Reinforcing of Sand With 3D Printed Fibres – Review of Properties, Fabrication of Fibres and Initial Testing Programme

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Abstract. Fibre reinforcement is an effective method of soil improvement that presents an alternative solution to other more common methods of ground reinforcement, such as mechanical stabilization by geosynthetics (geogrids, geotextiles, geocomposites, etc.). Research activities in this area are being carried out, but the main disadvantage of currently used fibres is their uniform cross-section and usually smooth surface given by available production methods. This study presents an alternative way of fabrication of synthetic fibres – utilization of fused deposition modelling (3D printing). With the rapid development in commercially available 3D printing techniques, it is now possible to refine the shape and dimensions of the 3D printed objects to a tenth of a millimetre. The review of the basic index and mechanical properties of fibre-reinforced soils is presented in the first part of the paper. The second part is devoted to the description of the production process of fibres including the suitability analysis of materials used for 3D printing. Finally, the initial testing programme of fibre-reinforced non-cohesive soil is presented. The preformed laboratory test confirmed that the inclusion of 3D printed fibres led to a significant increase in shear strength. Examination of samples after tests did not reveal breakage of fibres, thus the fibres pull-out was the governing failure mode.

1. Introduction
Fibre reinforcement of construction materials is a well-known technology [1-5]. In ancient times, the wheat straw or other organic fibres were added to soil/clay to increase the strength parameters of bricks [6]. Nowadays the most common application of the fibre reinforcing is in concrete structures. Thin metal wires with various shapes enhanced the tensile strength and ductility of concrete and eliminate cracking of concrete during shrinking [7].

The influence of fibres on the mechanical behaviour of soils has been studied by many researchers. Gray and Ohashi [4] analysed the influence of different types of fibres (natural/synthetics/metal) on the shear strength of non-cohesive soils using the shear box apparatus. This study also involves the limit equilibrium model to quantify the strength increase of the fibre-soil composite. Drained triaxial compression tests of fibre-soil composite with polyamide, steel and polypropylene fibres were conducted by Michalowski and Čermák [8]. Fine and medium sands were tested. Different fibre concentrations varying between 0.5% to 2% were used. As much as 70% increase in peak strength was achieved at fibre concentration of 2%. Wei [9] utilized wheat and rice straw, jute and polypropylene...
fibres in the testing programme. The uniaxial compressive strength of fibre-soil composite with polypropylene fibres was about 125% higher than of unreinforced soil. Noozrad and Zarinkolaei [10] in their study used polypropylene fibres mixed with sand. In total 40 direct shear box tests and 40 triaxial tests were performed.

A common feature of fibres used for soil reinforcement is their uniform cross-section, straight shape, and smooth surface in most cases. These attributes have an adverse effect on the pull-out capacity of fibres and thus more complex geometry of fibres would be favourable. This paper presents an alternative way of fabrication of synthetic fibres – utilization of fused deposition modelling (3D printing). Using this technology, it is now possible to freely modify the shape of the resulting products to a tenth of a millimetre and thus optimize the shape of fibres to increase their pull-out capacity. A nomenclature and a basic review of the index and the strength properties of fibre-reinforced soils are stated in the second chapter. The process of fibres fabrication is described in detail in the third chapter. Finally, the results of a series of drained triaxial tests are presented and analysed in the fourth chapter. The effect of fibres addition is quantified in terms of shear strength and ductility change.

2. Characterization of fibre-reinforced soil composite

2.1. Phases and index properties of fibre-reinforced soil
A fibre-reinforced soil is a composite material (figure 1), which in general consists of three phases (gas, liquid, solid). The solid phase involves two components: fibre solid and soil solid. An element of fibre-reinforced soil together with symbols of necessary variables is shown in figure 1.

\[
e = \frac{V_v}{V_s} = \frac{V_v}{V_s^s + V_f^s}
\]
The concentration (weight fraction) $p_f$ (2) and volumetric content of fibre $p_{v,f}$ (3) defines the contribution of fibres in a composite. The expression for the volumetric fibre content is modified in this study by replacing the total volume of composite $V$ with the volume of soil solids $V_s$ (4).

$$p_f = \frac{m_f}{m_s}$$

$$p_{v,f} = \frac{V_f}{V} = 1 - \frac{V_s + V_v}{V}$$

$$p_{v,f}^* = \frac{V_f}{V_s}$$

Fibres geometry (assuming cylindrical cross-section) is described by the aspect ratio $\eta$ (5) where $l$ is the length of the fibres and $r$ is its diameter.

$$\eta = \frac{l}{2r}$$

2.2. Models for determination of the shear strength of fibre-reinforced soil

Computational models quantifying the shear strength properties of fibre-reinforced soil might be divided into three groups:

- Models based on limit equilibrium methods in which equilibrium conditions between shear stress acting of the surface of fibre and internal tensile stresses are formulated. Gray and Ohashi [4] proposed the (6), where $\Delta S_R$ is the shear strength increase due to soil reinforcement, $t_r$ is the mobilized fibre tensile stress, $i$ is the initial orientation of fibres, $x$ is the horizontal displacement on a slip surface, $z$ is the thickness of a slip surface.

$$\Delta S_r = t_r [\sin(90 - \psi) + \cos(90 - \psi) \tan \varphi]$$

$$\psi = \tan^{-1} \left[ \frac{1}{z^r (\tan^{-1} i)^{-1}} \right]$$

- The mechanical behaviour of fibre-reinforced soil is described by one “composite” parameter. Michalowski, Čermák [8] utilized a homogenization technique and derived the expression (8) for the macroscopic angle of internal friction $\bar{\varphi}$ in triaxial conditions, where $K_p = \tan^2 \left( \frac{\pi}{4} + \frac{\varphi}{2} \right)$, $M = K_p \sin \theta_0$, $\theta_0$ is the angle of the surface between fibres in compression and tension.

