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Application of Direct Shear Test to Analysis of the Rate of Soil Improvement with Polyester Fibres

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Featured Application: Based on confirmed significant improvement of the shear strength parameters of soil using tested polyester fibres, there is a potential application of fibres in increasing the subsoil bearing capacity, increasing the slope stability or decreasing the soil pressure.

Abstract: When improving soil shear strength using various materials, determination of the improvement rate is a key issue and can be carried out using a direct shear test (DST). However, many standards for DST require only three specimens in the test and do not deal with test result uncertainty. In this study, shear strength parameters of clay of intermediate plasticity (CI) and sandy clays (CS1, CS2) improved with the addition of polyester fibres of 70 mm in length in amounts of 0.5%, 1.0%, and 1.5% of dry soil mass were obtained using DST with a shear box of size 0.3 m × 0.3 m × 0.08 m. The results show that using fibres provides significant improvement and the number of tested specimens (three or four) in DST has a significant impact on the obtained values of shear strength parameters. It is not recommended to carry out DST with only three specimens. The analysis of uncertainty shows that covariance between correlated input quantities (normal stresses and shear stresses) has a negligible influence on result uncertainty. The worst-case estimated uncertainties are very high and should not be applied. Analysis of the state of the fibre surface before and after shearing using scanning electron microscopy (SEM) shows that suitable fibre scratch resistance may be the reason for the large improvement.

Keywords: direct shear test; number of specimens; uncertainty of shear strength parameters; covariances; worst-case estimated uncertainties; fibre scratch resistance

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1. Introduction

In practice, in many cases, an improvement of soil properties proves necessary. Since soil shear strength is one of the most important properties, it is often required to be improved. To evaluate the improvement rate of soil shear strength, despite some shortcomings (predefined shear plan, uneven distribution of shear stress, small shear box, etc.) of the direct shear test (DST), many authors apply the DST in their research due to its simplicity. The DST has been used, e.g., to evaluate soil improvement with fibres [1–5], lime and fly ash [6], and palm oil fuel ash (POFA)-based geopolymer [7]. In addition to the use of DST in evaluation of the improvement rate of soil shear strength, DST has been used, e.g., for evaluation of the reinforcement effects of conventional geotextiles, geogrids, and novel geotextiles [8], evaluation of the influence of the scale effect on the shear strength of scaled coarse-grained soil (CGS) [9], and analysis of coarse-grained soil behavior during shearing [10]. Moreover, DST has been used, e.g., for the determination of soil shear strength parameters, which are further used in machine learning (ML) models built for their predicting for other soils without the need to carry out DST [11].

Tang et al. [1] investigated the effects of discrete short polypropylene fibre (PP-fibre) on the strength and mechanical behaviour of uncemented and cemented clayey soil (CL). In the presented investigation, 12 groups of soil samples were prepared at three different percentages of PP-fibre content (i.e., 0.05%, 0.15%, and 0.25% by weight of soil) and two different percentages of cement content (i.e., 5% and 8% by weight of soil), and unconfined compression and direct shear tests were carried out after 7-, 14-, and 28-day curing periods. The specimens for DST were shaped in a cylindrical mould of 20 mm in height with an inner diameter of 61.8 mm. The tests were performed at four vertical normal stresses, 50, 100, 200, and 300 kPa, in order to define the shear strength parameters. The authors stated that the test results indicated that the inclusion of fibre reinforcement within uncemented and cemented soil caused an increase in shear strength. The introduced increase in the values of the angle of internal friction was very small. So, e.g., after curing for 28 days, the values of the angle of internal friction of soil with 5% cement content and 0.05%, 0.15%, and 0.25% fibre content were 35.1°, 36.3°, and 36.7°, respectively (differences of 1.2° and 0.4°); the values of the angle of internal friction of soil with 8% cement content and 0.05%, 0.15%, and 0.25% fibre content were 37.0°, 37.5°, and 39.3°, respectively (differences of 0.5° and 1.8°). Since the differences were very small, it was also possible that such small changes could be smaller than the result uncertainty; therefore, uncertainty analysis could be useful.

Valipour et al. [3] investigated the effects of recycled tire polymer fibres (RTPFs) and glass fibres (GFs) on enhancing the strength/deformation properties of clays. A series of compaction, unconfined compression, and DST were performed on precisely prepared composite soils comprising clay with different amounts (0.5, 1.0 and 1.5%) of RTPFs and GFs having varying lengths (5 and 10 mm). For the clay reinforced with GFs and RTPFs, the shear strength was measured by a direct shear apparatus implementing the method of ASTM D3080 [12]. All specimens were sheared under constant vertical stresses of 55, 105, and 205 kPa. The differences between the peak friction angle of soil and soil composite were very small (from 0.1° to 3.3°; smaller than 1° in four cases). Similar small differences between the peak friction angle of composite with various amounts of RTPFs and GFs could be seen (from 0.4° to 2.7°; smaller than 1° in six cases). Small changes in both the peak friction angle and cohesion could be seen between 0.5% and 1% composite, e.g., 1° and 0.2 kPa (RTPF—L 10 mm), and 0.4° and 2.6 kPa (GF—L 5 mm). Therefore, it was also possible in this case that such small changes could be smaller than the result uncertainty, so uncertainty analysis could be useful.

Urian et al. [4] studied the mechanical characteristics of clay improved with shredded polyethylene terephthalate (PET). PET was provided by a local plastic waste repository. It comes from recycled water, beer, and soda bottles and was cleaned using specific methods for cleaning and recycling plastic waste. PET was shredded into irregular shapes with sizes ranging from 3 mm to 12 mm and was randomly distributed in percentages of 2%, 4%, and 6%. DST was performed according to the Romanian standard STAS 8942/2-82 [13] applying three normal stresses (100 kPa, 200 kPa, and 300 kPa). The values of the peak angle of internal friction of soil with 2%, 4%, and 6% PET were 20.93°, 20.20°, and 24.40°, respectively, so the improvement could be 2.10°, 1.37° and 5.57°, respectively (the peak angle of internal friction of soil without PET was 18.83°). Values of the residual angle of internal friction of soil with 2%, 4% and 6% PET were 12.21°, 11.33°, and 11.92°, respectively, so the improvement could be −0.17°, −1.04°, and −0.45°, respectively (the residual angle of internal friction of soil without PET was 12.37°). It was also possible in this case that such small changes could be smaller than the result uncertainty; therefore, uncertainty analysis could be useful.

Tang et al. [6] studied the mechanical properties of Xinyang red clay improved by lime and fly ash. The dry red clay soil that passed through the 2 mm sieve was divided into four groups. The first group was the single lime group, adding lime by 2%, 5%, 8%, and 11%. The second group was the single fly ash group, adding fly ash by 5%, 10%, 15%, and 20%. The third group was the mixed lime–fly ash group, and the mass ratios of lime–fly ash to dry soil were 1:2:7, 1:3:6, and 1:4:5. The fourth group was the control group, without lime

or fly ash. DST was used to determine the soil shear strength parameters of the improved soil, applying three normal stresses (100 kPa, 200 kPa, and 300 kPa). The values of the angle of internal friction of soil with 2%, 5%, 8%, and 11% lime content were 14°, 14°, 15°, and 17°, respectively, so the improvement could be 1.5°, 1.5°, 2.5°, and 4.5°, respectively (angle of internal friction of soil was 12.5°). The values of the angle of internal friction of soil with 5%, 10%, 15%, and 20% fly ash content were 11°, 13°, 12°, and 10°, respectively, so the improvement could be −1.5°, 0.5°, −0.5°, and −2.5°, respectively. The values of the angle of internal friction of soil with lime–fly ash–dry soil ratios of 1:2:7, 1:3:6, and 1:4:5 were 12.8°, 10.2°, and 13°, respectively, so the improvement could be 0.3°, −2.3°, and 0.5°, respectively. Similarly, in this case, it was possible that such small changes could be smaller than the result uncertainty, so uncertainty analysis could be useful.

Zhu et al. [11] used the shear strength parameters obtained from DST (with four applied normal stresses of 100, 200, 300, and 400 kPa) as guide values for predicting soil shear strength parameters using combined data and three different machine learning models. In total, 83 values of the angle of internal friction and 83 values of cohesion were obtained. The measured values of the internal friction angle ranged from 8.66° to 32.16°, with mean and median values of 18.73° and 17.70°, respectively. The cohesion value ranged from 1.74 to 38.95 kPa, with a mean of 20.77 kPa and a median of 20.91 kPa. Since the reliability of the predicted values of the shear strength parameters obtained from the models depended on the reliability of the above-mentioned values of the shear strength parameters, their uncertainty should be taken into account.

In our opinion, there is a big limitation to DST that is not addressed by many researchers: a large amount of DST is carried out in accordance with ASTM D3080/D3080M [12], STAS 8942/2-82 [13], AASHTO T 236-08: 2008 [14], BS 1377: Part 7:1990 [15], and ISO 17892-10:2018 [16], where only three specimens are sufficient and no limit value of the correlation coefficient between shear stresses and normal stresses is prescribed. One can propose that, in such cases, different combinations of three normal stresses (e.g., the combination 50 kPa, 100 kPa, and 200 kPa and the combination 100 kPa, 200 kPa, and 300 kPa) can provide different DST results (but are valid for the same common interval of normal stress from 100 kPa to 200 kPa). In contrast to the mentioned standards, STN 72 1030: 1988 [17] prescribes at least four specimens and PN-88/B-04481 [18] requires at least five specimens. Even in cases where researchers applied DST using four specimens, the improvement of shear strength parameters is small in some cases, but no uncertainty of the DST results is provided, so the improvement could not be confirmed.

DST was also applied in the evaluation of soil improvement using PES fibres TEXZEM PES 200 [19–21]. Nguyen et al. [19] reported the results of DST of soil improved by the mentioned fibres, TEXZEM PES 200, in amounts of 0.5%, 1.0%, and 1.5% of soil dry mass. Soil SC was used. DST was carried out using a fully automatic large shear box apparatus, SHEARMATIC 300 (Wykeham Farrance, CONTROLS Group, Milan, Italy). It was found that the optimal amount of fibres was 1%, at which the increase in the angle of internal friction measured was 6.1° (from 45.2° to 51.3°, corresponding to 13.5%) and the increase in cohesion obtained was 17.5 kPa (from 0 kPa to 17.5 kPa). The results of DST of soil CS mixed with the previously mentioned fibres, TEXZEM PES 200, can be also seen in the study by Nguyen [20]. DST was carried out using the above-mentioned large shear box apparatus, SHEARMATIC 300. The results showed that fibres in the amount of 0.5% significantly increased the angle of internal friction (by 8.7°, corresponding to 28.8%) as well as cohesion (by 14.4 kPa, corresponding 48.2%). Jakubík [21] also introduced a significant improvement of soil CS mixed with the previously mentioned fibres, TEXZEM PES 200. DST was carried out using the previously mentioned large shear box apparatus, SHEARMATIC 300. The results showed that fibres in the amount of 0.5% increased both the angle of internal friction by 16.1° (corresponding 86.0%) and cohesion by 32.3 kPa (corresponding 211.2%).

