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Laboratory Study of Soil Shear Strength Improvement with Polyester Fibres

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Abstract
The paper deals with a laboratory study of soil shear strength improvement with polyester fibres. Soils CS and CH were mixed with polyester fibres of 70 mm length as random reinforcement in an amount of 0.5% and 1.0%. Improvement of the soil shear strength was measured by direct shear tests with a shear box of 0.3 m × 0.3 m × 0.08 m size. Results show that the improvement rate is different for CS and CH. For soil CS, polyester fibres increased the angle of the internal friction (even by 45.2% with 1% of polyester fibres), as well as the cohesion (by 48.2% with 0.5% of polyester fibres), but also decreased it (by 27.5% with 1% of polyester fibres). For soil CH, fibres decreased the angle of internal friction (by 7.8%) but increased the cohesion by 322.7%. Analysis of the specimen number and result uncertainty shows that various combinations of the 3 specimens provide different results; hence tests with at least 4 specimens are recommended.

Key words: *polyester fibres, soil improvement, direct shear test, angle of internal friction, cohesion, test result uncertainty.*

Introduction

According to [1], the approaches incorporating ground improvement processes can generally be divided into four categories grouped by the techniques or methods by which improvements are achieved: mechanical modification, hydraulic modification, physical and chemical modification, and modification by inclusions, confinement, and reinforcement. One type of reinforcement is fibres. A simple review of their application can be found in [2]. In [3] the authors introduced a model of flexible, elastic fibre across the shear zone. In model mentioned, we can see that soil shearing is prevented by the tension strength of the fibre. In most cases, the tension strength of synthetic fibres is about hundreds or even thousands of MPa, which is sufficient to resist shearing. Therefore the more important issue is the shear resistance induced between the soil and fibre, which depends on the fibre length, fibre diameter, the friction coefficient between the soil and fibre, and on the normal stress on the fibre surface. The shear resistance mentioned should be higher than the force pulling out the fibre.

Based on literature studied, the authors in [2] introduced a summary of researches performed on widely-used synthetic fibres to reinforce soil. In the summary we can see that researches were performed on various synthetic fibres, such as polypropylene fibres, polyester fibres, polyethylene fibres, glass fibres, polyvinyl alcohol fibres, etc.

To evaluate the improvement rate of the shear strength parameter of soil improved by fibres, the direct shear test can be applied. The authors in [4] state that the choice of small direct shear apparatus as the testing platform brings some inherent problems into the experimental study. This limits the amount of fibre inclusion. Other problems such as the plane of shear failure imposed, the ambiguous stress state, and end effect in such a small sample size make it more difficult to model fibre-reinforced soil behaviour realistically. Despite these limitations, a direct shear device has been widely used for different theoretical and practical research projects in most laboratories all over the world due to its simplicity and other advantages (Athanasopoulos [5], Izgin and Wasti [6], Wasti and Ozduzgun [7]). The device was also employed in some researches, similar to their studies, to highlight the complexity of fibre-reinforced soil behaviour (Gray and Ohashi [3]). The authors mentioned used square direct shear apparatus of 60 × 60 × 25 mm size and applied 3 vertical normal stresses (100, 200 and 300 kPa) in order to completely define the shear strength parameters (the angle of shear strength φ and cohesion c) for both unreinforced sand and sand reinforced with Polypropylene fibres (Duomix F20/5.1, produced by Bekaert in Belgium) of 0.05 mm diameter and 20 mm length in an amount of 0.10; 0.25; 0.50, and 1.00%. Fibre-reinforced sand samples were prepared at the same dry density as that of unreinforced sand (relative density of Dr = 70%). The loading rate was 0.002 mm/s (0.12 mm/min). The regression analyses indicated that the shear envelopes for reinforced sands, similar to those for unreinforced sand, are linear with a zero cohesion intercept (c = 0 kPa). The correlation coefficients are almost equal to unity in the analyses (R^2 = 0.98 – 0.99). Values of the angles of internal friction introduced by the authors are 42.3° (without fibres), 42.1° (0.1% fibres), 41.8° (0.25% fibres), 40.6° (0.5% fibres) and 40.4° (1% fibres). As will be shown later in this paper, in this case, determination of result uncertainty can be useful since such small changes in the values of the angle of internal friction are probably smaller than the expanded uncertainty of the test results.

Results of direct shear tests of soil improved with polyester fibres are introduced in [8]. Soil classified by IS Classification as SC (angle of internal friction 29° and cohesion 16 kPa) was mixed with fibres in an amount of 0.5, 1, 1.5 and 2%. Direct shear tests were carried out to obtain shear strength parameters, but there is no detailed information on them. According to the authors, the cohesion of fibre specimens increases while increasing the fibre content up to 1% and then decreases with a further increase in the quantity of fibre. Due to the addition of 1% fibres, the increase in cohesion is 62.5% and 37.5%, respectively, for aspect ratios 200 and 400. Similarly, due to the addition of 2% of fibres with aspect ratios 200 and 400, the increase in cohesion is 12.5% and 0% (no change), respectively. The angle of internal friction decreases with the addition of 0.5% of fibres for both aspect ratios (AR 200 and AR 400). With a further increase in the quantity of fibre, the value of the angle of internal friction increases. The decrease in the angle of internal friction is 6.89 and 3.45%, respectively, due to the addition of 0.5% of fibres with aspect ratios 200 and 400. Due to the addition of 2% of fibres, the increase in the angle of internal friction is 6.45 and 20.7%, respectively, for aspect ratios 200 and 400. The quantity of fibre mixed with the soil and the aspect ratio influence the shear strength of the fibre-reinforced soil. The strength of the reinforced soil increases with an increase in fibre content up to 2%. Since there are no numerical data on the values of the angle of internal friction and cohesion introduced in the paper, estimation from ***Figures 1*** and ***2*** shows that in some cases changes in the cohesion are about 2 kPa, and those in the angle of internal friction – about 1°; again, in this case, determination of result uncertainty can be useful since such small changes in the values of the angle of internal friction can be smaller than the expanded uncertainty of the test results.

