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Shear Strength of Soil-Root Layer Formed on Degraded Soil Supplemented with New Zeolite Substrate

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ABSTRACT

The aim of the study was to determine the shear strength of the soil-root layer obtained as a result of growth of cocksfoot (*Dactylis glomerata* L.) on degraded soil enriched with the addition of a new zeolite substrate Z-ion. Measurement of shear strength for soil-root layers formed as a result of growth of a grass species (on degraded soil alone and on degraded soil with added Z-ion) was performed in a direct shear apparatus. The measurement results allowed determining parameters of equations describing the dependence of shear strength of studied soil-root layers on normal stress e.g. cohesion and internal friction coefficient. Under the experimental conditions, application of 1% v/v substrate addition to degraded soil induced development of cocksfoot root system which resulted in the significantly increased cohesion of soil-root layer (by 30%) as compared to that formed on degraded soil alone. The enhanced cohesion of the soil-root layer formed on soil enriched with Z-ion resulted in its significantly increased shear strength as compared to that of soil-root layer obtained on soil alone. Further research using higher doses of the Z-ion substrate (greater than 1% v/v) is needed to obtain the information at what dose ranges of the substrate one can expect even more intensive development of plant root systems and, consequently, further significant improvement in the shear strength of the soil-root layers.

Keywords: degraded areas, shear strength, zeolite substrate, landslides.

INTRODUCTION

The stability of slopes or escarpments in degraded areas (excavations and heaps) and in communication areas is still a significant problem due to potential natural disasters or technical failures caused by landslides (Szruba 2017). The loss of stability of a slope/escarpment occurs when all or part of it slides down by gravity as a result of shear stresses exceeding the shear strength of the soil material from which the slope/escarpment is built. Exceeding or reducing the shear strength of the ground is caused by various phenomena and processes which include, among others, cracking of the surface, increasing the pressure in the pores of the soil, swelling of the soil, gravitational creep and cyclic loads related to e.g. road or rail traffic (Zydroń 2014, Szruba 2017). Various methods are used to stabilize slopes/escarpments, including biological cover in the form of grass turf or shrub cover plants (De Baets et al. 2008, Ali and Osman 2008). The above-ground parts of the plants used protect the ground surface against the impact of raindrops and thus limit water erosion. Root systems of plants, binding soil particles, create a soil-root zone with fairly high shear strength, contributing to the improvement of the stability of the surface of scarps or slopes (Orzeszyna et al. 2006, Abdi and Deljouei 2019). The intensive development of plants on stabilized surfaces requires providing them with the necessary nutrients and ensuring the availability of water throughout the growth period. When forming the top layers of slopes/escarpments, it is possible to provide plants with the required nutrients by using fertilizing materials such as compost, peat, muck, sewage sludge or float soil. The range of these materials can be extended with a new type of zeolite substrates prepared under the name "Z-ion" and containing plant nutrients like nitrogen, phosphorus, potassium, calcium, and magnesium (Kosandrovich et al. 2019). These materials are prepared on the basis of natural ion exchanger (clinoptilolite loaded with potassium and ammonium cations) and phosphate rocks (containing weakly soluble calcium and magnesium salts). The particular types of Z-ion substrates differ from each other in regard to the nominal molar ratios of NH_4^+/K^+ as well as in terms of the pH values. Equivalent ion exchange of the plant metabolites with potassium and ammonium ions and weak solubility of the calcium and magnesium phosphates determine the concentration of nutrients in the solution equilibrated with the substrate type. In Z-ion substrates, nitrogen is present in the NH_4^+ form, contributing to the easier assimilation of N by plants, since ammonium ions are directly used in the amino acids synthesis without energy consumption for the conversion of NO_3^- to NH_4^+ ions. When used as an additive, the Z-ion substrates do not acidify soils, since the zeolite matrix (acting as an anion) is osmotically inactive (Kosandrovich et al. 2019).

The article presents preliminary studies aimed at determining the shear strength of the soil-root layer obtained as a result of growth of a grass species – cocksfoot (*Dactylis glomerata* L.) – on degraded soil enriched with the addition of a new zeolite substrate Z-ion.