Ungureanu et al. [22], after analysing various possible methods for the estimation of DST uncertainty, came to the conclusion that a hybrid ordinary least squares method, denoted as HOLS, which they presented, provided better results in both cases of ho-

moscedastic and heteroscedastic data compared to the ordinary least squares (OLS), iterative weighted least square (IWLS), and weighted line of organic correlation (WLOC) approaches, as OLS largely overestimated measurement uncertainties (MUs) while IWLS and WLOC strongly underestimated MUs. The HOLS simulations of the MU values of the DST outcomes, depending on the correlation coefficient values of the DST measurands, clearly showed that when these correlations were stated as zero, then the MUs were underestimated. Also, the simulations proved that the greatest MU values were obtained when the DST measurands were totally negatively correlated. Therefore, the authors stated that further research was needed for accurate estimation of the correlation coefficient values.

Concerning the use of scanning electron microscopy (SEM) in an analysis of specimens after shearing, Cai et al. [23], on the basis of the micrographs of the shear plane of a polypropylene fibre–lime specimen, stated that it was clearly seen that, after shearing, some fibres were left in the soil with part of the length exposed to the air and, on the other hand, some threadlike grooves appeared in the shear plane. This was likely due to the strong resistance of the fibres against tension. Part of the fibre was pulled out from the soil when shearing occurred and the fibre itself was not sheared off. From the abrasion trace in the fibre surface, it was indicated that the fibres strengthened the soil due to friction between the fibres and soil particles.

To evaluate the factors affecting the interfacial strength properties of polypropylene fibre-reinforced soil, Tang et al. [24] carried out a single fibre pull-out test using a modified special apparatus. The SEM image taken from a single fibre-reinforced specimen after the pull-out test showed a number of visible scratches along the fibre's longitudinal direction on the surface. The authors stated that this may have resulted from the plowing of angular hard particles into the fibre body during the shear process. It confirmed that an interlock forc developed between the soil particles and the fibre surface.

Rivera-Gómez et al. [25] introduced an analysis of the influence of the fibre type on the polymer matrix/fibre bond using a natural organic polymer stabiliser. The study compared the effect of polypropylene and wool fibres on the mechanical properties of natural polymer-based stabilised soils. The authors stated that SEM proved to be a useful tool for the direct study of polymer–soil matrix interfaces. According to the authors, the main factors that affected the adhesion between the fibres and the soil were: (a) the cohesive properties of the polymer–soil matrix; (b) the compression friction forces appearing on the surface of the reinforcing fibre due to the shrinkage of the soil; and (c) the shear resistance of the polymer–soil matrix due to the surface form and roughness of the fibre. The authors also came to the conclusion that the loss of strength observed was not only caused by the variation in the fibre type but was more importantly the result of the effect of the differing properties of different soil types.

Liu et al. [26] applied X-ray diffraction and SEM analyses to reveal the micromechanics of the deformation and strength of grout. In the paper cited, the SEM results of concrete grout in sand for 28 days under 0 kPa, 100 kPa, and 200 kPa are presented. In the case of a pressure of 0 kPa, one can see that there was a large amount of pores and many pores were connected. In the case of a pressure of 100 kPa, there were fewer pores that were less connected. The maximal pore size was about 25 μm. The SEM images of the grout under a pressure of 200 kPa showed many fewer pores that had smaller pore sizes (about 7–15 μm). The authors stated that when the pressure was increased, the grout material particles became denser and the amount of hydration products rose, resulting in an increase in the consolidation deformation and UCS of the grout.

Another significant study showing the importance of the roughness of the fibre surface for improving the properties of the soil–cement–fibre composite is presented in [27]. To investigate the influence of the roughness of the fibre surface on improvement, cylindrical specimens of stabilised sandy soil, unreinforced and reinforced with polypropylene and sisal fibres, were tested. The fibres had the same length (12 mm), but the sisal fibres had a larger diameter (140 μm in comparison with 32 μm of the polypropylene fibre), larger tension strength (558 MPa in comparison with 250 MPa of the polypropylene fibre), and

higher surface texture roughness in comparison with the polypropylene fibres. The results of the unconfined compression strength tests carried out with and without the application of cyclic loading showed that the inclusion of fibres induced a decrease in the accumulated permanent axial strain, and this reduction was more significant for the use of sisal fibres due to the greater roughness and higher mechanical properties of this type of fibre. Analysing the obtained values of axial strain and unconfined compressive strength, it could be stated that, independent of the application of cyclic loading, reinforcement with sisal fibres was more effective than the use of polypropylene fibres. The greater roughness and better mechanical properties of sisal fibres promoted more effective anchorage and mobilisation of a higher tensile strength. Furthermore, the larger diameter of the sisal fibres provided a larger contact area between the fibres and surrounding material for the same strain level in comparison with the polypropylene fibres, so the anchorage was more effective and higher tensile strength was mobilised.

From the above-mentioned literature review, it can be stated that there are many studies dealing with soil improvement using DST, but most of them applied only three specimens and the test result uncertainty was not provided, so improvement could not be confirmed. The application of the fibres TEXZEM PES 200 improves the soil shear strength parameters considerably. The surface condition of the fibres significantly affects the characteristics of the reinforced soil and it is useful to deal with this issue.

In this study, DST has been carried out for three different soils improved by the mentioned fibres and four specimens have been tested in DST, applying four different normal stresses. The shear strength parameters were determined for all four specimens and various combinations of three specimens so that the influence of specimen number on test results could be analysed. The uncertainty of shear strength parameters was determined, also considering covariance between correlated input quantities (normal stresses and shear stresses) and a worst-case strategy. The obtained values of uncertainty enabled us to confirm the improvement rate and deepen the understanding of DST uncertainty. The applied SEM uncovered the possible reason for the significant improvement.

2. Materials and Methods

Soil from a cut slide and excavated soil at the highway construction site near Žilina, Slovakia, and soil from a cut slide in Przybędza, Poland, were used, see Figure 1.



(**a**) (**b**) (**c**)

Figure 1. Highways under construction near Žilina, Slovakia and in Przybędza, Poland. (**a**) Location No. 1: cut slide (soil CI), near Žilina, Slovakia; (**b**) Location No. 2: excavated soil, about 360 m from location No. 1 (soil CS1); (**c**) Location No. 3: cut slide (soil CS2), Przybędza, Poland [28].

BS 1377: 1990. Part 2 [29] was applied to obtain soil particle size distribution, water content (w), liquid limit (w_L), and plastic limit (w_P), and British Standard BS 5930:2015 [30] was applied to classify the soils. The grain size distribution of the soils is presented in Figure 2 and the soil properties can be seen in Table 1.

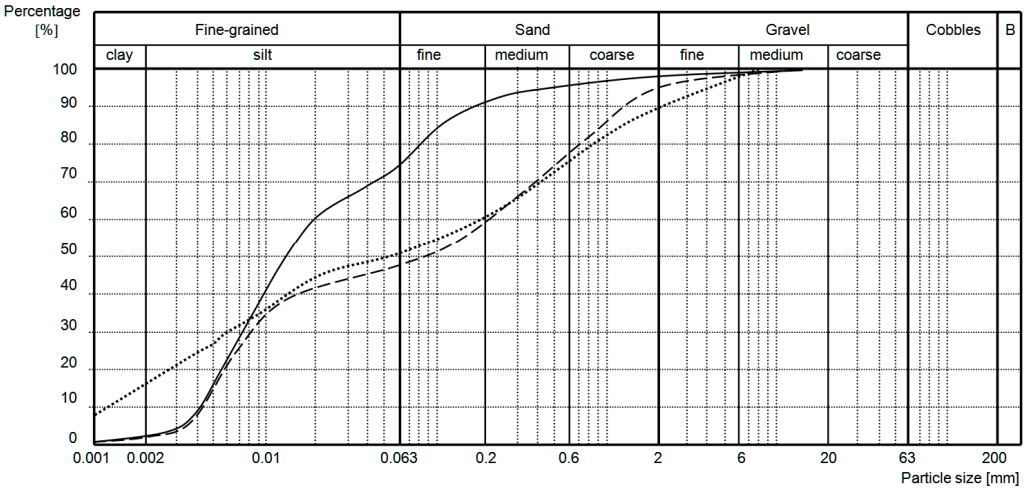


Figure 2. Grain size distribution diagram of soils: Full line is applied for CI; long dash line is applied for CS1; dotted line is applied for CS2.

Table 1. Soil properties.

Soil Parameters	CI	CS1	CS2
Water content (%)	18.1	21.6	10.2
Plastic limit (%)	20.6	27.8	19.7
Liquid limit (%)	44.2	54.7	40.2
Plasticity index (%)	23.6	26.9	20.5
Optimum water content (%)	18.6	21.0	13.7
Maximum dry density (kg·m^{-3})	1717	1630	1925

Polyester fibres TEXZEM PES 200 were used and the fibre properties are presented in Table 2. A picture of the fibres is presented in Figure 3a.

Table 2. Properties of polyester fibre [20].

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

Slovak technical standard STN 72 1030: 1988 on DST [17] was applied to determine the shear strength parameters of the soil and soil mixed with fibres. DST was carried out using a fully automatic large shear box apparatus, SHEARMATIC 300 (Wykeham Farrance, CONTROLS Group, Milan, Italy), presented in Figure 3b. The fibres were mixed with soils of optimum water content and maximum dry density in amounts of 0.5%, 1.0% and 1.5% (ratio of fibres to dry soil) and compacted in a box of size 0.3 m × 0.3 m × 0.08 m. The consolidation time was 5 h, and the shear speed was 0.05 mm/min. Normal stresses of 50 kPa, 100 kPa, 200 kPa, and 300 kPa were applied and tests were terminated at a horizontal displacement 35 mm (11.6% of the width of the specimen). A picture of a specimen of soil and fibres in the amount of 0.5% after testing under a normal stress of 50 kPa can be seen in Figure 3c.



(**a**) (**b**) (**c**)

Figure 3. Test device and tested fibres: (**a**) Polyester fibres TEXZEM PES 200 before testing; (**b**) Automatic large shear box apparatus SHEARMATIC 300; (**c**) Specimen of soil and fibre after testing (0.5% fibre, normal stress 50 kPa).

The shear strength parameters were calculated using formulae:

$$\tan\phi = \frac{n\sum \tau\sigma_{ef} - \sum \tau \sum \sigma_{ef}}{n\sum {\sigma_{ef}}^2 - \left(\sum \sigma_{ef}\right)^2} \quad (1)$$

$$c = \frac{\sum \tau \sum {\sigma_{ef}}^2 - \sum \sigma_{ef} \sum \tau\sigma_{ef}}{n\sum {\sigma_{ef}}^2 - \left(\sum \sigma_{ef}\right)^2} \quad (2)$$

where τ and σ_{ef} (kPa) are the pair of stresses obtained from each specimen and n is the number of specimens.

STN 72 1030: 1988 requires the test to be carried out with at least four specimens for the test of peak strength and requires the value of the correlation coefficient r calculated using Formula (3) to be larger than 0.9500:

$$r = \frac{n\sum\left(\tau\sigma_{ef}\right) - \sum \tau \sum \sigma_{ef}}{\sqrt{\left[n\sum {\sigma_{ef}}^2 - \left(\sum \sigma_{ef}\right)^2\right].\left[n\sum \tau^2 - (\sum \tau)^2\right]}} \quad (3)$$

Determination of uncertainty was carried out in accordance with EUROLAB Technical Report 1/2006 [31]. Here, only the most important issues are presented. So, e.g., a procedure to determine the uncertainties of normal stress $u(\sigma)$ and shear stress $u(\tau)$ is introduced. Determination of the uncertainties of the angle of internal friction and cohesion could be performed applying the same principle.