Results of direct shear tests of soil improved with polyester fibres are also introduced in [9]. Soils used in the investigation were classified as CH according to the Unified Soil Classification System (fine-grained 78.5%, sand 21.5%, liquid limit 54.6%, plastic limit 34.2%). In order to evaluate the shear strength parameters of soil in a direct shear test, three normal stresses: 100, 200 and 300 kPa were used. Direct shear tests were done with different percentages of recycled polyester fibres (0.1, 0.3 and 0.5% of soil dry weight. Recycled fibres had a diameter of 20-30 µm and length of 30-40 mm). Mixed soil was compacted into a shear box of 60 × 60 mm in the plane and 25 mm depth by tamping until a density of 1890 $kg{\cdot}m^{-3}$ for specimens for direct shear tests was obtained. This test was performed under unconsolidated, untrained conditions and according to Standard ASTM D3080-90. The velocity of the test was 1.25 mm/min. In this paper, horizontal displacement was recorded up to after rupture, and the parameters of the shear resistance of the reinforced and non-reinforced soil were evaluated. Results show that a larger amount of fibres provide larger values of both the angle of internal friction and cohesion. While soil without fibres has φ = 13.5° and c = 38 kPa, soil with 0.1% of fibres has φ = 14.6° and c = 56 kPa, soil with 0.3% of fibres – φ = 19.3° and c = 59 kPa, and soil with 0.5% of fibres – φ = 23.3° and c = 64 kPa (φ increased by 9.8° (72.5%) and c by 26 kPa (68.4%)). Even in this case, differences in φ and c are quite large; there is also one difference in φ of only 14.6° – 13.5° = 1.1° and one in c of only 59 kPa – 56 kPa = 3 kPa. Determination of result uncertainty can be useful since such small changes in the values of the angle of internal friction can be smaller than the expanded uncertainty of the test results.

Many tests on soil reinforced by fibres were carried out by Rubišarová [10]. Used soils are loess, classified as clay of intermediate plasticity CI, sand with fine particles S-F (both soils are from Ostrava, Czech Republic), fly ash from the power station in Mělnik (Czech Republic), sandy clay CS from the village Velké Albrechtice near Ostrava, and clay of intermediate plasticity CI from the village Studénka near Ostrava. Direct shear tests were carried out for soils improved with polyester fibres (PET) and polypropylene fibre (PP) of 24 mm and 70 mm length in an amount 0.5, 1.0 and 1.5%. In the following, we will only introduce some results of soil improvement using PET (TEXZEM PES 200 from Bonar Geosynthetics a. s.) of 70 m length, which were also used in our research and will be introduced in more detail in the next chapter of the paper.

Soil CI from Studénka near Ostrava has a liquid limit of 37.3%, plastic limit of 21.1%, optimum water content of 16.8%, and maximum dry density of 1790 $kg{\cdot}m^{-3}$. Specimens were tested on 2 different shear apparatuses. The smaller one has a diameter of 89 mm, and the larger has a box size of 300 × 300 mm. Specimens of 89 mm diameter have a height from 11.50 to 13.30 mm. The shear speed was 0.004 mm/min. The results of 3 specimens without fibres in a smaller shear box are as follows: φ = 26.1°, c = 12 kPa; φ = 27.1°, c = 11 kPa; φ = 25.5° and c = 9 kPa (average values from 3 specimens: φ = 26.2°, c = 10.6 kPa). The results of 3 specimens with 0.5% of fibres in a smaller shear box are as follows: φ = 31.1°, c = 23 kPa; φ = 34.3°, c = 7 kPa; φ = 34.5° and c = 9 kPa (average from the last 2 specimens: φ = 34.4°, c = 8 kPa). Thus the improvement of φ is 8.1° (31.1%), and the decrease in c is -2.6 kPa (-25.0%). Specimens of 300 × 300 mm size have a height from 80 mm, where the shear speed was 2 mm/min. The results of 1 specimen without fibres in the larger shear box are as follows: φ = 32.5° and c = 40 kPa. The results of 3 specimens with 0.5% of fibres in the larger shear box are as follows: φ = 43.2°, c = 12 kPa; φ = 45.5°, c = 10 kPa; φ = 48.5° and c = 7 kPa (average from 3 specimens: φ = 45.7°, c = 9.6 kPa). Thus the improvement of φ is 13.2° (40.7%), and the decrease in c is -30.3 kPa (-75.8%).

As we can see from the results posted above, fibres increased the angle of internal friction in both cases (31.1 and 40.7%) but decreased the cohesion (-25.0 and -75.8%). However, a small change in the cohesion of -2.6 kPa (even corresponding to -25%) can be smaller than the expanded uncertainty of the test results; hence determination of result uncertainty can be useful. Comparison of results from different shear box sizes is not possible since shear speeds are different. The author states that the apparatus with a larger shear box has only one shear speed – 2 mm. We can also see, probably for that reason, that one specimen is never identical with the second one; results of direct shear tests are different even for the "same" soil and same test condition. For this reason as well, analysis of test result uncertainty is useful.

The author of this paper was contacted by colleagues from the Faculty of Civil Engineering, VSB Technical University of Ostrava, at which PhD thesis [10] was being prepared, and was asked to enable a diploma student to carry out direct shear tests of soil improved with polyester fibres on direct shear apparatus in the Geotechnical laboratory at the author´s work place. The results of these tests can be seen in [11]. Soil SC with an amount of fine particles of 20.1%, sandy particles – 63.0%, gravelly particles – 14.9%, liquid limit – 31.2%, plastic limit – 14.1%, maximum dry density – 2091 $kg{\cdot}m^{-3}$ and optimal moisture content w_{opt} = 9% [10] was used. The previously mentioned polyester fibres TEXZEM PES 200 in an amount of 0.5, 1.0 and 1.5% were applied. Direct shear tests were carried out using fully automatic large shear box apparatus – SHEARMATIC 300 from CONTROLS S. p. A.. The specimens' size was 0.3 m × 0.3 m × 0.15 mm (specimens were compacted at the maximum dry density – 2091 $kg{\cdot}m^{-3}$ and optimal moisture content), the consolidation time

– 20 min, and shear speed – 0.5 mm/min. Specimens with and without polyester fibres were tested at normal stresses: 50, 100 and 200 kPa. It was found that fibres increased the angle of internal friction and also cohesion. The optimal amount of fibres was 1%, at which the increase in the angle of internal friction was 6.1° (from 45.2° to 51.3°, corresponding to 13.5%) and that in cohesion 17.5 kPa (from 0 to 17.5 kPa). In this case, only 3 specimens were applied in test 1 (in accordance with [12], applied in the Czech Republic) and the uncertainty of the test results was not established.