MATERIALS AND METHODS

The research was carried out in two basic stages. The first one included the pot experiment conducted to select the Z-ion substrate dose for fertilizing degraded soil and therefore, obtaining the significant increase in cocksfoot biomass. In the second stage, for the soil-root layers obtained as a result of growth of a grass species (on degraded soil alone and on degraded soil with added Z-ion) measurement of shear strength was performed.

Plant growing – the pot experiment

In the pot experiment, cocksfoot was grown on the media where degraded soil and Z-ion substrate were used as components. The degraded soil was collected from the excavation edge zone of sand mine in Rokitno (Lublin province, Poland). The soil was acidic and poor in nutrient contents – it contained very low phosphorus, potassium and magnesium, low sulfur as well as insufficient nitrogen and calcium amounts in terms of plant demands (Table 1). The Z-ion substrate was prepared at the experimental plant of "Project WISMUT" Ltd. in accordance with the procedure established by workers of Institute of Physical and Organic Chemistry of the Belarusian Academy of Sciences in Minsk. The contents of nutrients in the substrate are shown in Table 2.

For the need of the pot experiment five series of media were prepared: the control series (the degraded soil alone) and four test series – the mixtures of degraded soil with increasing Z-ion doses (1%, 2%, 5%, 10% (v/v) – Table 3). During media preparation, $CaCO_3$ was mixed with the soil to raise its pH value to 5.5. In each pot of particular series, 40 cocksfoot seeds were planted. After 7 days from seed sowing, the number of seedlings in each pot was standardized at 25. The plants were grown for six weeks in the phytotron where 13/11 photoperiod was used and 25±1/16±1 °C day/night temperature was maintained. After ending the plant growth cocksfoot stems were cut and roots were separated form the pots. Then, the wet and dry (105 °C) stem biomass and dry (105 °C) root biomass were determined. The obtained

Table 1. Plant available forms of nutrients in degraded soil

pH (in1MKCl)	$N-NH_4$ [mg/kg] [mg/dm^3]	$N-NO_3$ [mg/kg] [mg/dm^3]	P_2O_5 [mg/100g]	K_2O [mg/100g]	Mg [mg/100g]	Ca [mg/dm^3]	$S-SO_4$ [mg/100g]
4.25	2.05 2.60	10.75 13.64	3.25	1.55	1.75	196	0.44

Note: plant available forms of macronutrients in degraded soil were examined using methods described in Polish Standard PN-R-04020 (1994), Polish Standard PN-R-04022 (1996), Polish Standard PN-R-04023 (1996) and in Ostrowska et al. (1991).

Table 2. Contents of nutrients in the Z-ion substrate

Nutrient	N	P	K	Ca	Mg	Na	S
mmolkg^{-1}	324	100	110	113	80	101	1.4

Table 3. Media series used in the pot test

Media series	Soil [cm^{3}per pot]	Substrate dose [cm^3 per pot]	Pot number
Degraded soil	300	-	8
Degraded soil with 1% Z-ion dose	297	3	8
Degraded soil with 2% Z-ion dose	294	6	8
Degraded soil with 5% Z-ion dose	285	15	8
Degraded soil with 10% Z-ion dose	270	30	8

results allowed selecting the dose of the substrate (1% v/v) used in the further stage of research to intensify the growth of cocksfoot on the degraded soil and thus to develop the soil-root layer.

Plant growing – formation of soil-root layers

In this study stage, two media series were prepared (the degraded soil and the mixture of degraded soil with 1% addition of Z-ion substrate) and placed in boxes with dimensions of 30×20×15 cm (6 boxes in total). In each box, 747 cocksfoot seeds were sown, which corresponded to the dose of 125 kg per ha recommended in the reclamation of degraded lands (Chodak 2013). The plants were grown for six weeks in the phytotron under the same conditions as in the pot experiment.

