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INFLUENCE OF RANDOMLY ORIENTED FIBRES ON SHEAR STRENGTH OF MINERAL SOILS

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Abstract. The purpose of the paper was to determine two things: the influence of type and amount of reinforcement on shear strength of soil and the relation between the efficiency of reinforcement and soil moisture content. Shear strength was determined in a direct shear apparatus in a box with a square section of 80 × 80 mm. The range of normal stress was from 25 to 150 kPa and the shear velocity was 1.0 mm·min^{-1}. The tests were carried out on medium sand and clayey coarse silt at two moisture contents and with two types of reinforcement – polyolefine fibres and 40 × 3 mm foil stripes. The addition of reinforcement was 0.5 and 1.0% in relation to the dry mass of soil. Test results indicated that using polyolefine fibres as dispersed reinforcement in a sandy soil increased its shear strength, whereas the influence of using foil stripes on shear strength was little. However, using both types of reinforcement in a cohesive soil increased its shear strength and this influence was particularly clear at higher moisture content.

Keywords: shear strength, fibre reinforcement, reinforced sand, reinforced clayey silt

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INTRODUCTION

Soil shear strength is one of the main geotechnical characteristics that determine their usability in earthen structures. Soils with low shear strength are prone to denudation phenomena and require reinforcement and one of the methods is using steel rods or stripes made of steel, plastic or natural materials. Reinforcement as opposed to soil can bear tensile stresses and therefore it is often used in retaining constructions (Pollen and Simon 2005, Borys 2007, Gruchot 2013). Another method of increasing strength properties of soils is using the so-called dispersed reinforcement in the form of short, single fibres or their bundles, which can be considered as a substitute of natural reinforcement provided to soil by plant roots (i.a. Waldron and Dakessian 1981, Pollen and Simon 2005, Schwarz *et al*. 2012, Satriawian *et al*. 2016). Dispersed reinforcement has been widely used in concrete constructions (Glinicki 2010, Zych 2010), but for many years, it is also successfully used in low-bearing soils (Gray and Ohashi 1983, Consoli *et al*. 2002, Pawłowski *et al*. 2008, Ahmad *et al.* 2010, Freilich *et al*. 2010, Lovisa *et al.* 2010, Lirer *et al*. 2011). Currently, there are many types of materials that can be used as soil reinforcement, although in case of a specific soil, the result of reinforcement depends on its type, length and amount, it can also be connected with the soil moisture content. As Lovisa *et al*. (2010) showed in their tests on the influence of reinforcement on soil strength parameters that last factor is usually omitted.

The purpose of the paper was to determine the influence of two types of reinforcement on shear strength of two chosen mineral soils. It was assumed that efficiency of the reinforcement will depend on the soil moisture content and that its addition will influence the nature of shear failure.

SCOPE AND METHODOLOGY OF TESTS

The tests were carried out for a cohesive soil, which was clayey coarse silt, and for a non-cohesive soil – medium sand. The range of basic tests included determination of grain-size distribution, consistency limits, maximum dry density and optimum moisture content and maximum and minimum dry densities in case of the non-cohesive soil.

Shear strength was tested in a direct shear apparatus in a box where the sample was $80 \times 80 \times 74.9$ mm. Each sample was pre-consolidated for 10 minutes and then sheared at a rate of 1.0 mm·min^{-1} under normal stresses of 25, 50, 75, 100, 125 and 150 kPa until 15% of relative deformation of the sample was reached. The tests were carried out for samples without and with the addition of fibre reinforcement in the amount of 0.5 and 1.0% in relation to the dry mass of the soil.

The samples were prepared by manually mixing the reinforcement with the soil and then compacting the obtained composite in a box from the direct shear apparatus. In case of the non-cohesive soil the samples at air-dry or optimum moisture content were compacted by vibration until the degree of compaction $I_D = 0.55$ was reached, whereas in case of the cohesive soil the samples at optimum moisture content and higher than optimum by 5% were compacted manually until the compaction index $I_S = 0.95$ was reached. The shear strength test was carried out for 120 samples and shear strength parameters, i.e. the angle of internal friction and cohesion, were calculated using the least-square method.

The analysis of tests results included comparison of the maximum and residual values of shear strength parameters with and without the reinforcement. It was assumed that the addition of reinforcement will influence the relation between shear strength and sample deformation. In order to determine this influence, an equation which describes a brittleness index was used:

$$I_B = \frac{\tau_{max}}{\tau_{ult}} - 1 \qquad (1)$$

where: τ_{max} – maximum shear strength, τ_{ult} – residual shear strength at the maximum sample deformation.