From the above-mentioned literature review, we can see that many direct shear tests were carried out with only 3 specimens, but such a small number of specimens is in accordance with [12-15]. Furthermore in the standards mentioned there are no prescribed values of regression coefficients for the relation between normal stresses and shear stresses. In Slovakia, according to [16], for the peak strength, at least 4 specimens will be prepared which will be loaded under various 4 normal stresses, with the prescribed value of the regression coefficient being 0.9500 for 4 specimens.

In this paper, the author will introduce soil shear strength improvement with polyester fibres and also an analysis of the specimen number's influence on test results and result uncertainty.

Materials and methods

Materials

In this research we used soil from Čaradice, Slovakia. Determination of the soil particle size distribution was carried out in accordance with BS 1377: 1990. Part 2 (wet sieving method and sedimentation by the hydrometer method) [17]. Grain size diagrams of soils can be seen in ***Figure 1***.

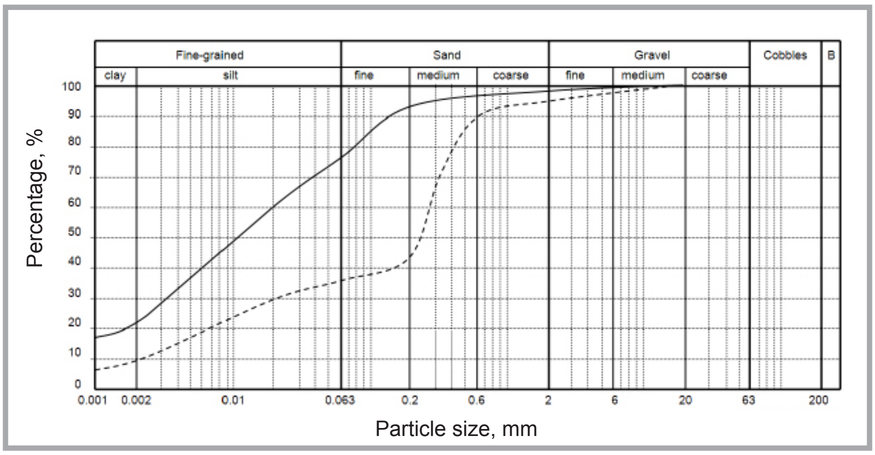

Figure 1. *Grain size distribution diagram of soils: full line: CH; dashed line: CS [8].*

Basic soil parameters such as water content (w), liquid limits (w_L) and plastic limits (w_P) were also determined in accordance with the standard mentioned. Based on the values obtained, soils classifications were carried out in accordance with the British Standard BS 5930:2015 [18]. Soils classifications and properties are posted in ***Table 1***.

As was mentioned, TEXZEM PES 200 polyester fibres from Bonar Geosynthetics a. s. were used. Fibre properties can be seen in ***Table 2***, and a picture of the fibres can be seen in ***Figure 2***.

Soils were prepared with the optimum water contents (see ***Table 1***) and masses corresponding to the volume of specimens of 0.3 × 0.3 × 0.08 m size and maximum dry density (see ***Table 1***) and mixed with the necessary amount of fibres, corresponding to 0.5 and 1.0% (percentage of fibres was calculated as a ratio between the mass of fibres and that of dry soil in the specimen). A part of the specimen with fibres can be seen in ***Figure 3***.

Table 1. *Soil properties.*

Soil parameters	CS	CH
Water contents, %	12.4	36.4
Plastic limit, %	14.2	20.8
Liquid limit, %	32.9	60.0
Plasticity index, %	18.7	39.2
Optimum water content, %	16.9	22.4
Maximum dry density, kg·m^{-3}	1710	1498

Table 2. *Polyester fibre properties.*

Polyester fibre parameters	TEXZEM PES 200
Length, mm	70
Colour	White
Density, g·cm^{-3}	1.38
Mass density, dtex	2200
Tensile strength, cN/dtex	7.77
Elongation at break, %	10.6

Figure 2. *Picture of TEXZEM PES 200 polyester fibres from Bonar Geosynthetics a. s. [8].*

Figure 3. *Part of specimen of soil CS mixed with 0.5% of fibres before compaction into a shear box.*

Methods

Direct shear tests were carried out in accordance with [16] using fully automatic large shear box apparatus – SHEARMATIC 300 from CONTROLS S. p. A. The specimens' size was 0.3 × 0.3 × 0.08 m, the consolidation time – 60 min, and the shear speed – 0.05 mm/min. Specimens with and without polyester fibres in an amount of 0.5% and 1.0% of the soil dry mass were tested at normal stresses: 50, 100, 200 and 300 kPa. The tests were terminated when the horizontal displacement had reached 20% of the width of the specimen.

According to [16], the normal effective stress (σ_{ef}) in kPa is calculated using the formula:

$$\sigma_{ef} = N/A \tag{1}$$

where, N – normal force in kN, A – cross area of sample in m^2.

The shear stress τ in kPa at the discretionary shear moment is calculated using the formula:

$$\tau = T/A \tag{2}$$

where, T – shear force (force against shearing) in kN,

The values of tgφ and c are obtained from the formulae:

$$\mathrm{tg}\varphi = \frac{1}{a}\left(n\sum\tau\sigma_{ef} - \sum\tau\sum\sigma_{ef}\right) \tag{3}$$

$$c = \frac{1}{a}\left(\sum\tau\sum{\sigma_{ef}}^2 - \sum\sigma_{ef}\sum\tau\sigma_{ef}\right) \tag{4}$$

Where, τ and σ_{ef} in kPa are the pair of stresses obtained from each specimen, and n the number of specimens.

$$a = n\sum{\sigma_{ef}}^2 - \left(\sum\sigma_{ef}\right)^2 \tag{5}$$

In the note it is stated that the number of addends in the summing symbol is equal to that of specimens.

Parameters φ and c correspond to the peak shear strength (φ_{ef}, c_{ef}) or residual shear strength (φ_r, c_r) depending on whether the values of $\tau_{\max}$ or $\tau_{\min}$ have been used.

According to [16], for the test of the peak strength, at least 4 specimens of the same physical properties will be prepared.

