	0.031	0.11
June 2007	0	0.006	0.041	0.242	0.289	0.35
	1	0.013	0.047	0.232	0.292	0.41
	2	0.015	0.044	0.248	0.307	0.43
LSD (α = 0.05):	doses D	n. s.	n. s.	n. s.	n. s.	n. s.

Explanations as in Table 1.

According to the classes proposed by Le Bissonnais (2006) based on the mean weight diameter, the aggregates in the control plots assessed in May and June 2005, June 2006 and 2007 were very unstable (MWD-wet 0.32-0.37 mm), and those assessed in July and August 2005 were unstable (MWD-wet 0.53-0.64 mm) (Table 2). At the same time, the aggregates from the plots treated with the hydrogel at the rates of 1 and 2 $g\ kg^{-1}$ in 2005 were classified mostly as moderately stable (MWD-wet 0.85-1.00 mm) or unstable (MWD-wet 0.55-0.61 mm).

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 (Hua and Qian, 2001). This results in loosening of the

T a b l e 3. Bulk density and water properties in Ap horizon (mean values in 3 plots)

Month, Year (M)	Dose of hydrogel ($g\ kg^{-1}$) (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 ($m\ day^{-1}$)
				-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	1.25	0.172	0.421	0.262	0.071	0.191	3.47
	2	1.20	0.189	0.456	0.274	0.076	0.198	5.84
August 2005	0	1.31	0.134	0.388	0.273	0.069	0.204	1.40
	1	1.20	0.142	0.454	0.270	0.070	0.200	4.08
	2	1.18	0.139	0.472	0.279	0.073	0.206	5.60
Mean	0	1.31	0.159	0.389	0.267	0.069	0.198	1.70
	1	1.23	0.157	0.438	0.266	0.071	0.195	3.77
	2	1.19	0.164	0.464	0.276	0.074	0.202	5.72
LSD (α = 0.05):	doses D	0.04	n. s.	0.027	0.010	0.003	n. s.	1.70
	interaction D×M	n. s.	0.010	n. s.	n. s.	n. s.	n. s.	n. s.

Explanations as in Table 1.

T a b l e 4. Total porosity, content of macropores and air permeability in Ap horizon (mean values in 3 plots)

Month, Year (M)	Dose of hydrogel ($g\ kg^{-1}$) (D)	Total porosity ($m^3\ m^{-3}$)	Content of macropores >20 μm ($m^3\ m^{-3}$)	Air permeability at -15.5 kPa ($10^{-8}\ m^2\ Pa^{-1}\ s^{-1}$)
June 2005	0	0.506	0.165	23.8
	1	0.526	0.197	63.1
	2	0.545	0.218	54.4
August 2005	0	0.505	0.148	18.9
	1	0.544	0.220	151.3
	2	0.554	0.223	313.6
Mean	0	0.506	0.157	21.3
	1	0.536	0.209	107.2
	2	0.550	0.221	184.0
LSD (α = 0.05):	doses D	0.016	0.025	97.6
	interaction D×M	n. s.	n. s.	138.1

Explanations as in Table 1.

granules which 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 loosened and aerated, 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. Lower after effects of Aquanika on the soil structure in the second and third year after the gel application may be explained by its high dispersion in the soil due to subsequent tillage treatments and by decomposition of the macronets into CO_2 and H_2O (when brought to the soil surface and exposed to ultraviolet radiation).

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 Aquanika has proven to be less marked than that achieved by addition of other gel-forming polymers, such as Viterra or Stockosorb (Owczarzak *et al.,* 2006; Paluszek, 2003).

Application of Viterra applied at 0.5 and 1 g kg^{-1} significantly decreased the content of clods >10 mm (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 (0.193-0.231 kg kg^{-1}) and the content of water-stable aggregates in the 0.25-10 mm size range (0.212- 0.325 kg kg^{-1}) in the soil surface layer (Paluszek, 2003). Viterra is a potassium propenoate-propenamide copolymer. 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, 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. Similarly, Owczarzak *et al.* (2006) reported a beneficial effect of Stockosorb added at the rates of 0.33, 0.66, 1.32, and 2.64 g kg^{-1} on static water resistance of aggregates moulded from material taken from gray-brown podzolic soil (loamy sand) and black earth (sandy loam).

The decrease in bulk density in the plots treated with Aquanika resulted from soil loosening due to swelling macronets. Increased aggregate stability also prevented the soil from compacting. Lower bulk density, in turn, brought about an increase in total porosity, maximum water capacity, air permeability, and in the content of macropores >20 μm (Tables 3-4).