The value of the index close to 0 indicates plastic failure.

CHARACTERISTICS OF THE TESTED MATERIALS

The basic geotechnical properties of the tested soils are presented in Table 1. According to the geotechnical nomenclature (PN EN ISO 14688-2:2004), the non-cohesive soil was classified as medium sand and the cohesive one – as clayey coarse silt.

Table 1. Geotechnical parameters of tested soils

Parameters		Name of soils	
		Medium sand	Clayey coarse silt
Fraction content [%]	sand (0.063–2 mm)	5.5	98.6
	silt (0.002–0.063 mm)	81.7	1.4
	clay (< 0.002 mm)	12.8	-
Symbol of soil acc. to [PN EN ISO 14688-2:2004]		MSa	clCSi
Optimum moisture content[1)], OMC [%]		11.45	16.80
Maximum dry density, ρ_{ds} [$g \cdot cm^{-3}$]		1.65	1.73
Dry density[2)] [$g \cdot cm^{-3}$]	minimum, ρ_{dmin}	-	1.42
	maximum, ρ_{dmax}	-	1.79
Liquid limit, w_L [%]		-	36.0
Plasticity limit, w_P [%]		-	20.0
Plasticity index, I_P [%]		-	16.0
Explanation: [1)]ramming method, [2)]vibration method			

Polyolefine fibres (Fig. 1a) and stripes of foil – 0.15 mm thick printing waste material (Fig. 1b) – were used as dispersed reinforcement. Fibres are used to reinforce concrete, their tensile strength is 400 MPa and elastic modulus 4.5 MPa. The length of fibres was 38±5 mm and dimensions of the foil stripes were 40×3 mm.

(a) (b)

Fig. 1. Overview of polyolefine fibres (a) and foil stripes (b)

TEST RESULTS AND THEIR ANALYSIS

Shear strength test results for both soils, with and without the reinforcement, are presented in Figures 2 and 3. The influence of the reinforcement was noticed in case of each soil and it was significant in the range of high values of normal stress. It should be indicated that this influence was also significant in case of maximum and residual values of shear strength.

Failure of medium sand samples without the reinforcement, regardless of their moisture content, was brittle. Using reinforcement caused "plasticizing" of the soil because the failure was plastic. Calculation of the brittleness index of the medium sand showed that using reinforcement lowered its value from 0.23–0.34 (soil without the reinforcement) to 0.21–0.27 (soil with polyolefine fibres) and to 0.11–0.17 (soil with foil stripes). It seems interesting that for dry sand (w = 0.1%) with fibres the brittleness index was higher than for soil without the reinforcement.

In case of the clayey coarse silt the failure of the samples was basically plastic; cases of brittle failure occurred for samples at optimum moisture content and low values of normal stress. The brittleness index for samples at optimum moisture content was on average 0.03 (soil without the reinforcement), 0.05 (soil with fibres) and from 0.01 to 0.04 (soil with foil stripes). Such low values of the brittleness index for non-cohesive soils are also given by, among others, Consoli *et al*. (2002) and Noorzad and Zarinkolaei (2015), whereas for cohesive soils – by Freilich *et al*. (2010). The obtained values of the brittleness index were much lower than the ones obtained by Consoli *et al*. (2002) for sand stabilized with cement.