According to [16], the close-fittingness of the equivalent shear strength line by the linear regression between σ_{ef} and τ at every straight line section is checked by comparison of the correlation coefficient selected r and critical values of this coefficient r_a. The correlation coefficient selected r is calculated using the ***Equation 6***:

$$r = \frac{n\sum\left(\tau\sigma_{ef}\right) - \sum\tau\sum\sigma_{ef}}{\sqrt{a\left[n\sum\tau^2 - \left(\sum\tau\right)^2\right]}} \tag{6}$$

The value of r_a can be found in ***Table 4*** of the standard (e.g. for n = 4, chosen significance level 0.05, it is r_a = 0.95000). The equivalent shear strength line is accepted if $r \geq r_a$. In a case where $r < r_a$, it is necessary to verify whether there is a reason to exclude some specimens from evaluation. In a case where even after verification the condition $r \geq r_a$ is still not fulfilled, it is necessary to find another fit line to better fit the effective shear strength. Usually the multi-refracted line is sufficient.

Determination of the uncertainty can be carried out using the procedure listed, for example, in [19]. Such procedures will be applied for the direct shear apparatus of the Department of Geotechnics, Faculty of Civil Engineering, University of Zilina, Slovakia, where the tests were carried out.

As we can see from ***Equations 3*** and ***4***, the sources of uncertainty consist in input data σ_i and τ_i. The following factors can influence, more or less, the values of σ_i and τ_i:

Human factor: During the test, we respect the procedures listed in [16], and data are recorded automatically; hence we do not consider the human factor in this analysis.

Laboratory conditions: We respect all issues prescribed in [16] (the changes in temperature around the apparatus should not be higher than 4 °C; the transport and storage of samples are carried out in such a way that sample properties will not change); hence we do not consider the influence of the environment on test results in this analysis.

Test methods: The test methods prescribed in [16] are respected. We propose that if the prescribed test methods are respected, no uncertainty caused by the test method arises.

Apparatus: The values of σ_i and τ_i are influenced by the accuracy of the force transducer and the sizes of the box in which the specimen is placed. Quantitative evaluations of their influences will be introduced in the next sections. In the tests, we also use transducers to measure specimen deformations in the horizontal and vertical directions; but for the reason that deformations will not be used to evaluate the test results (φ and c), in this case we do not consider them.

Test specimen: Concerning the influence of the test specimen on the values of σ_i and τ_i, the inconformity of the specimen can give a different shear stress at the same normal stress even if the same test procedure is applied. In this case we propose that standard uncertainty of type A $u_A(\tau)$ of the shear stress exists but does not exceed 0.5%. Therefore the value $u_{A_i}(\tau)$ = 0.5% will be used in the calculation of the combined standard uncertainty in the next parts.

We realise that there is also the question of the representativeness of the sample regarding the in-situ conditions, however we do not take it into account since our results will be valid for the test sample only.

In the following part we will deal with determination of the uncertainty of the shear strength parameters introduced above.

To obtain the standard uncertainty of φ and c, it is first necessary to determine the standard uncertainties of the input data, that is, the standard uncertainties of the normal stresses σ_i and shear stresses τ_i.

Determination of the standard uncertainty of the normal stresses σ_i: the normal stress σ is calculated using the formula:

$$\sigma = \frac{N}{A} = \frac{N}{a.b} \tag{7}$$

Where, N is the normal force in kN and a & b are the shear box dimensions in m.

Thus the sources of the uncertainty of the normal stress are inaccuracies in the normal force N and in the shear box dimensions, in which the specimen is placed.

According to the calibration protocol, the standard uncertainty of a force transducer of normal force u_N is in the range from 0.022 to 0.141% depending on the magnitude of the force measured. For the range of normal forces applied

Figure 4. *View of the shear zone after the test of soil CH with 1% of fibres.*

Figure 5. *Effect of fibres in a cohesion increase (soil CS, 1.0 % of fibre).*

in the tests, a standard uncertainty of 0.141% will be used.

Based on our experience, the standard uncertainty of the shear box dimension can be u_a = 0.2% (for dimension a); a similar value u_b = 0.2% will be used for dimension b.

The absolute value of standard uncertainty of the particular parameter, e. g. of the normal force, in ***Equation 7***, will be calculated by multiplying its estimated value by the standard uncertainty of the force transducer:

$$u(N) = N{\cdot}u_N \qquad (8)$$

The sensitivity coefficient c_i relating to the particular parameter x_i will be obtained by the partial derivative of the model function f, which is the ***Equation 7***, step by step, of N, a & b:

$$c_i = \frac{\partial f}{\partial x_i} = \frac{\partial f}{\partial X_i}\ \Big|_{X_1=x_1,\dots X_N=x_N} \qquad (9)$$

As for the sensitivity coefficient for N:

$$c_N = \frac{\partial f}{\partial N} = \frac{\partial\left(\frac{N}{a.b}\right)}{\partial N} = \frac{1}{a.b}\ \Big|_{a=0.30,b=0.30}$$

The contribution of the particular parameter to the standard uncertainty of the normal stress σ will be obtained by multiplying the standard uncertainty of the particular parameter $u(x_i)$ by its sensitivity coefficient c_i:

$$u_i(y) = c_i.u_i(x_i) \qquad (10)$$

Since parameters N, a and b are not dependent on one another (not correlated), the standard uncertainty of the normal stress σ_i in kPa will be obtained using the formula:

$$u(y) = \sqrt{\sum_{i=1}^{N} c_i^{\,2}.u^2(x_i)} = \sqrt{\sum_{i=1}^{N}\left[c_i.u(x_i)\right]^2} \qquad (11)$$

Determination of the combined standard uncertainty of the shear stress τ_i: the shear stress τ in kPa is calculated using the formula:

$$\tau = \frac{T}{A} = \frac{T}{a.b} \qquad (12)$$

According to the calibration protocol, the standard uncertainty of the force transducer of shear force u_N is in the range from 0.025 to 0.163% depending on the magnitude of the force measured. For the range of shear forces applied in the test, a standard uncertainty of u_{B,τ_i} = 0.158% will be used.