Based on our experience, the standard uncertainty of the shear box was proposed to be u_a = 0.2% and u_b = 0.2% (for dimensions a and b of the shear box). Based on calibration protocols and the magnitude of force measured, the standard uncertainties u_N = 0.141% of normal force and u_T= 0.158% of shear force were applied.

The normal stress is a function of normal force N and box size parameters a and b. The parameters N, a, and b are not dependent on one another (not correlated); the standard uncertainty of the normal stress σ in kPa was obtained using the formula:

$$u(\sigma) = \sqrt{[c_N.u(N)]^2 + [c_a.u(a)]^2 + [c_b.u(b)]^2} \quad (4)$$

where c_N, c_a, and c_b are the sensitivity coefficients relating to the particular parameters N, a, and b, respectively, and will be obtained by the partial derivative of the model function f, step by step, of N, a, and b. So, e.g., the sensitivity coefficient for N was determined as follows:

$$c_N = \frac{\partial f}{\partial N} = \frac{\partial\left(\frac{N}{a.b}\right)}{\partial N} = \frac{1}{a.b}\Bigg|_{a=0.30, b=0.30} \tag{5}$$

In the same way, c_a and c_b were determined.

The absolute value of the standard uncertainty of the particular parameter, e.g., of the normal force $u(N)$, was calculated by multiplying its estimated value by the standard uncertainty of the force transducer:

$$u(N) = N.u_N \tag{6}$$

In the same way, $u(a)$ and $u(b)$ and then $u(\sigma)$ were determined based on Formula (4).

Regarding the uncertainty of the shear stress $u_c(\tau)$, inconformity of the specimen can give different shear stresses at the same normal stress even if the same test procedure is applied. Therefore, in this case, it was proposed that the standard uncertainty of the type A $u_A(\tau)$ of shear stress existed but did not exceed 0.5%. The value $u_A(\tau)$ was used to calculate the combined standard uncertainty of the shear stress, applying the following formula:

$$u_c(\tau) = \sqrt{u_A(\tau)^2 + u_B(\tau)^2}, \tag{7}$$

where $u_B(\tau)$ is determined in the same way as in the case of $u(\sigma)$.

In order to determine the uncertainty as precisely as possible, a further source of uncertainty was considered, namely, the covariances between correlated input quantities (normal stresses and shear stresses). In the case of DST, covariances between stresses exist since they are calculated using a common specimen area A. So, e.g., covariance $u(\sigma_i, \tau_j)$ could be obtained using the formula:

$$u(\sigma_i, \tau_j) = \left(\frac{\partial \sigma_i}{\partial A}\right).\left(\frac{\partial \tau_j}{\partial A}\right).u(A)^2 \tag{8}$$

Then, the correlation coefficient $r(\sigma_i, \tau_j)$ could be obtained using the formula:

$$r(\sigma_i, \tau_j) = \frac{u(\sigma_i, \tau_j)}{u(\sigma_i).u(\tau_j)} \tag{9}$$

Applying a similar procedure, the correlation coefficients $r(\sigma_i, \sigma_j)$ and $r(\tau_i, \tau_j)$ could be calculated.

A standard uncertainty $u(tan\varphi)$ caused by parameters σ_i and τ_i and also their correlation was determined similarly as in the case of $u(\sigma)$, applying Equation (1), considering $tan\varphi$ as a function of eight parameters (four normal stresses and four shear stresses). A formula in [22] was used, as follows:

$$\begin{aligned} u(\tan\phi)^2 = u(\beta) = \sum_{i=1}^{n} (c(\sigma_i)u(\sigma_i))^2 + \sum_{i=1}^{n} (c(\tau_i)u(\tau_i))^2 + \\ +2.\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c(\sigma_i)c(\sigma_j)r(\sigma_i, \sigma_j)u(\sigma_i)u(\sigma_j) + \\ +2.\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c(\tau_i)c(\tau_j)r(\tau_i, \tau_j)u(\tau_i)u(\tau_j) + \\ +2.\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c(\sigma_i)c(\tau_j)r(\sigma_i, \tau_j)u(\sigma_i)u(\tau_j) \end{aligned} \tag{10}$$

The uncertainty range of the angle of friction φ is asymmetric [22] since uncertainty is defined for $tan\varphi$ (not for φ). According to [22], if one notes $\beta_0 = tan(\varphi_0)$, then β (slope of strength line) belongs to the $[\beta_0 - u(\beta);\ \beta_0 + u(\beta)]$ interval. Consequently, φ varies in the $[atan(\beta_0 - u(\beta)); atan(\beta_0 + u(\beta))]$ range. Thus, two components of $u(\varphi)$ can be differentiated, i.e.,

$$u_{-}(\phi) = atan(\beta_0) - atan(\beta_0 - u(\beta)), \quad (11)$$

which is the left-hand side of $u(\varphi)$, and

$$u_{+}(\phi) = atan(\beta_0 + u(\beta)) - atan(\beta_0) \quad (12)$$

which is the right-hand side of $u(\varphi)$.

The expanded uncertainty (using a coverage factor k = 2) of φ should be split in the right-hand interval $U_{\varphi+;95\%} = 2{\cdot}[atan(\beta_0 + u(\beta)) - \varphi_0]$ and the left-hand interval $U_{\varphi-;95\%} = 2 \cdot [\varphi_0 - atan(\beta_0 - u(\beta))]$. The larger values from them will be introduced in the paper as U_φ.

The standard uncertainty of cohesion $u(c)$ was determined in the same way as in the case of $u(tan\varphi)$, applying Equation (2), and the expanded uncertainty U_c was determined by multiplying the standard uncertainty $u(c)$ by the coverage factor k = 2.

To examine the influence of covariance between correlated input quantities (normal stresses and shear stresses), U_φ and U_c were calculated without using correlation coefficients, marked as case A, and using correlation coefficients, marked as case B (see Formulae (9) and (10)).

To explore the magnitude of the uncertainty in the case of the worst-case estimation, marked as case C, the uncertainty was calculated by adding linearly the uncertainty contributions $c(\sigma_i).u(\sigma_i)$ and $c(\tau_i).u(\tau_i)$ and not considering the correlation coefficients.

The morphology of the fibres before and after shearing under various normal stresses was investigated by SEM. Fibres were taken from the shear surface of the center ninth of specimens of size 10 cm × 10 cm (shear box of size 30 cm × 30 cm) after shearing under normal stresses of 50 kPa and 300 kPa, and their morphologies were compared. A JEOL JSM 5500 LV microscope (JEOL Ltd., Tokyo, Japan) operating in backscattered electron mode was used. The observations were carried out for fibres sputtered with gold using the JEOL JFC 1200 ionic sputter coater.

3. Results

3.1. Improvement of Soil Shear Strength Parameters

Maximal values of shear stress for various amounts of fibres can be seen in Table 3. Dependence of shear stress on normal stress in soil CI, CS1, and CS2 is introduced in Figures 4–6.

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

Soil	Maximal Values of Shear Stress for Various Amounts of Fibres (kPa)							
	0%		0.5%		1.0%		1.5%	
	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)
CI	50.1	85.667	50.1	94.667	50.1	91.111	50.3	110.333
	100.3	125.889	100.2	123.778	100.2	143.889	100.3	168.889
	200.3	177.444	200.1	183.778	200.1	218.111	200.3	215.778
	300.4	246.778	300.1	241.556	300.2	**274.222**	300.3	257.444
CS1	50.2	74.556	50.1	**137.556**	50.3	131.000	50.3	125.444
	100.2	143.889	100.2	**182.444**	100.2	173.667	100.0	146.444
	200.1	171.111	200.1	**248.111**	200.1	207.556	200.2	183.778
	300.2	249.889	300.4	**319.556**	300.3	261.778	300.2	192.000

Table 3. *Cont.*

Soil	Maximal Values of Shear Stress for Various Amounts of Fibres (kPa)							
	0%		0.5%		1.0%		1.5%	
	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)	Normal Stress σ (kPa)	Shear Stress τ (kPa)
CS2	50.3	71.111	50.3	80.333	50.3	75.889	50.3	72.222
	100.1	107.000	100.2	122.222	100.2	109.778	100.2	114.444
	200.1	151.000	200.3	184.778	200.2	196.667	200.2	189.444
	300.1	167.222	300.2	228.889	300.2	259.889	300.3	263.444

Note: Since there are many numbers in tables, bold and colour are applied to differ them. Generally, blue numbers indicate favourable values. Red numbers indicate unfavorable values. This rule is applied in further tables. More information is introduced and commented in the paper.

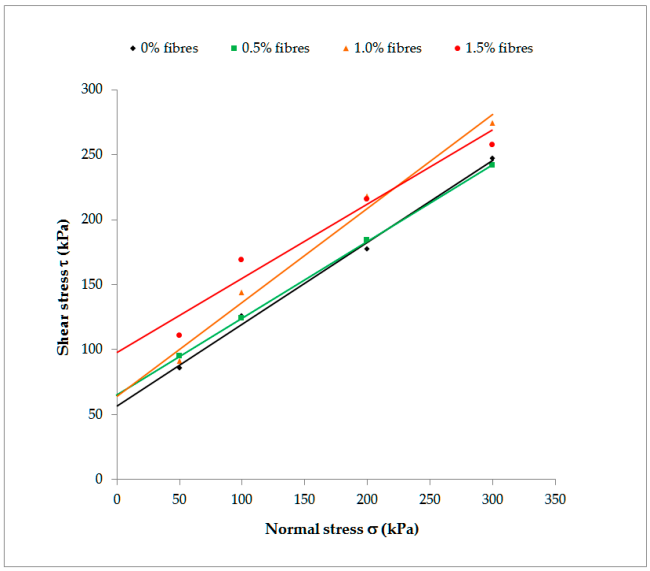


Figure 4. Shear stress versus normal stress in soil CI.

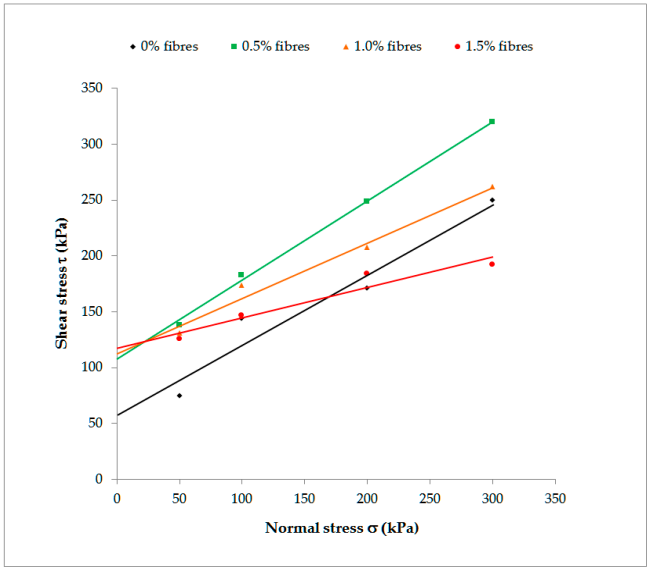


Figure 5. Shear stress versus normal stress in soil CS1.