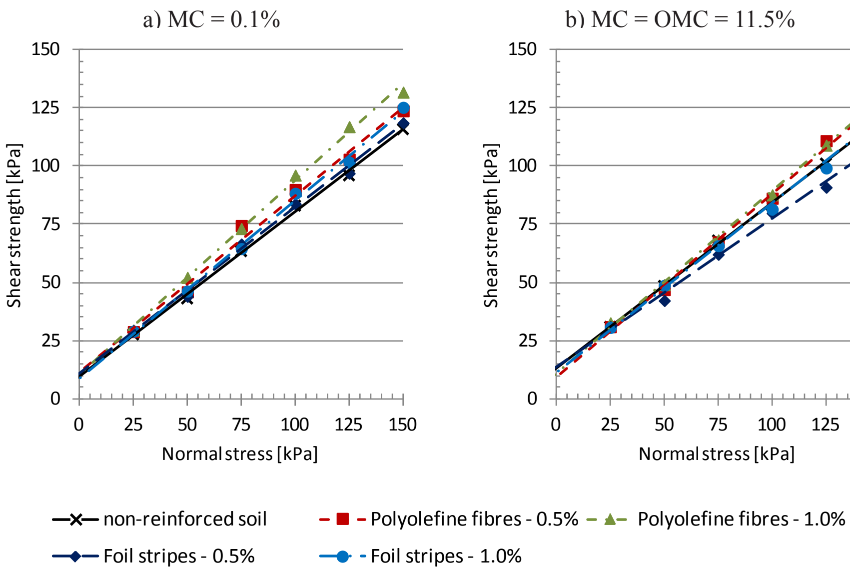

Fig. 2. Shear strength of the medium sand with and without the reinforcement

The values of shear strength indicate that in most of the tests the addition of the fibre reinforcement increased shear strength and the higher the values of normal stresses, the greater this influence. In case of dry medium sand (Fig. 2a) the maximum shear strength increased on average by 16% with 1% addition of fibres reinforcement. Much lower increase – by 3 and 6% – was noticed for adequately 0.5 and 1% addition of foil stripes. On the other hand, comparison of the shear strength residual values of soil with and without the reinforcement showed that using reinforcement increased these values by 3 to 15% and using 1% addition of foil stripes was the most effective. In case of sand at optimum moisture content (Fig. 2b) the maximum shear strength increased on average by 2 and 5% adequately with 0.5 and 1.0% addition of fibres, whereas in case of using foil stripes a small decrease in shear strength was noticed, on average by 7 and 1% for adequately 0.5 and 1% addition of the reinforcement in relation to the soil without the reinforcement. Test results presented by Freilich *et al*. (2010) and Gruchot and Sieczka (2013) also indicate that shear strength of a reinforced soil may decrease. However, the addition of fibre reinforcement at optimum moisture content increased the residual values of shear strength from 11 to 16% in relation to the soil without the reinforcement. This relation seems to be consistent with the theoretical assumptions of the root reinforcement model described by Pollen and Simona (2005). It is assumed that strength of plant roots, which corresponds with dispersed reinforcement (Pawłowski *et al*. 2008), is mobilized when the soil deformation is large; usually after maximum shear strength is reached.

The maximum values of shear strength of the clayey coarse silt (Fig. 3) were obtained at optimum moisture content with the addition of reinforcement and they were higher by 3 to 15% in relation to the silt without the reinforcement. At this moisture content the biggest increase of shear strength was obtained with 1% addition of foil stripes and slightly smaller – about 13% – with fibres, whereas the residual values of shear strength of the soil with reinforcement were higher by 1 to 16% in relation to the soil without the reinforcement. The most clear influence of the reinforcement on the increase of shear strength was noticed at the moisture content higher than optimum. In this case shear strength increased over 3-times for a soil without the reinforcement and the best effect was noticed for soil with fibres.

Table 2 presents results of calculations of the shear strength parameters of the tested soils with and without the reinforcement. Soils without the reinforcement at optimum moisture content were characterized by high values of the angle of internal friction and cohesion. Lowering of the moisture content in case of medium sand caused slight changes of the tested parameters and the soil failure was brittle (Fig. 4). In case of clayey coarse silt a significant influence of the moisture content on the shear strength parameters was noticed. At the moisture content higher than optimum the angle of internal friction was over 3-times lower and cohesion – over 6-times. Here the samples failure was basically plastic at both moisture contents.

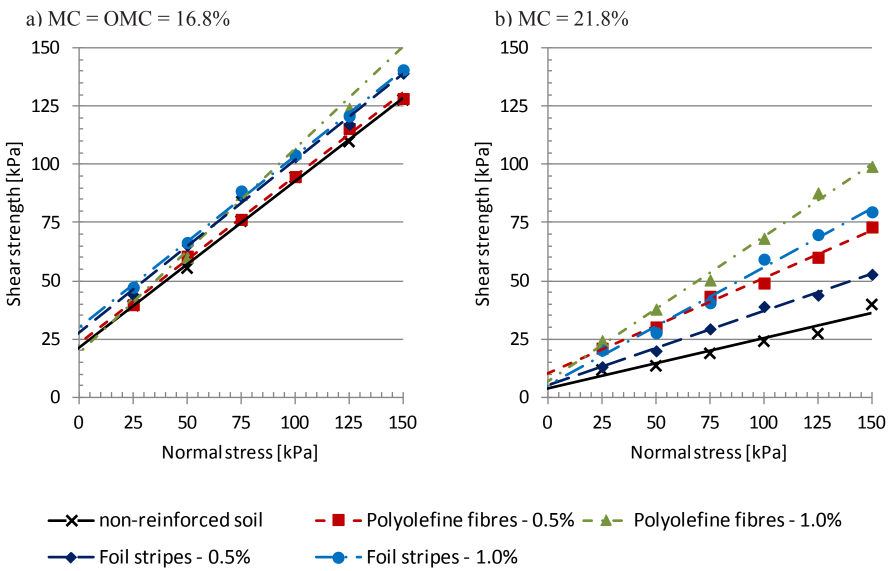

Fig. 3. Shear strength of the clayey coarse silt with and without the reinforcement