The standard uncertainty of type B of the shear stress $u_B(\tau)$ is determined in a similar way to that in the case of normal stress. Since in the case of shear stress we also consider the uncertainty of type A ($u_A(\tau)$ = 0.5%, see previous part), the combined uncertainty $u_c(\tau)$ will be determined by the ***Equation (13)***:

$$u_c(\tau) = \sqrt{u_A(\tau)^2 + u_B(\tau)^2} \qquad (13)$$

Determination of the standard uncertainty of the angle of the internal friction φ: based on ***Equation 3*** along with the fact that we will consider $tg\varphi$ as a function of 8 variables (parameters) X_i, i = 1 – 8 (4 values of normal stresses $\sigma_{1...4}$ and 4 values of shear stresses $\tau_{1...4}$).

The calculation procedure of the contribution of the particular parameters σ_i and τ_i to the standard uncertainty of the angle of internal friction φ is similar to that in the calculation of the contribution of the normal force N and shear box dimensions a and b to the standard uncertainty of normal stress σ. Since σ_i and τ_i are dependent on one another (mutually correlated), the further source of their standard uncertainty will depend on the rate of their correlation. The covariance $u(x_i, x_k)$ of x_i and x_k (in our case σ_i and τ_k) will be calculated using the formula:

$$\begin{aligned} u(x_i,x_k) &= u(x_i).u(x_k).r(x_i,x_k) = \\ &= u(\sigma_i).u(\tau_k).r(\sigma_i,\tau_k) \end{aligned} \qquad (14)$$

Where, $r(\sigma_i, \tau_k)$ is the coefficient of correlation and can be calculated using the formula:

$$r(\sigma_i,\tau_k) = \frac{n.\sum(\tau.\sigma) - \sum\tau.\sum\sigma}{\sqrt{a.\left[n.\sum\tau^2 - \left(\sum\tau\right)^2\right]}} \qquad (15)$$

The standard uncertainty $u(y)$ depends on the standard uncertainty $u_i(y)$, caused by a particular parameter and depends also on the correlation of the parameters (in our case, the standard uncertainty of the angle of internal friction φ depends on the standard uncertainty $u_i(\varphi)$, caused by parameters σ_i & τ_i, and also on their correlation):

$$u(y) = \\ = \sqrt{\sum_{i=1}^{N} c_i^{\,2}.u^2(x_i) + 2.\sum_{i=1}^{N-1}.\sum_{k=i+1}^{N} c_i.c_k.u(x_i,x_k)} \qquad (16)$$

Determination of the standard uncertainty of cohesion c: Determination of the standard uncertainty of cohesion c is similar to that in the case of the angle of internal friction using ***Equation 4***, taking into account the correlation between σ_i and τ_i.

Calculation of the expanded uncertainty U: the expanded uncertainty U will be determined by multiplying the standard uncertainty $u(\varphi)$ and $u(c)$ by the coverage factor k = 2, thus the expanded un-

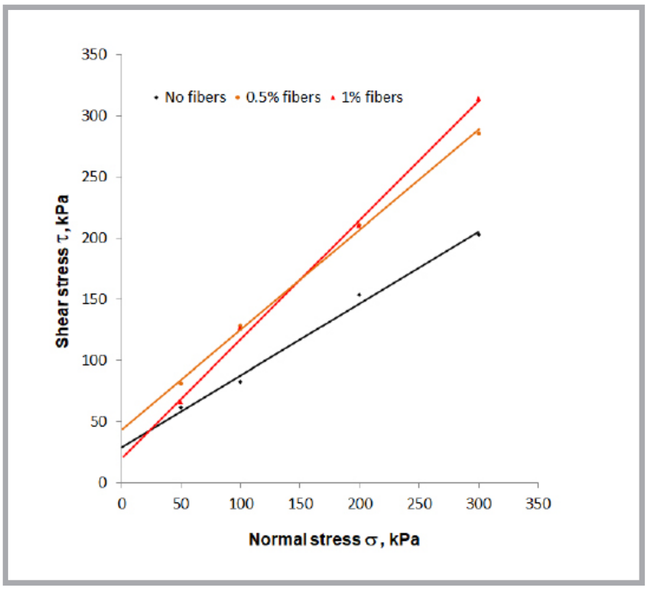

Figure 6. *Shear stress versus normal stress of soil CS.*

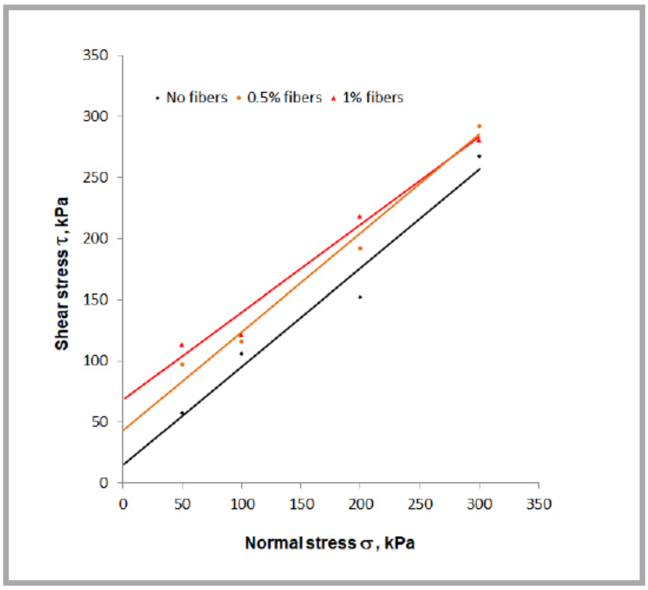

Figure 7. *Shear stress versus normal stress of soil CH.*

certainty of the angle of internal friction and cohesion will be:

$$U(\varphi)=k.u(\varphi) \quad (17)$$

$$U(c)=k.u(c) \quad (18)$$

Results and discussion

A view of the shear zone after the test of soil CH with 1% of fibres can be seen in ***Figure 4***.

The effect of fibres in a cohesion increase can be seen in ***Figure 5***, where pieces of soil CS are connected together by fibres in the vertical direction.

Shear stresses are calculated using ***Equation (2)*** and results are introduced in ***Table 3.*** Shear stress versus normal stress of soil CS and CH can be seen in ***Figure 6*** and *7*, respectively. Taking into account the fact that a shear speed of 0.05 mm/min (respecting requirement from practice) is too high for full pore pressure dissipation, the stresses are total. Values of shear strength parameters of the soils and those reinforced by fibres are introduced in ***Table 4***, and their differences are introduced in ***Table 5***. Expanded uncertainties of the test results (shear strength parameters) are also introduced in ***Table 4***. A graphical representation of soil improvement with fibres can be seen in ***Figure 8***.