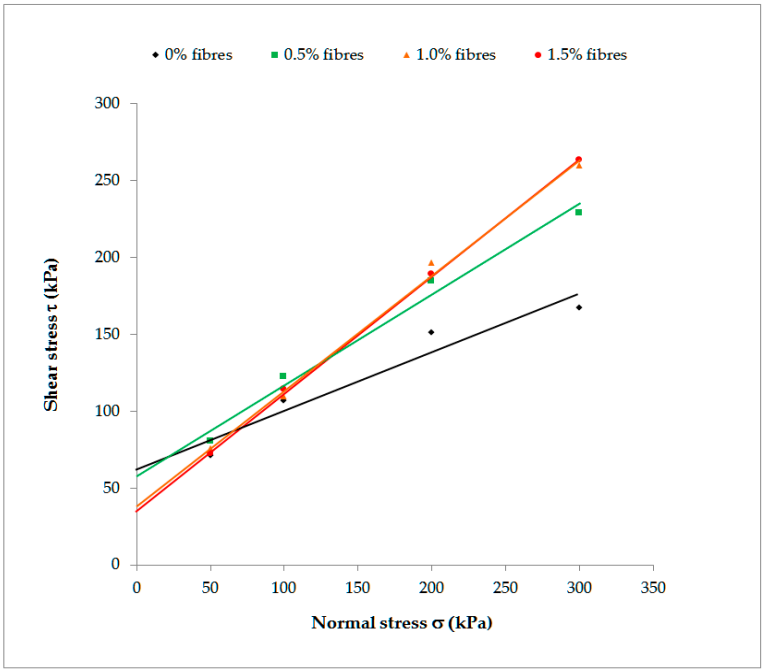


Figure 6. Shear stress versus normal stress in soil CS2.

Values of the shear strength parameters of soils and soils reinforced by fibres as well as their expanded uncertainty are introduced in Table 4 (soil CI), Table 5 (soil CS1), and Table 6 (soil CS2).

Table 4. Shear strength parameters of soils and soils reinforced by fibres and their expanded uncertainty (soil CI).

Soil	Case No.	Fibre Amount	Strength Parameters		R-Value	Expanded Uncertainty											
						Without Covariance (A)				With Covariance (B)				Worst-Case (C)			
			φ	c		U(φ)		U(c)		U(φ)		U(c)		U(φ)		U(c)	
		(%)	(°)	(kPa)		(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CI (4 specimens; No. 1, 2, 3, and 4)	1	0.0	32.019	57.158	0.99752	0.524	1.64	1.603	2.81	0.520	1.62	1.604	2.81	1.052	3.29	3.593	6.29
		0.5	30.502	65.141	0.99996	0.534	1.75	1.619	2.48	0.528	1.73	1.620	2.49	1.070	3.51	3.631	5.57
		1.0	35.842	64.344	0.99296	0.542	*1.51*	1.811	2.82	0.540	*1.51*	1.820	2.83	1.086	*3.03*	4.190	6.51
		1.5	29.097	97.507	0.97594	0.596	2.05	1.896	*1.94*	0.586	2.01	1.914	*1.96*	1.212	4.17	4.227	*4.34*
CI (3 specimens; No. 1, 2, and 3)	2	0.0	30.858	59.821	0.99305	0.734	2.38	1.741	2.91	0.722	2.34	1.720	2.88	1.296	4.20	3.745	6.26
		0.5	30.753	64.578	0.99997	0.760	2.47	1.814	2.81	0.746	2.43	1.784	2.76	1.328	4.32	3.829	5.93
		1.0	39.758	53.869	0.99575	0.724	1.82	2.035	3.78	0.718	1.81	2.022	3.75	1.280	3.22	4.451	8.26
		1.5	33.803	86.688	0.96794	0.842	2.49	2.214	2.55	0.828	2.45	2.186	2.52	1.506	4.46	4.750	5.48
CI (3 specimens; No. 2, 3, and 4)	3	0.0	31.139	62.338	0.99644	0.738	2.37	3.030	*4.86*	0.728	2.34	2.994	*4.80*	1.268	4.07	6.092	*9.77*
		0.5	30.506	65.122	0.99994	0.736	2.41	2.997	4.60	0.728	2.39	2.968	4.56	1.254	4.11	6.129	9.41
		1.0	33.090	81.638	0.99675	0.794	2.40	3.454	4.23	0.784	2.37	3.422	4.19	1.368	4.13	7.105	8.70
		1.5	23.883	125.349	0.99942	0.908	*3.80*	3.559	2.84	0.876	*3.67*	3.466	2.77	1.502	*6.29*	6.749	5.38

Note: The authors are aware of the unsuitable introduction of values of shear strength parameters with 3 digits after the decimal in this and further tables. The underlying reason is the necessity of comparison since, in some cases, there will be no difference if 1 or 2 digits after the decimal is (are) applied, leading to misunderstandings. Specimen No. 1 was loaded by normal stress of about 50 kPa; specimen No. 2 was loaded by normal stress of about 100 kPa; specimen No. 3 was loaded by normal stress of about 200 kPa; and specimen No. 4 was loaded by normal stress about of 300 kPa. The same is applied in further tables. In Tables 4–6, for every column, maximal absolute values are marked as red underlined numbers, maximal relative values are marked as italic red underlined numbers, minimal absolute values are marked as blue underlined numbers, and minimal relative values are marked as italic blue underlined numbers. More information is introduced and commented in the paper.

Table 5. Shear strength parameters of soils and soils reinforced by fibres and their expanded uncertainty (soil CS1).

Soil	Case No.	Fibre Amount	Strength Parameters		R-Value	Expanded Uncertainty											
						Without Covariance (A)				With Covariance (B)				Worst-Case (C)			
			φ	c		U(φ)		U(c)		U(φ)		U(c)		U(φ)		U(c)	
		(%)	(°)	(kPa)		(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CS1 (4 specimens; No. 1, 2, 3, and 4)	1	0.0	32.398	56.633	0.97043	0.526	*1.62*	1.634	2.89	0.522	*1.61*	1.636	2.89	1.066	*3.29*	3.616	6.39
		0.5	35.539	105.696	0.99886	0.634	1.78	2.245	2.12	0.622	1.75	2.250	2.13	1.276	3.59	4.953	4.69
		1.0	26.252	113.245	0.98957	0.638	2.43	1.997	1.76	0.618	2.35	2.002	1.77	1.288	4.91	4.239	3.74
		1.5	15.209	117.690	0.96082	0.568	3.73	1.693	*1.44*	0.540	3.55	1.712	*1.45*	*1.132*	7.44	3.525	*2.99*
CS1 (3 specimens; No. 1, 2, and 3)	2	0.0	30.589	60.788	0.90622	0.722	2.36	1.738	2.86	0.714	2.33	1.728	2.84	1.316	4.30	3.831	6.30
		0.5	35.968	104.608	0.99670	0.918	2.55	2.559	2.45	0.896	2.49	2.510	2.40	1.610	4.48	5.358	5.12
		1.0	25.942	113.888	0.96729	0.960	3.70	2.322	2.04	0.926	3.57	2.264	1.99	1.684	6.49	4.761	4.18
		1.5	21.144	106.703	0.99949	0.918	4.34	2.096	1.96	0.876	4.14	2.028	1.90	1.570	7.43	4.164	3.90
CS1 (3 specimens; No. 2, 3, and 4)	3	0.0	27.928	82.190	0.96292	0.800	2.86	3.187	*3.88*	0.778	2.79	3.104	*3.78*	1.382	4.95	5.975	*7.27*
		0.5	34.407	112.899	0.99973	0.900	2.62	4.120	3.65	0.880	2.56	4.050	3.59	1.520	4.42	8.132	7.20
		1.0	23.768	126.168	0.99135	0.924	3.89	3.612	2.86	0.886	3.73	3.500	2.77	1.532	6.45	6.659	5.28
		1.5	12.822	128.524	0.93839	0.798	*6.22*	2.913	2.27	0.754	*5.88*	2.814	2.19	1.308	*10.20*	5.337	4.15

Table 6. Shear strength parameters of soils and soils reinforced by fibres and their expanded uncertainty (soil CS2).

Soil	Case No.	Fibre Amount	Strength Parameters		R-Value	Expanded Uncertainty											
						Without Covariance (A)				With Covariance (B)				Worst-Case (C)			
			φ	c		U(φ)		U(c)		U(φ)		U(c)		U(φ)		U(c)	
		(%)	(°)	(kPa)		(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CS2 (4 specimens; No. 1, 2, 3, and 4)	1	0.0	20.755	62.443	0.96472	0.450	2.17	1.236	*1.98*	0.442	2.13	1.250	*2.00*	0.904	4.36	2.830	*4.53*
		0.5	30.510	58.150	0.99256	0.512	1.68	1.535	2.64	0.508	1.67	1.542	2.65	1.026	3.36	3.541	6.09
		1.0	36.933	38.232	0.99776	0.498	1.35	1.609	4.21	0.496	1.34	1.612	4.22	0.980	2.65	3.753	9.82
		1.5	37.257	36.098	0.99973	0.498	*1.34*	1.613	4.47	0.496	*1.33*	1.614	4.47	0.982	*2.64*	3.720	10.31
CS2 (3 specimens; No. 1, 2, and 3)	2	0.0	27.469	48.963	0.99123	0.668	2.43	1.476	3.02	0.660	2.40	1.460	2.98	1.184	4.31	3.191	6.52
		0.5	34.452	48.888	0.99703	0.704	2.04	1.742	3.56	0.698	2.03	1.728	3.53	1.244	3.61	3.791	7.76
		1.0	39.172	32.197	0.99835	0.622	1.69	1.744	5.42	0.658	1.68	1.734	5.39	1.148	2.93	3.796	11.79
		1.5	37.862	34.490	0.99953	0.662	1.75	1.706	4.95	0.660	1.74	1.698	4.92	1.162	3.07	3.746	10.86
CS2 (3 specimens; No. 2, 3, and 4)	3	0.0	16.758	81.488	0.96632	0.648	*3.87*	2.313	2.84	0.630	*3.76*	2.268	2.78	1.108	*6.61*	4.568	5.61
		0.5	28.074	71.832	0.99511	0.736	2.62	2.906	4.05	0.726	2.59	2.876	4.00	1.268	4.52	5.964	8.30
		1.0	36.890	38.516	0.99588	0.683	1.85	3.087	*8.01*	0.681	1.85	3.080	*8.00*	1.192	3.23	6.646	*17.25*
		1.5	36.672	40.012	0.99999	0.690	1.88	3.108	7.77	0.688	1.88	3.098	7.74	1.188	3.24	6.561	16.40

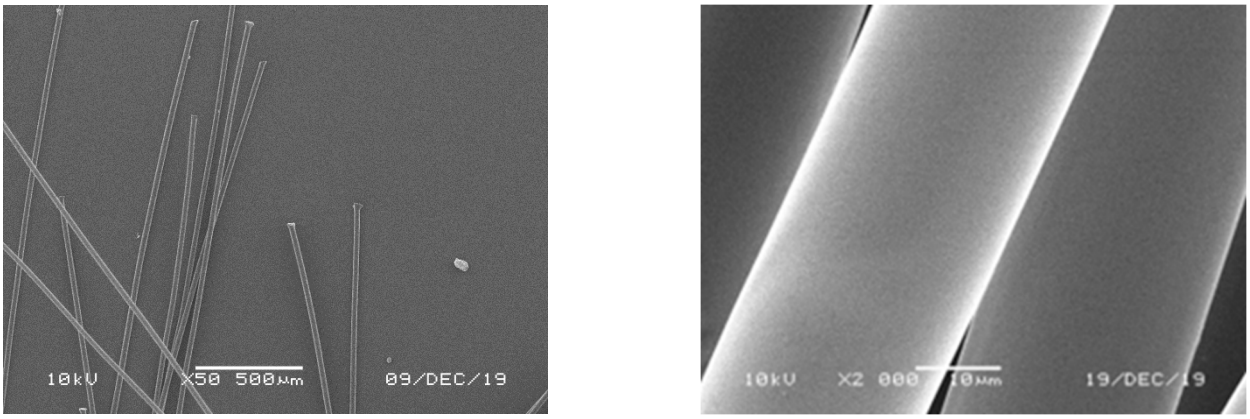
Differences in shear strength parameters for various amounts of fibres (i.e., improvement), considering all four specimens (case No. 1), are introduced in Table 7.