Table 2. Values of the angle of internal friction and cohesion

Soil	Moisture content (MC)	Kind of reinforcement	Angle of internal friction [°]			Cohesion [kPa]		
			Additive of reinforcement [%]					
			0	0.5	1.0	0	0.5	1.0
Medium sand	0.1%	Fibres	35.3 (30.7)	37.0 (33.7)	40.7 (33.2)	9.6 (9.5)	11.7 (4.7)	7.3 (9.3)
		Foil stripes		35.4 (31.0)	37.5 (37.4)		11.1 (10.2)	8.8 (3.0)
	OMC = 11.5%	Fibres	35.4 (29.7)	38.1 (33.0)	38.1 (32.8)	13.3 (7.5)	9.6 (7.0)	10.9 (9.9)
		Foil stripes		35.2 (30.7)	36.0 (35.1)		13.6 (11.4)	11.6 (6.0)
Clayey coarse silt	OMC = 16.8%	Fibres	35.5 (36.6)	35.5 (37.2)	41.3 (42.7)	21.4 (17.4)	23.4 (17.0)	19.0 (12.0)
		Foil stripes		36.5 (38.2)	36.0 (36.8)		27.7 (21.9)	30.2 (28.2)
	21.8%	Fibres	12.1	22.1	31.8	3.8	10.6	7.2
		Foil stripes		17.7	26.8		5.1	5.4

Explanation: the maximum values of the angle of internal friction and cohesion are without brackets and the residual ones are in brackets

Changes of shear strength of the tested soils with the reinforcement addition were reflected in the values of the angle of internal friction and cohesion. In case of medium sand it was stated that using both types of fiber reinforcement increased both maximum and residual values of the angle of internal friction and decreased cohesion (Fig. 4). Similar relations are presented by Gruchot and Sieczka (2013) who also carried out tests with polyolefine fibres. In case of clayey coarse silt (Fig. 5) the influence of the reinforcement on shear strength was slightly different. Using polyolefine fibres at optimum moisture content increased maximum and residual values of the angle of internal friction and decreased cohesion, whereas at the moisture content higher than optimum the addition of polyolefine fibres increased values of the angle of internal friction and cohesion, but much more significant changes were noticed for the first parameter. In case of foil stripes their addition to the soil at the optimum moisture content caused slight changes of the angle of internal friction and significantly increased cohesion. On the other hand, when the moisture content of the soil was higher than optimum, the addition of this type of reinforcement increased values of both shear strength parameters.

Test results concerning influence of different types of reinforcement on shear strength of soils which are presented in literature are very different. Tests carried out by Consoli *et al*. (2002), Freilich *et al*. (2010) and Lirer *et al*. (2011) indicate that addition of the reinforcement influences mainly the values of the angle of internal friction. On the other hand, Lovisa *et al*. (2010) indicate that the reinforcement addition in sandy soil improves interlocking which is reflect-