Table 3. *Maximal values of shear stress for various amounts of fibres.*

Soils	Normal stress, kPa	Maximal values of shear stress for various amounts of fibres, kPa		
		0%	0.5%	1%
CS	50	61.6	81.3	66.1
	100	82.4	128.5	126.0
	200	153.2	210.4	209.7
	300	203.0	285.2	313.3
CH	50	56.8	96.8	113.3
	100	106.1	115.8	121.2
	200	151.7	191.8	217.8
	300	267.4	292.2	280.1

Table 4. *Values of shear strength parameters of soils and those reinforced by fibres.*

Soils	Fibre amount, %	Strength parameter		R-squared value	Expanded uncertainty			
		φ, °	c, kPa		U(φ), °	U(φ), %	U(c), °	U(c), %
CS	0.0	30.32	30.03	0.99311	0.61	2.0	1.27	4.2
	0.5	39.06	44.51	0.99822	0.85	2.1	1.80	4.0
	1.0	44.02	21.75	0.99699	0.93	2.1	1.87	8.6
CH	0.0	38.60	15.84	0.96627	0.75	2.0	1.55	9.7
	0.5	38.41	45.38	0.98119	0.85	2.2	1.80	3.9
	1.0	35.56	66.97	0.97543	0.84	2.3	1.86	2.7

As we can see in ***Table 5*** and ***Figure 8***, fibres in an amount of 0.5% increased the angle of internal friction of soil CS by 8.74° (28.8%) and also the cohesion by 14.48 kPa (48.2%). Larger amounts of fibres (1.0%) increased the angle of the internal friction of soil CS by 13.70° (45.1%) but decreased the cohesion by 8.28 kPa (27.5%). Correlations coefficients of the relation between the shear stress and normal stress are high (larger than 0.993, see ***Table 4***). These facts can also be seen in ***Figure 6***. Having compared the values of expanded uncertainty (see ***Table 4***) and changes mentioned, we can see that the changes are larger than the uncertainty, hence improvement of soil with fibres (mainly in the case of an amount of fibres of 0.5%) can be confirmed.

Concerning soil CH (see ***Table 5*** and ***Figure 8***), fibres in an amount of 0.5% decreased the angle of internal friction by -0.19° (-0.4%) but increased the cohesion by 29.54 kPa (186.4%). Larger amounts of fibres (1.0%) decreased the angle of internal friction by -3.04° (-7.8%) but increased the cohesion by 51.13 kPa (322.7%). Correlation coefficients of the relation between the shear stress and normal stress are not so high as in the case of soil CS (larger than 0.966, see ***Table 4***, and the 0.9500 prescribed in [16]). These facts can also be seen in ***Figure 7***. Having compared the values of expanded uncertainty (see ***Table 4***) and changes mentioned, we can see that a decrease in the angle of internal friction of 0.19° (in case of a fibre amount of 0.5%) could be not confirmed since this value is smaller than 0.75° + 0.85° = 1.60°. However, a decrease in the angle of internal friction of 3.04° (in the case of a fibre amount of 1.0 %) could be confirmed since 3.04° is larger than 0.75° + + 0.84° = 1.15°. An increase in cohesion in both cases could also be confirmed.

Analyses of the influence of the specimen number on test results were carried out to point out the possibility of different evaluation of the improvement of soil shear strength parameters if only 3 specimens are applied in the test. Values of shear strength parameters of the soils and those reinforced by fibres evaluated from 3 specimens only are introduced in ***Table 6***, and their differences are introduced in ***Table 7*** (for soil CS), with the same in ***Tables 8*** and ***9*** for soil CH. Values of shear strength parameters (see ***Tables 6*** and ***8***) were evaluated based on normal stresses and shear stresses, posted in ***Table 3***, where specimen No. 1 is loaded by normal stress of 50 kPa, specimen No. 2 – by normal stress of 100 kPa, specimen No. 3 – by normal stress of 200 kPa, and specimen No. 4 – by normal stress of 300 kPa.

As we can see in ***Tables 6*** and ***8***, R-squared values are high, and tests results can be accepted since tests with 3 specimens are in accordance with [12-15], where no prescribed value of the correlation coefficient is posted. As we can see, in researches many analyses are made just from data obtained from direct shear tests of only 3 specimens. However, various combinations of 3 specimens provide different results, hence the interpretation of soil improvement will also be different. For example, for soil CS (see ***Table 6***), based on tests results of the combination of specimens No. 1, 2 and 3 (and also the combination of specimens No. 1, 2 and 4), one can state that an amount of fibres of 1% increased the angle of internal friction but decreased the cohesion (cohesion decreases from 26.28 kPa to 24.22 kPa based on results from the combination of specimens No. 1, 2 and 3, and cohesion decreases from 29.29 kPa to 22.38 kPa based on results from the combination of specimens No. 1, 2 and 4). But based on test results of

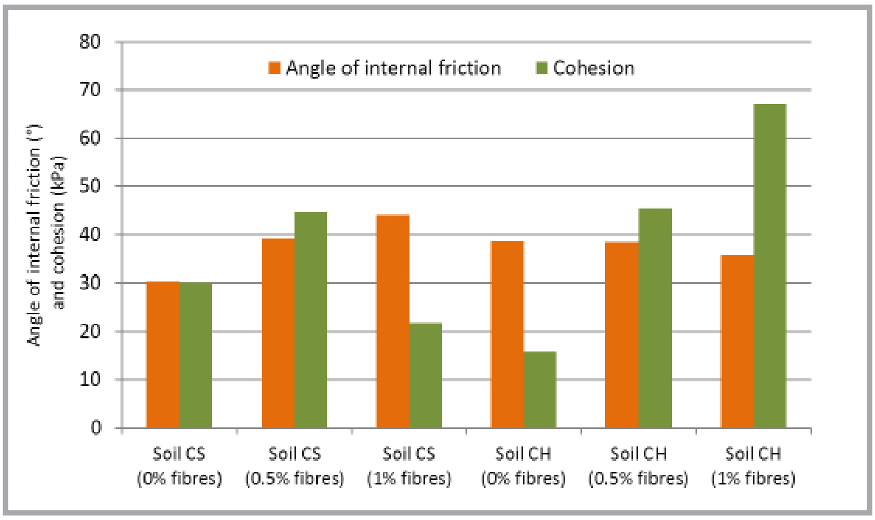

Figure 8. *Graphical representation of soil improvement with fibres.*

Table 5. *Differences in shear strength parameters for various amounts of fibres*