Table 7. Differences (improvement) in shear strength parameters for various amounts of fibres.

Soils	Improvement of Shear Strength Parameters by Various Amounts of Fibres	Differences in Strength Parameters			
		φ		c	
		(°)	(%)	(kPa)	(%)
CI	Differences between 0.5% and 0.0%	−1.517	−4.74	7.983	13.97
	Differences between 1.0% and 0.0%	**3.823**	**11.94**	**7.186**	**12.57**
	Differences between 1.5% and 0.0%	−2.922	−9.13	40.349	70.59
CS1	Differences between 0.5% and 0.0%	**3.141**	**9.70**	**49.063**	**86.63**
	Differences between 1.0% and 0.0%	−6.146	−18.97	56.612	99.96
	Differences between 1.5% and 0.0%	−17.189	−53.06	61.057	107.81
CS2	Differences between 0.5% and 0.0%	9.755	47.00	−4.293	−6.88
	Differences between 1.0% and 0.0%	**16.178**	77.95	**−24.211**	−38.77
	Differences between 1.5% and 0.0%	**16.502**	79.51	**−26.345**	−42.19

The SEM images of fibres before testing can be seen in Figure 7a (50× magnification) and Figure 7b (2000× magnification). The SEM images of fibres mixed with soil CI in

various amounts after shearing under normal stresses of 50 kPa and 300 kPa are posted in Figure 8. The SEM images of fibres mixed with soil CS1 in various amounts after shearing under normal stresses of 50 kPa and 300 kPa are posted in Figure 9. The SEM images of fibres mixed with soil CS2 in various amounts after shearing under normal stresses of 50 kPa and 300 kPa are posted in Figure 10.



(**a**) (**b**)

Figure 7. The SEM images of fibres before testing: (**a**) 50× magnification; (**b**) 2000× magnification.

As can be seen in Table 7 (blue coloured numbers), fibres in the amount of 1.0% increased the angle of internal friction of soil CI by 3.823° (11.94%) and also increased cohesion by 7.186 kPa (12.57%). The increase in the angle of internal friction could be confirmed since 3.81° was larger than the uncertainty of 0.520° + 0.540° = 1.060° (see expanded uncertainty with covariance in Table 4 for 0% and 1% fibres; four specimens). The increase in cohesion could be also confirmed since 7.186 kPa was larger than the uncertainty of 1.604 kPa + 1.820 kPa = 3.424 kPa (see expanded uncertainty with covariance in Table 4 for 0% and 1% fibres; four specimens). The increases in both the angle of internal friction and cohesion in the case of fibres in the amount of 1.0% was caused by the fact that all shear stresses were higher in comparison with the case of 0% fibres (compare blue numbers with red numbers in Table 3 and see a yellow line in Figure 4) and there was the highest shear stress from all shear stress values (274.2 kPa, corresponding to a normal stress of 300 kPa). It is possible that such a high value of shear stress was reached due to friction between the soil particles and fibres (see a great number of depth scratches on the fibre surface in Figure 8d).

Regarding soil CS1 (see blue coloured numbers in Tables 3 and 7 and a green line in Figure 5), fibres in the amount of 0.5% increased the angle of internal friction of soil CS1 by 3.141° (9.70%) and also increased cohesion by 49.063 kPa (86.63%). The increase in the angle of internal friction could be confirmed since 3.141° was larger than the uncertainty of 0.522° + 0.622° = 1.144° (see expanded uncertainty with covariance in Table 5 for 0% and 0.5% fibres; four specimens). The increase in cohesion could be also confirmed since 49.063 kPa was much larger than the uncertainty of 1.636 kPa + 2.250 kPa = 3.886 kPa (see expanded uncertainty with covariance in Table 5 for 0% and 0.5% fibres; four specimens). These increases were caused by high values of all maximal shear stresses corresponding to all normal stresses. It should be noted that the mentioned maximal shear stresses were the highest in comparison with the maximal shear stresses obtained from other amounts of fibres (1.0% and 1.5%). It is possible that such high values of shear stresses were reached due to friction between the soil particles and fibres (see scratches on the fibre surface in Figure 9a,b). It is worth noting that the maximal shear stresses in the case of fibres in the amount of 1.5% were very low in comparison with the other amounts of fibres (see a red line in Figure 5). This could be caused by a specific behaviour of this soil CS1, which had a higher liquid limit, plastic limit, and optimal water content, but a lower maximum dry

density than soil CI (see Table 1). It can be proposed that the specific behaviour of this soil CS1 also caused more soil particles to attach to the fibre surface and less scratches on the fibre surface, as shown in Figure 9c–f.

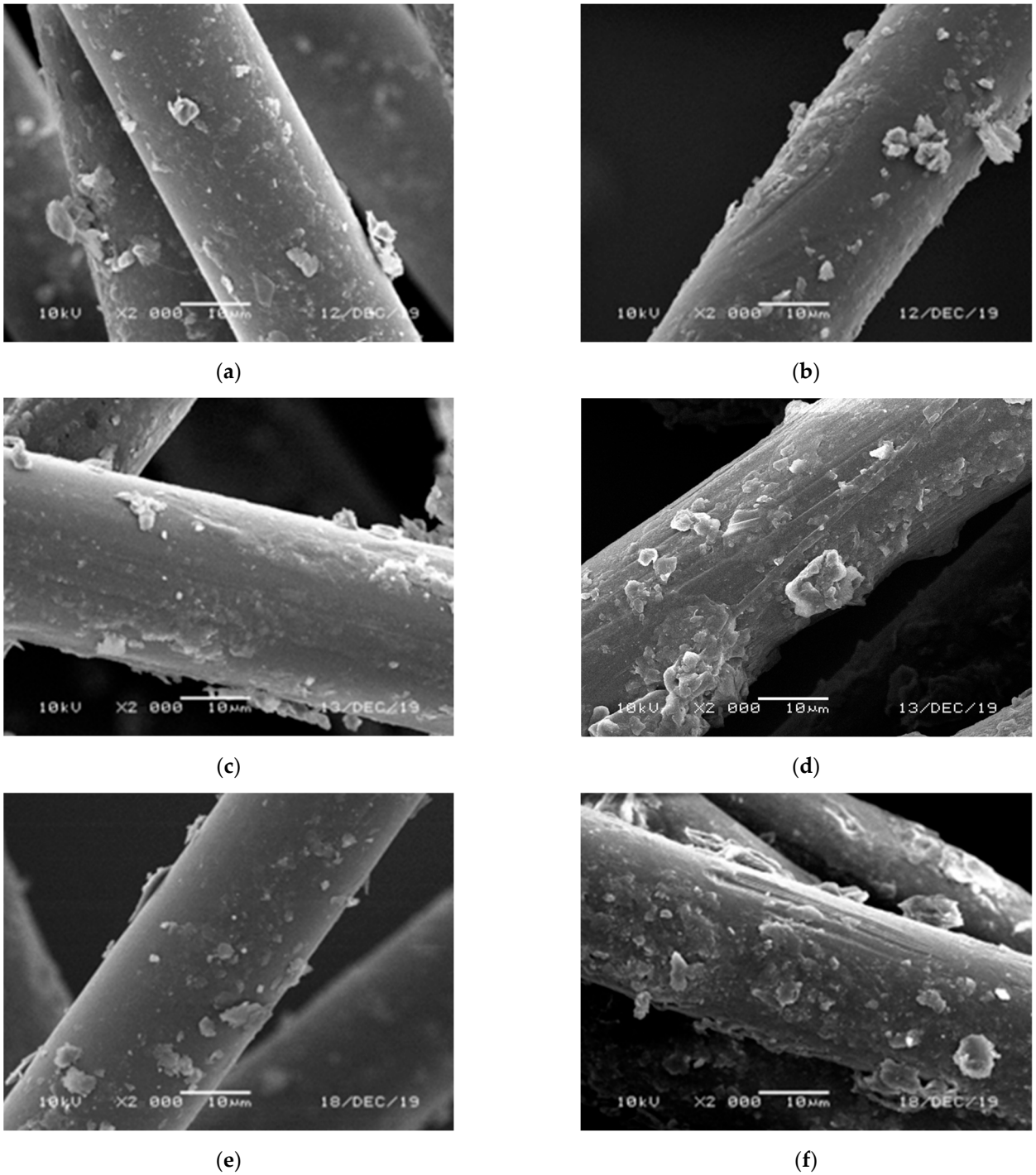
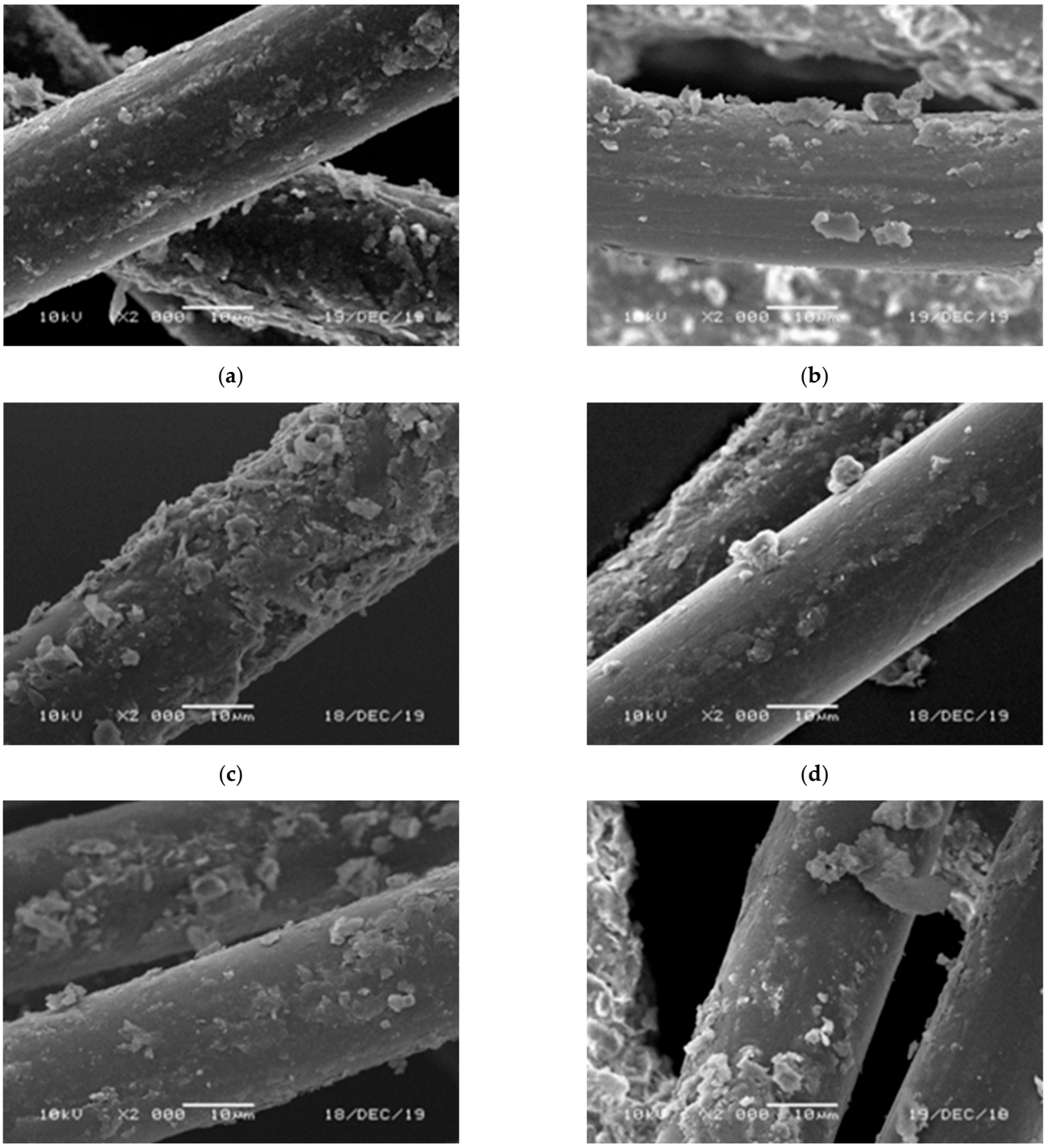