The beneficial effect of hydrophilic gels on water properties of soil results from water retention in their swelling macronets. According to producers specifications, gel-forming polymers should increase soil moisture, its field water capacity, water retention, and hydraulic conductivity, as well as reduce unproductive soil evaporation (Akhter *et al.*, 2004; Bhardwaj *et al.*, 2007; Sivapalan, 2006). However, both the presence of Ca, Mg and Fe cations in soil and mineral fertilization tend to cause even a several-fold decrease in the water absorption capacity of hydrogels. Consequently, the low polymer rates used in the field experiment only slightly increased actual soil moisture during sampling. The effect of Aquanika on water-air properties of the eroded soil was weaker in comparison with that of other hydrogels (Akhter *et al.*, 2004; Bhardwaj *et al.*, 2007; Geesing and Schmidhalter, 2004; Sivapalan, 2006).

Sivapalan (2006) showed that field water capacity (at -10 kPa) increased by 23 and 95% by adding 0.3 and 0.7 g kg^{-1} of Alcosorb 400 hydrogel to sandy soil, respectively. Amending loamy soil with 1, 2 and 3 g kg^{-1} of a gel-forming polyacrylamide, Akhter *et al.* (2004) noted that field water capacity and retention of water useful to plants increased proportionally to the applied doses. According to the results by Geesing and Schmidhalter (2004), the application of 3 and 5 g dm^{-3} of sodium polyacrylate contributed to a significant rise in retention of water useful to plants in loamy soils. Bhardwaj *et al.* (2007) observed that the doses of 0.5, 2.5 and 5 g kg^{-1} of Stockosorb (HCMG, 500 Medium, and 500 Micro), increased hydraulic conductivity in sandy soil taken from arid and subarid regions.

The lower effect of Aquanika on the structure and water-air properties of the soil as compared to that of the aforementioned polymers may be ascribed to differences in methods of polymerization, in their chemical composition, and in the size and structure of their macronets (Hua and Qian, 2001).

The absolute values of Dexter index, *S*, greater than 0.050 indicate a very high physical quality of the soil (Dexter, 2004). Proper growth and functioning of crop plants roots require an appropriate ratio between mesopores with diameters of 0.2-20 μm retaining water useful to plants and macropores >20 μm responsible for adequate aeration. An optimal balance between near-surface soil water holding capacity and aeration may be achieved when field capacity is 0.6-0.7 of total porosity and air capacity is 0.3-0.4 (Reynolds *et al.*, 2008). In the Ap horizon of the eroded Haplic Luvisol, this relationship was close to the optimum: field water capacity was on average 0.69 in the control plots and between 0.61 to 0.60 in the plots treated with Aquanika, while air capacity values were 0.31 and 0.39-0.40, respectively. Given the above-presented criteria, both water and air properties of the examined soil can be regarded as highly beneficial. However, high costs of gel-forming polymers may limit their widespread applicability in agriculture.

CONCLUSIONS

1. A beneficial direct effect of Aquanika added at the doses of 1 and 2 g kg^{-1} manifested itself in a significant reduction in an unfavourable content of clods >10 mm accompanied by a significant increase in a content of air-dry aggregates with sizes of 0.25-10 mm, and in their MWD-dry. No significant after effect of the polymer on aggregate size distribution was observed in the second and third year after its application. Aquanika increased significantly the content of water-stable aggregates between 0.25 to 10 mm (including those with sizes of 5-10 and 1-5 mm), and their mean weight diameter. The dose of 2 g kg^{-1} was more effective than the dose of 1 g kg^{-1}.

2. In the second year of study, the same trend was noted in the plots with the dose of 2 g kg^{-1}, with a significantly higher proportion of water-stable aggregates in the range of 0.25-10 mm having also significantly higher MWD-wet. No significant after effect of the polymer on aggregate water stability was observed in the third year of the study.

3. Aquanika in both doses contributed to a significant decrease in bulk density and to significant increases in maximum water capacity, saturated hydraulic conductivity, total porosity, air permeability at field water capacity, and the content of macropores >20 μm in diameter.

4. The addition of the gel-forming polymer had no significant effect on actual soil moisture, field water capacity and retention of water useful to plants within the 0-5 cm layer of the soil.

5. The values of Dexter index *S* (>0.050) are indicative of a very high physical quality of the soil (and its water properties in particular) both with and without the addition of Aquanika.

6. The basic water and air properties of the eroded Haplic Luvisol have proven to be the most useful for evaluating the effectiveness of Aquanika, followed by the proportion of air-dry clods >10 mm and MWD-wet.

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