Soils	Improvement of shear strength parameters with various amounts of fibres, %		Differences in shear strength parameters	
			φ, ° (%)	c, kPa (%)
CS	Differences between	0.5 and 0.0	8.74 (28.8)	14.48 (48.2)
		1.0 and 0.0	13.70 (45.1)	-8.28 (-27.5)
		1.0 and 0.5	4.96 (12.7)	-22.76 (-51.1)
CH	Differences between	0.5 and 0.0	-0.19 (-0.4)	29.54 (186.4)
		1.0 and 0.0	-3.04 (-7.8)	51.13 (322.7)
		1.0 and 0.5	-2.85 (-7.4)	21.59 (47.5)

Table 6. *Values of shear strength parameters of soils and those reinforced by fibres (soil CS).*

Soils	Fibre amount, %	Strength parameter		R-squared value	Expanded uncertainty			
		φ, °	c, kPa		U(φ), °	U(φ), %	U(c), °	U(c), %
CS (3 specimens; No. 1, 2 and 3)	0.0	31.97	26.28	0.98675	0.85	2.6	1.41	5.3
	0.5	40.52	40.39	0.99868	1.18	2.9	2.02	5.0
	1.0	43.25	24.22	0.99111	1.18	2.7	1.94	8.0
CS (3 specimens; No. 1, 2 and 4)	0.0	29.94	29.29	0.99713	0.67	2.2	1.18	4.0
	0.5	38.88	44.08	0.99891	0.94	2.4	1.70	3.8
	1.0	44.24	22.38	0.99805	1.04	2.3	1.78	7.9
CS (3 specimens; No. 2, 3 and 4)	0.0	31.08	25.66	0.98999	0.83	2.6	2.46	9.6
	0.5	38.07	51.41	0.99932	1.16	3.0	3.50	6.8
	1.0	43.13	29.04	0.99630	1.27	2.9	3.71	12.7

Table 7. *Differences in shear strength parameters between various specimen combinations (soil CS).*

Soils	Fibre amount, %	Differences in soil strength parameter between specimen combinations			
		Combination No. 1, 2, 4 and No. 1, 2, 3		Combination No. 2, 3, 4 and No. 1, 2, 3	
		φ, ° (%)	c, kPa (%)	φ, ° (%)	c, kPa (%)
CS	0.0	-2.03 (-6.3)	3.01 (11.4)	-0.89 (-2.7)	-0.62 (-2.3)
	0.5	-1.64 (-4.0)	3.69 (9.1)	**-2.45 (-6.0)**	**11.02 (27.2)**
	1.0	0.99 (2.2)	-1.84 (-7.6)	-0.12 (-0.2)	4.82 (19.9)

the combination of specimens No. 2, 3 and 4, one can state that an amount of fibres of 1% increased the angle of internal friction and also the cohesion (cohesion increases from 25.66 kPa to 29.04 kPa). Practically for a common interval of normal stress from 50 kPa to 100 kPa (between specimens No. 1 and 2), there are 3 different couples of shear strength parameters (compare results obtained from the combination of specimens No. 1, 2 & 3 and that of specimens No. 1, 2 & 4 in ***Table 6***, see also ***Table 7***). Similarly for a common interval of normal stress from

Table 8. Values of shear strength parameters of soils and those reinforced by fibres (soil CH).

Soils	Fibre amount, %	Strength parameter		R-squared value	Expanded uncertainty			
		φ, °	c, kPa		U(φ), °	U(φ), %	U(c), °	U(c), %
CH (3 specimens; No. 1, 2 and 3)	0.0	31.28	34.05	0.95579	0.86	2.7	1.45	4.2
	0.5	33.08	58.88	0.97959	1.07	3.2	1.87	3.1
	1.0	36.33	65.00	0.93107	1.21	3.3	2.11	3.2
CH (3 specimens; No. 1, 2 and 4)	0.0	39.76	18.66	0.99876	0.89	2.2	1.51	8.0
	0.5	39.01	46.82	0.98967	0.96	2.4	1.73	3.7
	1.0	35.13	66.02	0.97820	0.92	2.6	1.76	2.6
CH (3 specimens; No. 2, 3 and 4)	0.0	38.89	13.77	0.94094	1.07	2.7	3.05	22.1
	0.5	41.40	23.65	0.99369	1.18	2.8	3.43	14.4
	1.0	38.47	47.51	0.98459	1.15	2.9	3.49	7.3

Table 9. Differences in shear strength parameters between various specimen combinations (soil CH).

Soils	Fibre amount, %	Differences in soil strength parameter between specimen combinations			
		Combination No. 1, 2, 4 and No. 1, 2, 3		Combination No. 2, 3, 4 and No. 1, 2, 3	
		φ, ° (%)	c, kPa (%)	φ, ° (%)	c, kPa (%)
CH	0.0	8.49 (27.1)	-15.39 (-45.20)	7.61 (24.3)	-20.28 (-59.5)
	0.5	5.93 (17.9)	-12.06 (-20.4)	**8.32 (25.1)**	**-35.23 (-59.8)**
	1.0	-1.21 (-3.3)	1.02 (1.57)	2.13 (5.86)	-17.49 (-26.9)

100 kPa to 200 kPa (between specimens No. 2 and 3), there are also 3 different couples of shear strength parameters (compare results obtained from the combination of specimens No. 1, 2 & 3 and that of specimens No. 2, 3 & 4 in ***Table 6***, see also ***Table*** *7*). An example of such couples for soil CS improved with 0.5% of fibres can be seen in ***Figure 9***.