Figure 8. The SEM images of fibres applied in soil CI after shearing: (**a**) 0.5% fibres, normal stress of 50 kPa; (**b**) 0.5% fibres, normal stress of 300 kPa; (**c**) 1.0% fibres, normal stress of 50 kPa; (**d**) 1.0% fibres, normal stress of 300 kPa; (**e**) 1.5% fibres, normal stress of 50 kPa; (**f**) 1.5% fibres, normal stress of 300 kPa.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 9. The SEM images of fibres applied in soil CS1 after shearing: (**a**) 0.5% fibres, normal stress of 50 kPa; (**b**) 0.5% fibres, normal stress of 300 kPa; (**c**) 1.0% fibres, normal stress of 50 kPa; (**d**) 1.0% fibres, normal stress of 300 kPa; (**e**) 1.5% fibres, normal stress of 50 kPa; (**f**) 1.5% fibres, normal stress of 300 kPa.

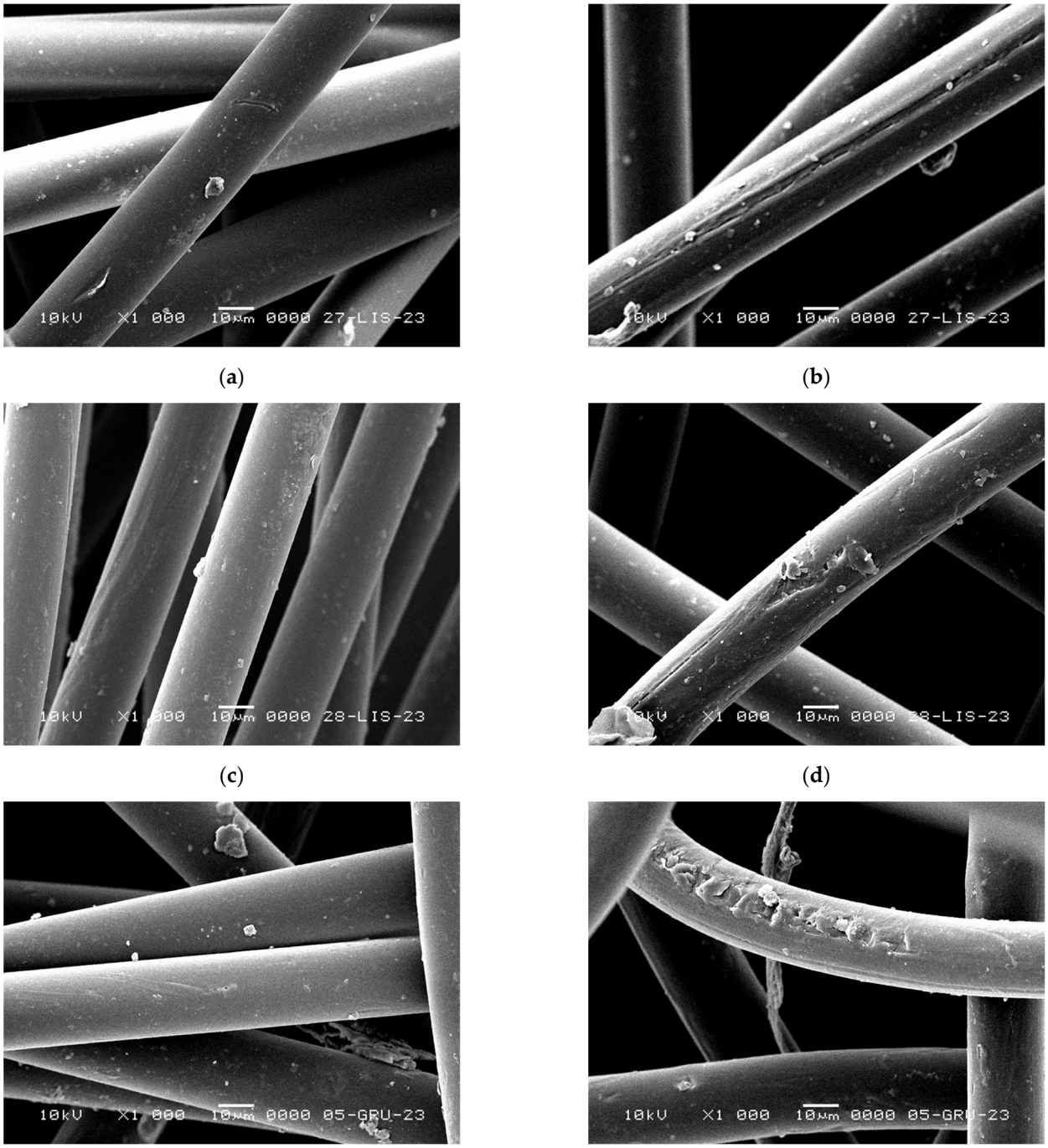


Figure 10. The SEM images of fibres applied in soil CS2 after shearing: (**a**) 0.5% fibres, normal stress of 50 kPa; (**b**) 0.5% fibres, normal stress of 300 kPa; (**c**) 1.0% fibres, normal stress of 50 kPa; (**d**) 1.0% fibres, normal stress of 300 kPa; (**e**) 1.5% fibres, normal stress of 50 kPa; (**f**) 1.5% fibres, normal stress of 300 kPa.

The behaviour of soil CS2 was different in comparison with the aforementioned soils (see Tables 3, 6 and 7 and Figure 6). Fibres in the amount of 0.5% increased the angle of internal friction of soil CS2 by 9.755° (47.00%) but decreased cohesion by 4.293 kPa (6.88%). The increase in the angle of internal friction could be confirmed since 9.755° was larger than the uncertainty of 0.442° + 0.508° = 0.950° (see expanded uncertainty with covariance in Table 6 for 0% and 0.5% fibres; four specimens). The decrease in cohesion could be confirmed

since 4.923 kPa was larger than the uncertainty of 1.250 kPa + 1.542 kPa = 2.792 kPa (see expanded uncertainty with covariance in Table 6 for 0% and 0.5% fibres; four specimens). There were large increases in the angle of internal friction and large decreases in cohesion in the case of soil mixed with 1% and 1.5% fibres (see bold blue and red coloured numbers in Table 7 and a yellow and red line in Figure 6). This fact was caused by the high values of shear stress at a normal stress of 300 kPa but low values of shear stress at a normal stress 50 kPa, see blue and red numbers in Table 3. Soil CS2 without fibres had the lowest shear stress at a normal stress of 300 kPa in comparison with the above soils (only 167.222 kPa, see red coloured number in Table 3). It is proposed that high values of shear stress of soil mixed with fibres were reached due to the suitable composition of soil particle and fibre scratch resistance (see Figure 10b,d,f).

3.2. Influence of the Specimen Number on Test Results

An analysis of the influence of specimen number on the test results was also carried out. Values of the shear strength parameters of the soils and those reinforced by fibres evaluated from various combinations of specimens (all four tested specimens and chosen combinations of only three specimens) are introduced in Table 4 (for soil CI), Table 5 (for soil CS1), and Table 6 (for soil CS2). Values of the shear strength parameters were evaluated based on normal stresses and shear stresses, posted in Table 3, where specimen No. 1 was loaded by a normal stress of about 50 kPa, specimen No. 2—by a normal stress of about 100 kPa, specimen No. 3—by a normal stress of about 200 kPa, and specimen No. 4—by a normal stress of about 300 kPa. The reason for introducing these combinations of specimens No. 1, 2, and 3 and No. 2, 3, and 4 was that these two combinations had a common interval of normal stress from 100 kPa to 200 kPa; therefore the shear strength parameters obtained from them would be valid for the mentioned interval of normal stress (but they were very different), as can be seen later. Differences in shear strength parameters, obtained by various combinations, are introduced in Table 8 (for soil CI), Table 9 (for soil CS1), and Table 10 (for soil CS2).

Table 8. Differences in shear strength parameters between various specimen combinations (soil CI).

	Fibre Amount	**Differences in Strength Parameters**			
		φ		**c**	
	(%)	**(°)**	**(%)**	**(kPa)**	**(%)**
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 2 (3 specimens: No. 1, 2, and 3) (° or kPa, %)	0.0	1.161	3.76	−2.663	−4.45
	0.5	−0.251	−0.82	0.563	0.87
	1.0	**−3.916**	**−9.85**	**10.475**	**19.45**
	1.5	**−4.706**	**−13.92**	**10.819**	**12.48**
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	0.0	0.88	2.83	−5.18	−8.31
	0.5	−0.004	−0.01	0.019	0.03
	1.0	**2.752**	**8.32**	**−17.294**	**−21.18**
	1.5	**5.214**	**21.83**	**−27.842**	**−22.21**
Case No. 2 (3 specimens: No. 1, 2, and 3)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	0.0	−0.281	−0.90	−2.517	−4.04
	0.5	0.247	0.81	−0.544	−0.84
	1.0	**6.668**	**20.15**	**−27.769**	**−34.01**
	1.5	**9.920**	**41.54**	**−38.661**	**−30.84**

Note: in Tables 8–10, underlined red numbers show the worst case (extremely large differences in shear strength parameters, caused by different combinations of 3 specimens); no underlined red numbers show more favorable case, but there are still very large differences in shear strength parameters.