Measurments of shear strength of soil-root layers

Shear strength test was performed in a direct shear apparatus (Wykeham Farrance) in accordance with UNE EN-EN ISO 17892-10. Soil-root samples were carefully collected in situ from growing boxes using a standard 60×60 mm sampler. In total, 17 samples of soil- root layers were sheared in the test – 9 obtained as a result of plant growth on soil alone and 8 obtained as a result of plant growth on soil enriched in 1% Z-ion substrate. During the study, the following normal stresses (σ) were used: 50 kPa, 100 kPa and 150 kPa. The consolidation time of the samples was 25 minutes. After its completion, they were sheared at a speed of 0.20 mm·min^{-1}. A specimen strain of 20%, corresponding to a horizontal displacement of 12 mm, was used as a shear criterion. On the basis of the horizontal force measured during shear, the shear stresses (τ_f) along the shear plane were calculated using the following equation:

$$\tau_f = \frac{F}{A} \quad (1)$$

where: F – horizontal force (kN);
A – initial area of the shear plane of the sample (3600 mm^2).

The measurement results allowed determining parameters of equation describing the dependence of shear strength of studied soil-root layers on normal stress (Tan et al. 2019):

$$\tau_f = \sigma tg\Phi + c \quad (2)$$

where: τ_f – the shear strength or shear stresses (kPa),
σ – the normal stress (kPa),
$tg\Phi$ – the slope of the failure envelope (internal friction coefficient),
c – the intercept of the failure envelope with the τ axis. The parameter c is called cohesion while Φ is called the angle of internal friction (Labuz and Zang 2012, Staat 2021).

After shear strength measurements, cocksfoot roots were separated from the sheared samples, washed with water and dried at 105 °C.

Statistical analysis

The data obtained as the results of the pot experiment and shear strength measurments were subjected to statistical analysis using the Statistica 13.3 software and R software. The significance of differences between mean values for cocksfoot wet stem biomass and dry root biomass obtained in the pot experiment (variance heterogeneity) was tested by F Welch's test followed by T3 Dunnett's post hoc test. In the case of dry stem biomass (variance homogeneity) the data were subjected to ANOVA and the means were separated using Tukey's post hoc test. The significance of differences between mean values for dry root biomass (obtained from soil-root layers) was tested by v Aspin-Welch's test after prior verification of variance homogeneity (by the F Fisher–Snedecor test). The significance of parameters of regression equations (describing dependence between normal stress and shear strength) was tested by ANCOVA after verifying the assumptions of this model. All analyses were performed at the 0.05 significance level.

RESULTS AND DISCUSSION

Table 4 presents the results on the cocksfoot yield obtained in the pot experiment. It is seen that the Z-ion additions to degraded soil affected the grass growth favorably. Already the applied 1% v/v substrate dose caused a statistically significant increase in vegetative parameters of the test species. Wet and dry stem biomass as well as dry root biomass of the plants growing on soil supplemented with 1% substrate addition exceeded those obtained on soil alone by 317%, 314% and 87%, respectively. Hence, the 1% Z-ion addition was selected for further research to intensify the growth of cocksfoot on the degraded soil and thus to develop the soil-root layer.

The dependences of shear strength of studied soil-root layers on normal stress are described by regression equations shown in Figure 1. Testing the assumptions of ANCOVA showed that the effect of normal stress and soil-root layer on shear strength was statistically significant (the calculated p values were lower than 0.05 – Table 5). At the same time, there was no significant effect of interaction between normal stress and soil-root layer on shear strength (the calculated p value was higher than 0.05 – Table 5), Thus, there was no reason

Table 4. Mean values of vegetative parameters of cocksfoot growing in the pot experiment

Media series	Wet stem biomass [g per pot]	Dry stem biomass [g per pot]	Dry root biomass [g per pot]
Degraded soil	1.42±0.08[a]	0.29±0.02[a]	0.41±0.05[a]
Degraded soil with 1% Z-ion dose	5.92±0.18[b]	1.20±0.05[b]	0.74 ±0.11[bc]
Degraded soil with 2% Z-ion dose	7.46±0.33[c]	1.34± 0.06[c]	0.97±0.13[cd]
Degraded soil with 5% Z-ion dose	9.48±0.29[d]	1.49±0.06[d]	1.13±0.04[d]
Degraded soil with 10% Z-ion dose	11.19±0.48[e]	1.7±0.08[e]	1.07±0.1[d]

Note: The values in the same column and with the same letter do not differ significantly at $p \leq 0.05$; ± - standard deviation.