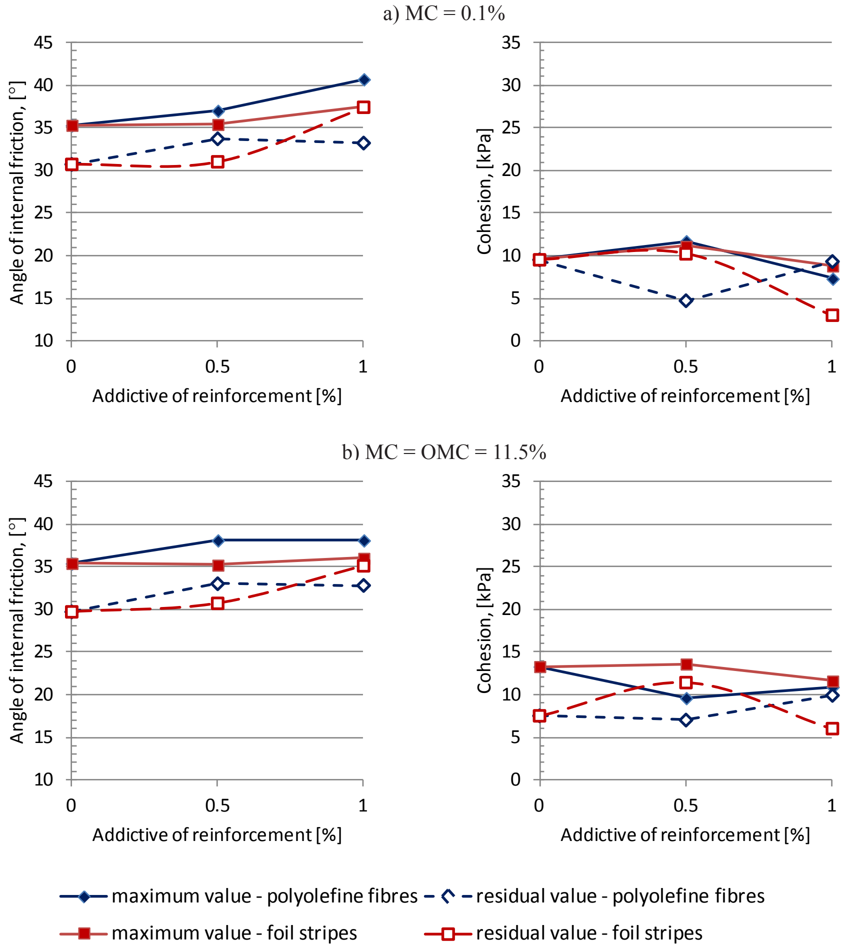

Fig. 4. Relation between shear strength parameters of the medium sand and addition of the reinforcement at both moisture contents

ed in higher values of cohesion (2.6–5.3 kPa) and this effect does not depend on the moisture content of the soil. These authors did not notice a significant influence of the reinforcement on the angle of internal friction. Erdoğan and Altun's (2015) research showed that dispersed reinforcement can decrease the values of the angle of internal friction (approx. up to 10°) and at the same time – increase cohesion (even up to 100 kPa). Results of the tests carried out by Noorzad and Zarinkolaei (2015) indicated that dispersed reinforcement increases the values of the angle of internal friction and cohesion (up to 8° and 19 kPa, respectively) in case of sand in loose state, which is in line with test results of loose and dense compacted sands obtained by Diambra *et al*. (2010). On the other hand, Anagnostopoulus (2013) showed that in case of moderately compacted and compacted sand the influence of the reinforcement on shear strength is ambiguous. In most cases the reinforcement slightly increased the values of the angle of internal friction (increase in range of 0.0÷2.7°) and increased or decreased the value of cohesion (from -2.3 to 3.3 kPa). Anagnostopoulus (2013) showed that regardless of compaction state the addition of the reinforcement increased shear strength of sand, especially in the range of large deformations.