As can be seen in Tables 4–6, the values of the correlation coefficient R between shear stresses and normal stresses were high and the test results could be accepted since tests with only three specimens were in accordance with [12–16], where no prescribed value of the correlation coefficient was posted. As has been mentioned, many analyses in existing

research are carried out from data obtained from DST of only three specimens. However, various combinations of three specimens provided different results.

Table 9. Differences in shear strength parameters between various specimen combinations (soil CS1).

	Fibre Amount	Differences in Strength Parameters			
		φ		c	
	(%)	(°)	(%)	(kPa)	(%)
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 2 (3 specimens: No. 1, 2, and 3) (° or kPa, %)	**0.0**	**1.809**	**5.91**	**−4.155**	**−6.84**
	0.5	−0.429	−1.19	1.088	1.04
	1.0	0.31	1.19	−0.643	−0.56
	1.5	**−5.935**	**−28.07**	**10.987**	**10.30**
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	**0.0**	**4.47**	**16.01**	**−25.557**	**−31.10**
	0.5	1.132	3.29	−7.203	−6.38
	1.0	**2.484**	**10.45**	**−12.923**	**−10.24**
	1.5	2.387	18.62	−10.834	−8.43
Case No. 2 (3 specimens: No. 1, 2, and 3)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	**0.0**	**2.661**	**9.53**	**−21.402**	**−26.04**
	0.5	1.561	4.54	−8.291	−7.34
	1.0	2.174	9.15	−12.28	−9.73
	1.5	**8.322**	**64.90**	**−21.821**	**−16.98**

Table 10. Differences in shear strength parameters between various specimen combinations (soil CS2).

	Fibre Amount	Differences in Strength Parameters			
		φ		c	
	(%)	(°)	(%)	(kPa)	(%)
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 2 (3 specimens: No. 1, 2, and 3) (° or kPa, %)	**0.0**	**−6.714**	**−24.44**	**13.48**	**27.53**
	0.5	**−3.942**	**−11.44**	**9.262**	**18.95**
	1.0	−2.239	−5.72	6.035	18.74
	1.5	−0.605	−1.60	1.608	4.66
Case No. 1 (4 specimens: No. 1, 2, 3, and 4)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	**0.0**	**3.997**	**23.85**	**−19.045**	**−23.37**
	0.5	**2.436**	**8.68**	**−13.682**	**−19.05**
	1.0	0.043	0.12	−0.284	−0.74
	1.5	0.585	1.60	−3.914	−9.78
Case No. 2 (3 specimens: No. 1, 2, and 3)—Case No. 3 (3 specimens: No. 2, 4, and 4) (° or kPa, %)	**0.0**	**10.711**	**63.92**	**−32.525**	**−39.91**
	0.5	**6.378**	**22.72**	**−22.944**	**−31.94**
	1.0	2.282	6.19	−6.319	−16.41
	1.5	1.19	3.24	−5.522	−13.80

For example, for soil CI, see Table 4 (case No. 2, 1.5% fibres), based on the test results of the combination of specimens No. 1, 2, and 3, one can state that the angle of internal friction of soil with an amount of fibres of 1.5% was 33.803° and cohesion was 86.688 kPa. But based on the results from the combination of specimens No. 2, 3, and 4 (case No. 3), these values were 23.833° and 125.349 kPa. The differences were very high, up to 9.920° (41.54%) and −38.661 kPa (−30.84%), see underlined red number in Table 8 (Case No. 2 (three specimens: No. 1, 2, and 3)—Case No. 3 (three specimens: No. 2, 4, and 4)). The second largest differences were applied for 1% fibres: 6.668° (20.15%) and −27.769 kPa (−34.01%), see underlined red number in the immediate top line in Table 8.

Similar large differences could be also seen for soil CS1 and CS2, see Tables 9 and 10. Therefore, it is not recommended to carry out DST with only three specimens.

3.3. Uncertainty of Shear Strength Parameters

Values of the expanded uncertainties of the shear strength parameters are introduced in Table 4 (for soil CI), Table 5 (for soil CS1), and Table 6 (for soil CS2). In the mentioned tables, for every column, maximal absolute values of uncertainties are marked as red underlined numbers, maximal relative values of uncertainties are marked as italic red underlined numbers, minimal absolute values of uncertainties are marked as blue underlined numbers, and minimal relative values of uncertainties are marked as italic blue underlined numbers.

As can be seen in the tables, the lowest uncertainties were applied for DST with four specimens (case No. 1) and the highest uncertainties were applied for DST with three specimens (case No. 3). This fact supports the recommendation to not carry out DST with only three specimens, especially in the case of using DST to evaluate the rate of shear strength parameter improvement by various materials.

The values of the uncertainties of the shear strength parameters in case B (with covariances) were closest to the real uncertainties since covariances between correlated input quantities (normal stresses and shear stresses) were taken into account. In this case, for soil CI (see Table 4), the maximal absolute value of the uncertainty of the angle of internal friction $\max U(\varphi)$ was 0.876° (3.67%) and the minimal absolute value of the uncertainty of the angle of internal friction $\min U(\varphi)$ was 0.520° (1.62%). The maximal absolute value of the uncertainty of cohesion $\max U(c)$ was 3.466 kPa (2.77%) and minimal absolute value of the uncertainty of cohesion $\min U(c)$ was 1.604 kPa (2.81%). For soil CS1 (see Table 5), $\max U(\varphi)$ = 0.926° (3.57%), $\min U(\varphi)$ = 0.522° (1.61%), $\max U(c)$ = 4.050 kPa (3.59%), and $\min U(c)$ = 1.636 kPa (2.89%). For soil CS2 (see Table 6), $\max U(\varphi)$ = 0.726° (2.59%), $\min U(\varphi)$ = 0.442° (2.13%), $\max U(c)$ = 3.098 kPa (7.74%), and $\min U(c)$ = 1.250 kPa (2.00%). So, generally, in this study, the uncertainties of the angle of internal friction were under 1° and 4% and the uncertainties of cohesion were under 5 kPa and 8%. These values are not negligible and should be taken into account since, when evaluating improvement rate, the difference (improvement) in shear strength parameters should be larger than the uncertainties.

The uncertainties of the shear strength parameters in case C (worst-case estimated uncertainties) were very high. For soil CI (see Table 4), $\max U(\varphi)$ = 1.506° (4.46%) and $\max U(c)$ = 7.105 kPa (8.70%). For soil CS1 (see Table 5), $\max U(\varphi)$ = 1.684° (6.49%) and $\max U(c)$ = 8.132 kPa (7.20%), and for soil CS2 (see Table 6), $\max U(\varphi)$ = 1.268° (4.52%) and $\max U(c)$ = 6.646 kPa (17.25%). Therefore, it is not recommended to apply the worst-case estimation of uncertainty.

For easier comparison, differences in expanded uncertainty between various cases (case A: without covariance; case B: with covariance; and case C: worst-case) were calculated and are presented in Table 11 (for soil CI), Table 12 (for soil CS1), and Table 13 (for soil CS2). The manner of marking and colouring the numbers is the same as in the case of the numbers in Tables 4–6. As can be seen, for all soils, differences in expanded uncertainty between case B and case A were minimal, so covariances between correlated input quantities (normal stresses and shear stresses) had a negligible influence on result uncertainty. On the contrary, differences in expanded uncertainty between case C and case A and also between case C and case B were very high, even much more than 100% in many cases.

Table 11. Differences in expanded uncertainty between various cases (case A: without covariance; case B: with covariance; and case C: worst-case), soil CI.

Soil	Case No.	Fibre Amount	Differences in Expanded Uncertainty											
			Case B—Case A				Case C—Case A				Case C—Case B			
			ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)	
		(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CI (4 specimens; No. 1, 2, 3, and 4)	1	0.0	−0.004	−0.76	0.001	0.06	0.528	100.76	1.990	124.14	0.532	102.31	1.989	124.00
		0.5	−0.006	−1.12	0.001	*0.06*	0.536	100.37	2.012	124.27	0.542	102.65	2.011	124.14
		1.0	−0.002	−0.37	0.009	0.50	0.544	100.37	2.379	*131.36*	0.546	101.11	2.37	*130.22*
		1.5	−0.010	−1.68	0.018	0.95	0.616	*103.36*	2.331	122.94	0.626	*106.83*	2.313	120.85

Table 11. *Cont.*

Soil	Case No.	Fibre Amount	Differences in Expanded Uncertainty											
			Case B—Case A				Case C—Case A				Case C—Case B			
			ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)	
		(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CI (3 specimens; No. 1, 2, and 3)	2	0.0	−0.012	−1.63	−0.021	−1.21	0.562	76.57	2.004	115.11	0.574	79.50	2.025	117.73
		0.5	−0.014	−1.84	−0.030	−1.65	0.568	74.74	2.015	111.08	0.582	78.02	2.045	114.63
		1.0	−0.006	−0.83	−0.013	−0.64	0.556	76.80	2.416	118.72	0.562	78.27	2.429	120.13
		1.5	−0.014	−1.66	−0.028	−1.26	0.664	78.86	2.536	114.54	0.678	81.88	2.564	117.29
CI (3 specimens; No. 2, 3, and 4)	3	0.0	−0.010	−1.36	−0.036	−1.19	0.530	71.82	3.062	101.06	0.540	74.18	3.098	103.47
		0.5	−0.008	−1.09	−0.029	−0.97	0.518	70.38	3.132	104.50	0.526	72.25	3.161	106.50
		1.0	−0.010	−1.26	−0.032	−0.93	0.574	72.29	3.651	105.70	0.584	74.49	3.683	107.63
		1.5	−0.032	−3.52	−0.093	−2.61	0.594	65.42	3.190	89.63	0.626	71.46	3.283	94.72

Note: In Tables 11–13, for every column, maximal absolute values are marked as red underlined numbers, maximal relative values are marked as italic red underlined numbers, minimal absolute values are marked as blue underlined numbers, and minimal relative values are marked as italic blue underlined numbers. More information is introduced and commented in the paper.

Table 12. Differences in expanded uncertainty between various cases (case A: without covariance; case B: with covariance; and case C: worst-case), soil CS1.