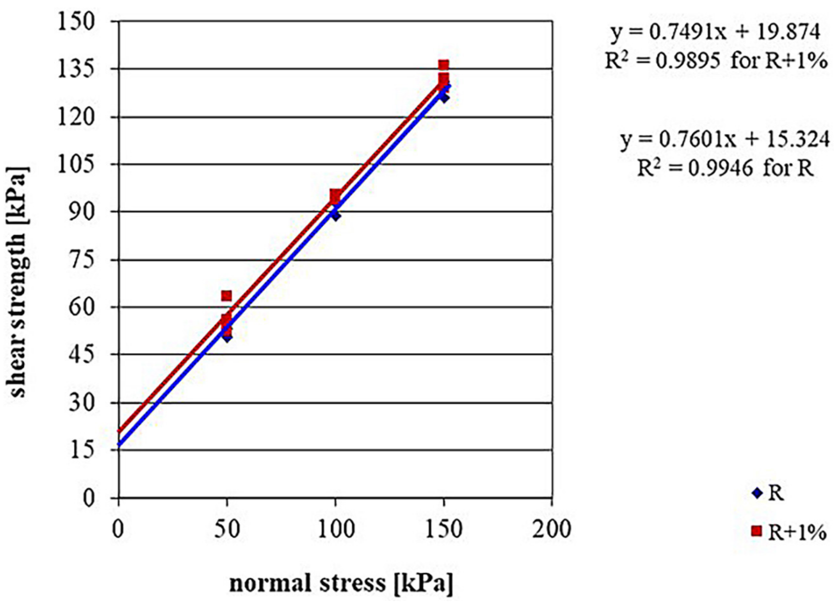

Figure 1. The dependence of shear strength of studied soil-root layers on normal stress

to reject the hypothesis that soil-root layer had no effect on the slope coefficients of the regression lines. Consequently, this means that the slopes of both regression equations were homogeneous, i.e. they did not differ significantly, which also means that internal friction coefficients for both soil-root layers practically were the same. Since the second assumption of ANCOVA was fulfilled (the effects of normal stress and soil-root layer were independent, p=1), the ANCOVA model was built and indicated that the slope coefficients of the regression lines were significantly different from zero (the calculated p value was lower than 0.05 – Table 6, the second row) and intercepts were significantly different from each other (calculated p value was lower than 0.05 – Table 6, the third row). Regarding ANCOVA results thus, it can be said that the soil-root layer formed on soil alone did not differ significantly from that developed on soil with substrate added in terms of the friction angle. In contrast, the soil-root layer formed on soil supplemented with 1% Z-ion was characterized by significantly higher cohesion (by 30%) than that obtained as a result of plant growth on soil alone. The observed increase in cohesion could have resulted from the more intensive development of the root system of plants growing on soil with substrate added. Grasses have a fibrous root system that can act as a reinforcement and binds soil particles together, which increases cohesion (Zydroń 2014, De Beats 2008, Ali and Osman 2008). More intensive development of cocksfoot roots mentioned was caused by the nutrients introduced into the degraded soil along with the substrate addition. It was confirmed by the root biomass separated from sheared samples of soil-root layers – the root biomass from the layer formed on soil with Z-ion addition was significantly higher (by 54%) than that from the layer developed on soil alone (Figure 2). The increased cohesion of the soil-root layer formed on soil enriched with Z-ion resulted in its significantly increased shear strength as compared to that of the layer obtained on soil alone (Figure 1, Table 5). The mean shear strength of the soil-root layer on soil supplemented with substrate added (for σ = 50, 100, 150kPa) was greater by 3–8% than that of the soil-root layer formed on soil alone. The shear strength values calculated according to both regression equations obtained in the described study (for σ = 10 and 20 kPa, Figure 1) were higher than those reported by Zydroń (2014) for the soil reinforced with hornbeam roots by 53–83% and 33–51% at root area ratio equal to 0.26%, respectively. The shear strength found by Ali and Osman (2008) for the soil with vetiver grass roots was lower (by 1.5–2.5-fold for σ = 10 and 20) than that observed in the presented study. At the same time, the authors mentioned reported shear strength for the soil reinforced with *Leucaena leucocephala* roots to be similar to that obtained for the soil-root layers in the study. The differences in shear strength values obtained in own tests and cited studies for the soils reinforced with plant roots could resulted from root parameters (root system architecture, root diameters, root length density) and soil material features. It is also worth noting that in the presented studies and those described in the literature, a similar regularity was observed that there was no significant effect of increased root presence in soil on the friction angle.