A similar situation occurs with the angle of internal friction of soil CH (see ***Table 8***): based on tests results of the combination of specimens No. 1, 2 and 3, one can state that an amount of fibres of 1% increased the angle of internal friction (from 31.28° to 36.33°). But based on tests results of the combination of specimens No. 1, 2 and 4, it can be stated that an amount of fibres of 1% decreased the angle of internal friction (from 39.76° to 35.13°). Thus again, there are also 3 different couples of shear strength parameters valid for a common interval of normal stress from 50 to 200 kPa and a further 3 different couples of shear strength parameters valid for a common interval of normal stress from 100 to 200 kPa (see ***Tables 8*** and ***9***). An example of such couples for soil CH improved with 0.5% of fibres can be seen in ***Figure 10***. We would like to note that there are very large differences in shear strength parameters (the difference in φ is 8.32° (25.1%) and that in c 35.23 kPa (59.8%)); see also the bold numbers in ***Table 9***).

It is also necessary to note that the different values of shear strength parameters from the various combinations of 3 specimens could also be caused by the different soil behaviour at low and high normal stress. This problem is complicated even for soil without fibres. We propose that added fibres influence the behaviour of soil in terms of dilatancy, contactancy, pore pressure dissipation, etc.; hence more research is required. On the other hand, many standards accept the evaluation of the direct shear test for only 3 specimens; therfore this procedure is applied not only in practice but also in many researches.

Concerning uncertainty; generally the expanded uncertainty of the angles of friction is under 1° and under 2.5% (max. at

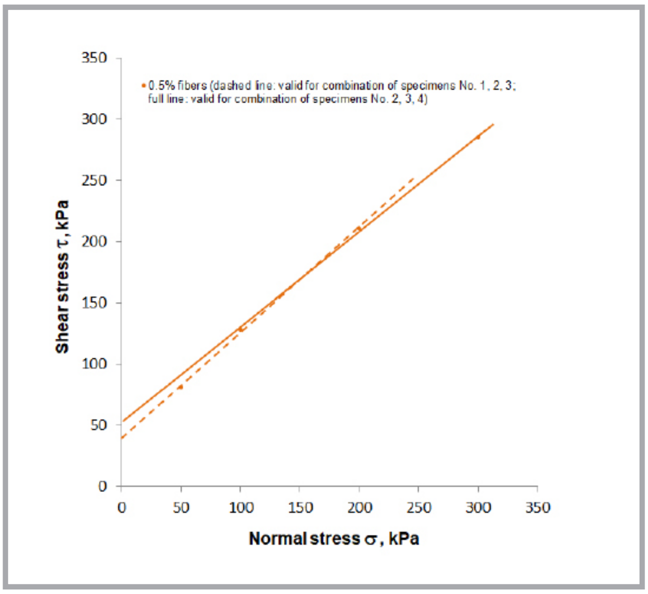

Figure. 9. *Two valid couples of shear strength parameters for an interval of normal stress from 100 to 200 kPa, soil CS reinforced by 0.5% of fibres (the combination of specimens No. 1, 2 and 3 gives φ = 40.52° and c = 40.39 kPa; the combination of specimens No. 2, 3 and 4 gives φ = 38.07° and c = 51.41 kPa; the difference in φ is 2.45° (6.0 %) and that in c is 11.02 kPa (27.2 %); see bold numbers in **Table** 7).*

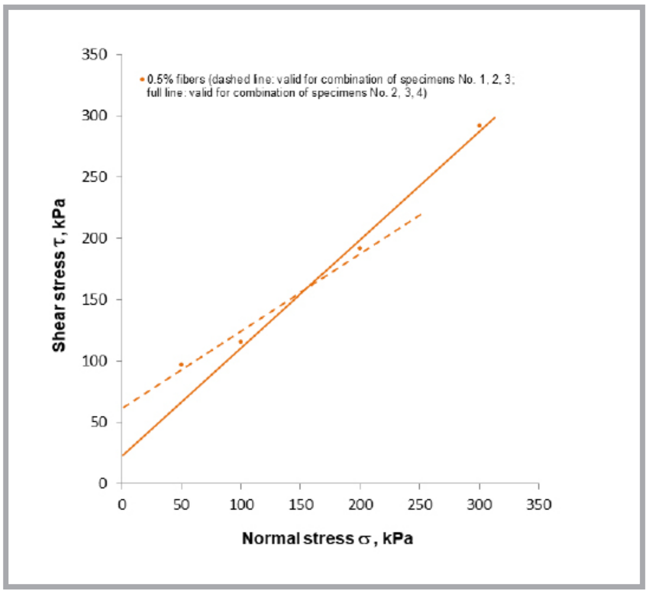

Figure 10. *Two valid couples of shear strength parameters for an interval of normal stress from 100 to 200 kPa, soil CH reinforced by 0.5% of fibres (the combination of specimens No. 1, 2 and 3 gives φ = 33.08° and c = 58.88 kPa; the combination of specimens No. 2, 3 and 4 gives φ = 41.40° and c = 23.65 kPa; the difference in φ is 8.32° (25.1%) and that in c is 35.23 kPa (59.8%); see bold numbers in **Table 8**).*

the absolute value is 0.93° (2.1%) for soil CS with 1.0% of fibres; max. at the relative value is 2.3% (0.84°) for soil CH with 1.0% of fibres, see ***Table 4***). The uncertainty of cohesion is larger, about 2 kPa and about 10% (max. at the absolute value is 1.87 kPa (8.6%) for soil CS with 1.0% of fibres; max. at relative value is 9.7% (1.55 kPa) for soil CH without fibres, see ***Table 4***). Determination of result uncertainty is helpful in the analysis of test results as well as in evaluation of the improvement rate.

Conclusions

Fibres in an amount of 0.5% significantly increased the angle of internal friction and also cohesion of soil CS. A larger amount of fibres (1.0%) also increased its angle of internal friction but decreased its cohesion. Therefore for practical application, taking into account economical issues, a fibre amount of 0.5% can be optimum.

Concerning soil CH, fibres in an amount of 0.5% practically did not change the angle of internal friction but significantly increased the cohesion. A larger amount of fibres (1.0%) decreased the angle of internal friction but decreased its cohesion. Again, for practical application, taking into account economical issues, a fibre amount of 0.5% can be optimum.

Direct shear tests with 3 specimens only provide various different values of shear strength parameters of soil and soils reinforced with fibres. Analyses based on such different values give a different interpretation of soil improvement with fibres. Therefore we would like to recommend, not only for research purposes but also for application in practice, carrying out tests with at least 4 specimens.

Even analysis of test result uncertainty requires more effort; it is useful to carry out such analysis not only in research but also in practice.

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