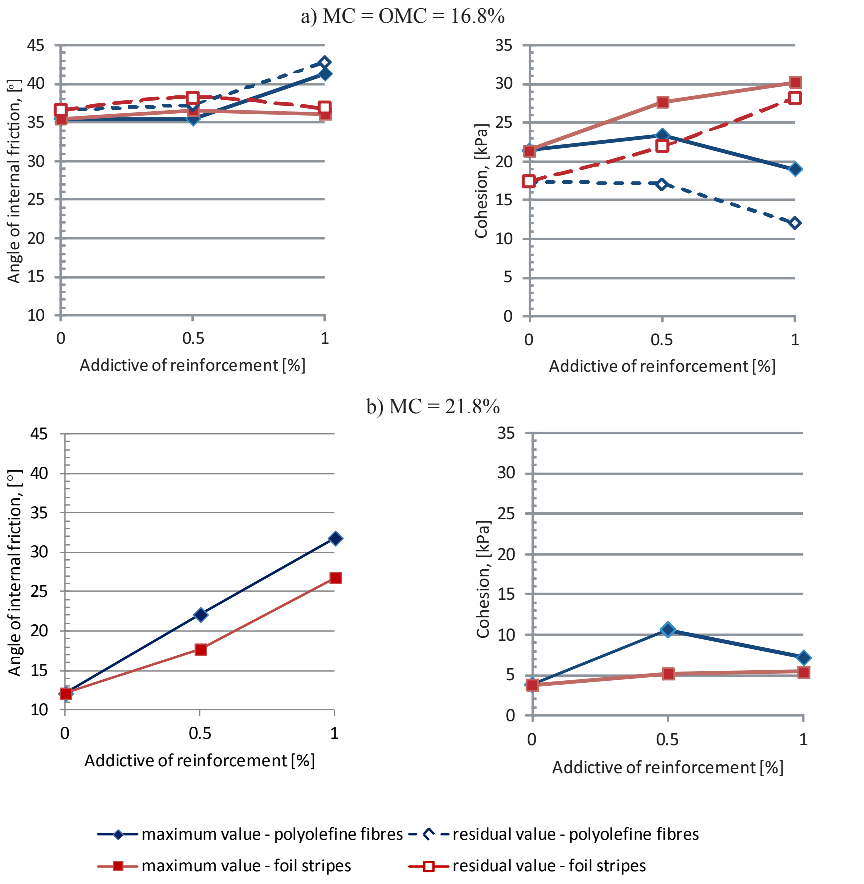

Fig. 5. Relation between shear strength parameters of the clayey coarse silt and addition of the reinforcement at both moisture contents

While analyzing the obtained test results and relations described in the mentioned publications it can be stated that dispersed reinforcement essentially increases shear strength of the soil, but much less than other stabilizers (Consoli *et al*. 2002, Gruchot and Pacławska 2012). It is also noticeable that another effect of using reinforcement was that by giving the soil more plastic character its strength characteristics changed. It was mainly connected with the increase of shear strength residual values which can be the result of mobilizing tensile strength of the reinforcement material. Figure 6 presents exemplary test results

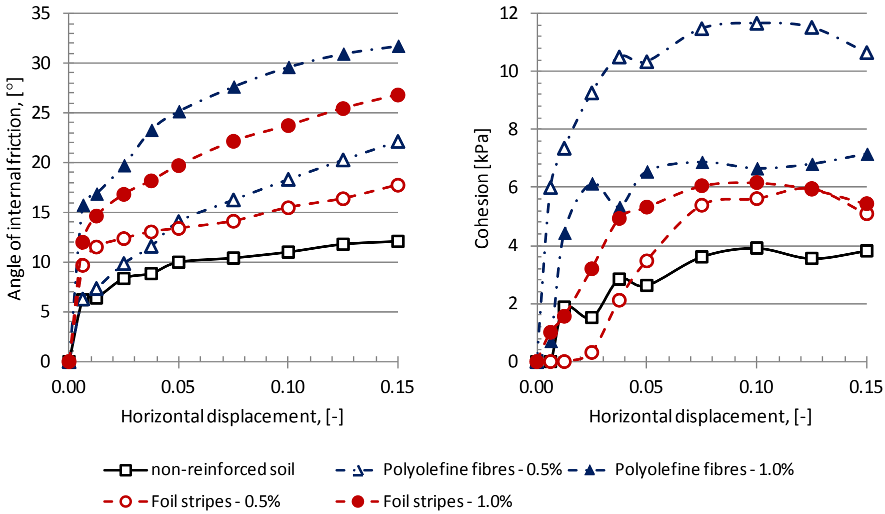

Fig. 6. Changes of shear strength parameters of the clayey coarse silt at the moisture content higher than optimum along with the increase of horizontal deformation of the sample

of calculations of shear strength of the clayey coarse silt along with the increase of sample deformation during shearing. Obtained relations indicate that the maximum value of the angle of internal friction for soil without the reinforcement was at 5% relative deformation (displacement) of sample and in case of soil with reinforcement the angle of internal friction increased till the end of the test, whereas the maximum values of cohesion of the soil with and without the reinforcement were obtained at 8% relative deformation of sample.

CONCLUSIONS

Test results showed that the influence of the reinforcement addition on shear strength of the soil is diverse. Using polyolefine fibres as dispersed reinforcement in a non-cohesive soil (medium sand) increased its shear strength. On the other hand, the influence of foil stripes on shear strength of the medium sand was little and at 0.5% addition of this reinforcement a slight decrease of shear strength was noticed. Whereas using both types of reinforcement in a cohesive soil (clayey coarse silt) increased its shear strength and the influence was especially clear at high moisture content of the soil. In case of the tested soils the addition of the dispersed reinforcement increased the values of the angle of internal friction, but in case of cohesion the influence was ambiguous.

It was shown that using polyolefine fibres to reinforce soils is more effective than using foil stripes. Obtained test results indicate that there is a need to use dispersed reinforcement to increase shear strength, mainly in cohesive soils at high moisture content. Therefore, it seems valid to continue tests on using different types of reinforcement mainly to strengthen cohesive soils.

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