Table 5. Significance of the effect of normal stress, root-soil layer and interaction between normal stress and root-soil layer on shear strength

Effect	DFn	DFd	F	p	p<0.05	ges
Normal stress	1	13	1620.233	0.000	*	0.992
Root-soil layer	1	13	4.776	0.048	*	0.269
Normal stress: root-soil layer	1	13	0.086	0.773		0.007

Note: DFn – the number of freedom degrees of the numerator, DFd – the number of freedom degrees of the denominator, F – the test statistics, p – probability, ges – the generalized effect size factor.

Table 6. Significance of slope coefficients and difference between intercepts of the regression lines

Effect	DFn	DFd	F	p	p<0.05	ges
Normal stress	1	14	1733.350	0.00	*	0.992
Root-soil layer	1	14	5.109	0.04	*	0.267

Note: DFn – the number of freedom degrees of the numerator, DFd – the number of freedom degrees of the denominator, F – the test statistics, p – probability, ges – the generalized effect size factor.

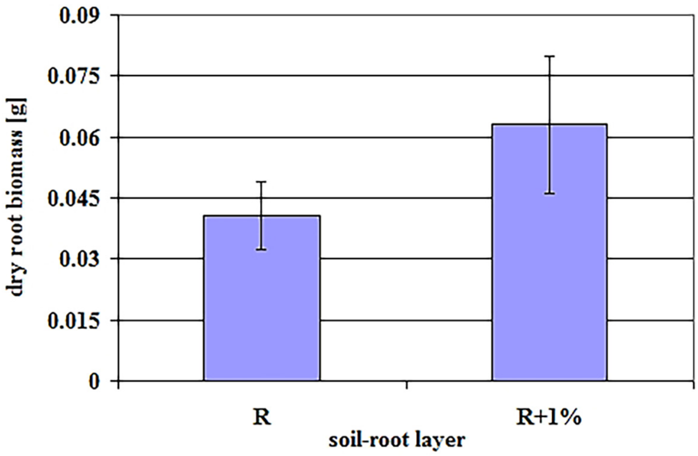

Figure 2. Mean dry root biomass separated from sheared samples of soil-root layers; explanations: R – soil-root layer on degraded soil, R+1% – soil-root layer on degraded soil supplemented with 1% Z-ion addition, I – standard deviation, mean values differ significantly at p ≤0.05

CONCLUSIONS

The study results revealed that the addition of Z-ion substrate to degraded soil influenced the plant growth favorably. Already 1% v/v Z-ion dose caused more than fourfold increase in stem biomass and more than 1.5-fold increase in root biomass of cocksfoot. Under the experiment conditions, application of 1% substrate addition to degraded soil induced development of cocksfoot root system which resulted in the significantly increased cohesion of soil-root layer, as compared to that formed on degraded soil alone. The enhanced cohesion of the soil-root layer formed on the soil enriched with Z-ion resulted in its significantly increased shear strength as compared to that of the soil-root layer obtained on soil alone. It would be valuable to conduct further research using higher doses of the Z-ion substrate (greater than 1% v/v) in order to obtain the information at what dose ranges of the substrate one can expect even more intensive development of plant root systems and, consequently, further significant improvement in the shear strength of the soil-root layers. This would make it possible to recommend the use of this dose range under real conditions to improve the stability of the surface layers of escarpments/slopes.

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