Soil	Case No.	Fibre Amount	Differences in Expanded Uncertainty											
			Case B—Case A				Case C—Case A				Case C—Case B			
			ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)	
		(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CS1 (4 specimens; No. 1, 2, 3, and 4)	1	0.0	−0.004	−0.76	0.002	0.12	0.540	102.66	1.982	121.30	0.544	104.21	1.980	121.03
		0.5	−0.012	−1.89	0.005	0.22	0.642	101.26	2.708	120.62	0.654	105.14	2.703	120.13
		1.0	−0.020	−3.13	0.005	0.25	0.650	101.88	2.242	112.27	0.670	108.41	2.237	111.74
		1.5	−0.028	−4.93	0.019	1.12	0.564	99.30	1.832	108.21	0.592	109.63	1.813	105.90
CS1 (3 specimens; No. 1, 2, and 3)	2	0.0	−0.008	−1.11	−0.010	−0.58	0.594	82.27	2.093	120.43	0.602	84.31	2.103	121.70
		0.5	−0.022	−2.40	−0.049	−1.91	0.692	75.38	2.799	109.38	0.714	79.69	2.848	113.47
		1.0	−0.034	−3.54	−0.058	−2.50	0.724	75.42	2.439	105.04	0.758	81.86	2.497	110.29
		1.5	−0.042	−4.58	−0.068	−3.24	0.652	71.02	2.068	98.66	0.694	79.22	2.136	105.33
CS1 (3 specimens; No. 2, 3, and 4)	3	0.0	−0.022	−2.75	−0.083	−2.60	0.582	72.75	2.788	87.48	0.604	77.63	2.871	92.49
		0.5	−0.020	−2.22	−0.070	−1.70	0.620	68.89	4.012	97.38	0.604	72.73	4.082	100.79
		1.0	−0.038	−4.11	−0.112	−3.10	0.608	65.80	3.047	84.36	0.646	72.91	3.159	90.26
		1.5	−0.044	−5.51	−0.099	−3.40	0.510	63.91	2.424	83.21	0.554	73.47	2.523	89.66

Table 13. Differences in expanded uncertainty between various cases (case A: without covariance; case B: with covariance; and case C: worst-case), soil CS2.

Soil	Case No.	Fibre Amount	Differences in Expanded Uncertainty											
			Case B—Case A				Case C—Case A				Case C—Case B			
			ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)		ΔU(φ)		ΔU(c)	
		(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)	(°)	(%)	(kPa)	(%)
CS2 (4 specimens; No. 1, 2, 3, and 4)	1	0.0	−0.008	−1.78	0.014	1.13	0.454	100.89	1.594	128.96	0.462	104.52	1.58	126.40
		0.5	−0.004	−0.78	0.007	0.46	0.514	100.39	2.006	130.68	0.518	101.97	1.999	129.64
		1.0	−0.002	−0.40	0.003	0.19	0.482	96.79	2.144	133.25	0.484	97.58	2.141	132.82
		1.5	−0.002	−0.40	0.001	0.06	0.484	97.19	2.107	130.63	0.486	97.98	2.106	130.48
CS2 (3 specimens; No. 1, 2, and 3)	2	0.0	−0.008	−1.20	−0.016	−1.08	0.516	77.25	1.715	116.19	0.524	79.39	1.731	118.56
		0.5	−0.006	−0.85	−0.014	−0.80	0.540	76.70	2.049	117.62	0.546	78.22	2.063	119.39
		1.0	−0.040	−0.60	−0.010	−0.57	0.526	84.57	2.052	117.66	0.490	74.47	2.062	118.92
		1.5	−0.002	−0.30	−0.008	−0.47	0.500	75.53	2.040	119.58	0.502	76.06	2.048	120.61
CS2 (3 specimens; No. 2, 3, and 4)	3	0.0	−0.018	−2.78	−0.045	−1.95	0.460	70.99	2.255	97.49	0.478	75.87	2.300	101.41
		0.5	−0.010	−1.36	−0.030	−1.03	0.532	72.28	3.058	105.23	0.542	74.66	3.088	107.37
		1.0	−0.002	−0.29	−0.007	−0.23	0.509	74.52	3.559	115.29	0.511	75.04	3.566	115.78
		1.5	−0.002	−0.29	−0.010	−0.32	0.498	72.17	3.453	111.10	0.500	72.67	3.463	111.78

It was found that, in this study, correlation coefficient $r(\sigma_i, \sigma_j)$ had a value of 0.80095, $r(\sigma_i, \tau_j)$ had a value of 0.42487, and $r(\tau_i, \tau_j)$ had a value of 0.22537. Covariance between correlated input quantities (normal stresses and shear stresses) decreased the uncertainties of the angle of internal friction and increased the uncertainties of cohesion for all tested soils in the case of DST using all four specimens (see differences in expanded uncertainty

in columns "Case B—Case A" in Tables 11–13). In the case of DST using three specimens, covariance decreased the uncertainties of the angle of internal friction and decreased the uncertainties of cohesion for all tested soils (see differences in expanded uncertainty in columns "Case B—Case A" in Tables 11–13). However, the changes were very small (the largest change in φ was −0.044° (−5.51%), see Table 12, CS1, Case 3) and had no impact on geotechnical design since the obtained values of the shear strength parameters from DST should be rounded (e.g., according to [17,18], the obtained value of the angle of internal friction φ should be rounded to 0.1° and the value of cohesion c should be rounded to 1 kPa).

4. Discussion

The obtained values of the shear strength parameters of soils CI and CS1 improved with fibres TEXZEM PES 200, showing significant improvement. Similarly as in previous studies [18–20], the optimal amounts of fibres were 0.5% or 1%, depending on the type of soil. In the case of soil CS2, even if there was no simultaneous increase in both shear strength parameters, it is proposed that, in many cases, regarding subsoil bearing capacity, slope stability, and soil pressure, an increase in the angle of internal friction of soil CS2 by 9.755° (47.00%) and decrease in cohesion by 4.293 kPa (6.88%) can be considered as an improvement. However, a calculation check is required. It is also necessary to note that the mentioned improvement only applies to the cases of static loads. In the cases of dynamic loads induced from, e.g., urban vibration, industrial machinery, earthquakes, wind loads, and sea waves, among others [27], further tests should be carried out. In any case, based on the findings presented in [27], the issue regarding the specific strain level required for mobilisation of the tensile strength of the fibers should be investigated.

The SEM images taken in this study showed visible scratches on the fibre surface, which were present not only locally but also along the fibre's longitudinal direction on the surface, similarly as presented in [24]. It can also be proposed that this may result from the plowing of angular hard particles into the fibre body during the shear process, due to the suitable scratch resistance of the tested fibres. The SEM images also confirmed the conclusion presented in [25] that soil properties are very important since the surfaces of the fibres were very different after shearing in soil CI and CS1. The contact area between the soil and fibres is also important since, as can be seen in [26], higher consolidation stress makes the tested material denser with less pores of smaller size. So, it is proposed that higher normal stress provides larger contact area between the soil and fibres compared to lower normal stress; therefore, in the case of higher normal stress, there are more scratches of larger depth. However, the issues presented above are very complex and require further study. It is planned to test the same soil with fibres TEXZEM PES 200 and other fibres.

In this study, the minimal uncertainty of the angle of internal friction φ was 0.422° (see expanded uncertainty with covariance in Table 6; 0% fibres; four specimens) and the minimal uncertainty of cohesion c was 1.250 kPa (see expanded uncertainty with covariance in Table 6; 0% fibres; four specimens). When comparing improvement, the difference between two cases should be calculated and the difference (improvement) should be larger than the sum of the uncertainties of two cases, e.g., larger than 2.0.422° = 0.844° and 2. 1.250 kPa = 2.500 kPa. In this study, the differences should be larger than the mentioned values 0.844° and 2.500 kPa since the values of 0.422° and 1.250 kPa were minimal (specific values to be compared are calculated and presented in the Section 3.1). It is therefore useful to check if the difference (improvement) in shear strength parameters of 0.5° [1]; 0.1° and 0.4°, 0.2 kPa [3]; −0.17° and −0.45° [4]; 0.3° and 0.5° [6] can be confirmed based on result uncertainty analysis.

Taking into account the above-mentioned values of 0.422° and 1.250 kPa, in our opinion, it would also be useful to determine the uncertainty of the shear strength parameters presented in [11] with 2 digits after the decimal (values of φ from 8.66° to 32.16°, with mean and median values of 18.73° and 17.70°, and values of c from 1.74 to 38.95 kPa, with a mean of 20.77 kPa and a median of 20.91 kPa), which were used as guide values for the pre-

diction of soil shear strength parameters using combined data and three different machine learning models.

It was found that in DST, correlation coefficients between normal stresses and shear stresses can be determined precisely since they are calculated using the same shear surface. Correlation coefficient r(σi,σj) had a value of 0.80095, r(σi,τj) had a value of 0.42487, and r(τi,τj) had a value of 0.22537. These values enabled a more precise determination of the uncertainty of shear strength parameters by considering the covariance between normal stresses and shear stresses, so it does not call for the worst-case strategy to be applied, implying totally negative error correlation so increasing uncertainty by up to 28% [22].

Since in practice, in some cases, the worst-case strategy, considering the linearly added uncertainty contributions $c(\sigma_i).u(\sigma_i)$ and $c(\tau_i).u(\tau_i)$ and not considering correlation coefficients, can be accepted, the magnitude of the uncertainty for this case was also explored. It was found that, in DST, this procedure gave very high uncertainty and, in many cases, it was higher than 100% in comparison with the uncertainty considering squared uncertainty contributions $c(\sigma_i).u(\sigma_i)$ and $c(\tau_i).u(\tau_i)$ and the real obtained correlation coefficients presented above. The maximal relative differences were 109.63% for φ (see Table 12; CS1; Case C—Case B; Case 1) and 132.82% for c (see Table 13; CS2; Case C—Case B; Case No.1). The minimal relative differences were still very high, which were 71.46% for φ (see Table 11; CI; Case C—Case B; Case 3) and 89.66% for c (see Table 12; CS1; Case C—Case B; Case No.3). Therefore, this procedure is highly not recommended.

5. Conclusions

From the obtained results, the following conclusions can be made:

1. The tested fibres improved the soil shear strength parameters differently; both the angle of internal friction and cohesion were increased for soil CI using 1.0% fibres and for soil CS1 using 0.5% fibres. For soil CS2, the angle of internal friction increased but cohesion decreased.
2. SEM is a useful tool for exploring the fibre surface after shearing. Suitable fibre scratch resistance can significantly increase the shear strength parameters, but there are additional fibre properties contributing to the improvement rate, such as fibre surface roughness, adhesion of soil particles to the fibre surface, etc., which requires further study.
3. It is not recommended to carry out DST with only three specimens since different combinations of three specimens provide different results.
4. Improvement rates of shear strength parameters of soil using various materials require determination of their uncertainty so that the improvement can be confirmed. Determination of the uncertainty of shear strength parameters is also important in the case when they are used as guide values for the prediction of soil shear strength parameters using machine learning models.
5. In this study, correlation coefficients between normal stresses and shear stresses existed and were not negative. Covariance between normal stresses and shear stresses has a negligible influence on shear strength parameter uncertainty.
6. The worst-case strategy, considering linearly added uncertainty contributions $c(\sigma_i).u(\sigma_i)$ and $c(\tau_i).u(\tau_i)$ and not considering correlation coefficients, provides too high uncertainty and is not recommended.
7. This study also has various limitations. The tests were carried out only for clayey soils with insufficient shear strength. It will be useful to carry out further tests for silty soils and sandy soils.
8. A further limitation of this study is the focus of the research only on shear strength parameters, without dealing with deformation properties. Since soil mixed with fibres can be compacted to reach a maximum dry soil density obtained from a standard Proctor test, it is proposed that there will not be a problem with excessive deformation. It is planned to carry out an oedometer test of soil mixed with fibres using an

oedometer with a diameter of 30 cm so that the deformation in practical applications can be quantified.

9. This study presents the results of laboratory tests where the preparation of specimens can be different from the preparation of soil in practical applications. Using a modern soil stabiliser with a powerful milling and mixing rotor can minimise the difference. In the case of soil where the preparation of soil in practical applications does not provide similar conditions as in the laboratory, verification using in situ testing is required.

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