$$\bar{\varphi} = 2 \tan^{-1} \left[ \frac{\rho \eta M \tan \varphi + 6 K_p}{6 - \rho \eta M \tan \varphi} \right]$$

- Individual quantification of shear strength of unreinforced soil and fibre-distributed tension. Based on this framework, Zornberg [11] proposed the failure criteria as follows:

$$S_{eq} = S + \alpha t = c + \sigma_n \tan \varphi + \alpha t$$

Where $S_{eq}$ is the equivalent shear strength of reinforced soil, $S$ is the shear strength of unreinforced soil, $t$ is the fibre induced tension, $\alpha$ is the empirical coefficient that accounts for the orientation of the fibres and $c, \varphi$ are the shear strength parameters of the unreinforced soil. The proposed failure criterion is bilinear (figure 2).
Failure surface of reinforced soil

Under lower confining pressures, the fibre induced tension is governed by the pullout of the fibres (10), where \( c_{l,c}, c_{l,\varphi} \) are the interaction coefficients and \( \sigma_{n,ave} \) is the average normal stress acting on the fibres.

\[
t = p_{v,f} \eta \left( c_{l,c} c + c_{l,\varphi} \tan \varphi \sigma_{n,ave} \right)
\]  

Under higher confining pressures, the fibre induced tension is limited by yielding of the fibres (11), where \( \sigma_{f,ult} \) is the ultimate tensile strength of fibres.

\[
t = p_{v,f} \sigma_{f,ult}
\]  

3. Fabrication of fibres utilizing Fusion Deposition Modelling (FDM)

3.1. Design the fibres

Two types of fibres were analysed in this study:

- Straight fibres (figure 3a) with a uniform cross-section. The fibres are 20 mm long, their width and height are 1 mm and 0.48 mm, respectively. These fibres are being used as reference ones to be able to quantify the influence of different shapes. Technological aspects and settings of a 3D printing process were fine-tuned on this type of fibre.

- Profiled fibres (figure 3b) which were based on steel fibres used in concrete engineering. The width (1 mm) and height (0.48 mm) are the same as for the straight fibre. However, their length (18.75 mm) is shorter to maintain the same volume of individual fibres and thus the same number of fibres in tested samples.
An important technological task was the manufacturing of the fibres. The commercially available 3D printer, Original Prusa I3 MK2.5S [12] was utilized. PET-G (Polyethylene terephthalate glycol) was chosen as printing material. Comparison with other types of printing materials (Acrylonitrile butadiene styrene - ABS, Polylactic acid - PLA, Polypropylene – PP) is stated in table 1 [13]. PET-G is a modified PET with added glycol to decrease the melting temperature and to achieve higher ductility. Printability is comparable to PLA and the tensile strength is about 50 MPa. Compared to PLA, it is more flexible and the price is also favourable.

### Table 1. Summary of material properties

| Material | Tensile strength [MPa] | Stiffness | Durability | Density [g/cm³] | Printability | Price [a] |
|----------|------------------------|-----------|------------|-----------------|--------------|-----------|
| ABS      | 40                     | Mid       | High       | 1.04            | Poor         | $10 – 40  |
| PLA      | 65                     | High      | Mid*       | 1.24            | Very good    | $10 – 40  |
| PET-G    | 50                     | Mid       | High       | 1.23            | Very good    | $20 – 60  |
| PP       | 32                     | Mid       | High       | 0.9             | Poor         | $60 - 120 |

* When exposed to UV or thermal radiation

The 3D printers are usually driven by so-called “G-code”. That is a set of commands which are prepared in software called “Slicer” from three-dimensional models presented above. The 3D printer contains predefined printing profiles (settings) for a variety of materials and nozzles. The G-code generation is controlled by these profiles. However, the predefined profiles are not designed for printing as many small objects as fibres are. A customized printing profile was therefore prepared with the following main changes:

- Reduction of the printing temperature to eliminate the formation of thin webs of plastic material under the nozzle when the extruder moves from one position to the other.
- The retraction was decreased. Too long retraction might result in gaps in fibres because melted material did not extrude properly.
- The printing fan was turned off to achieve better adhesion between layers.
• Usage of the nozzle with a diameter of 0.25 mm to achieve higher precision. With this nozzle, it is possible to manufacture fibre with a width of 0.48 mm, when melted plastic is placed in two passes alongside. The stability of the fibre was higher and the overlaying layers did not disturb the layers below.

• Optimization of deployment of fibres on the printing area to maximize their number. The standard deployment process of articles in “Slicer” was bypassed to increase manufacturing productivity. Up to 1900 and 1300 pieces of straight and profiled fibres, respectively, were manufactured in one set-up (figure 4a).

![Fabricated fibres and fibre-soil mixture](image)

Figure 4. Printing and mixing of fibres

4. Initial testing program
A series of consolidated drained triaxial test was performed. The diameter and height of the tested samples were 50 mm and 100 mm, respectively. Three samples were tested:

- without fibre reinforcement,
- with straight fibres and volumetric fibre content $p_{v,f}^* = 4\%$,
- with profiled fibres and volumetric fibre content $p_{v,f}^* = 4\%$.

The samples were prepared (figure 4b, 5a) at the maximum dry unit weight ($\gamma_{d,max} = 20.06 kN/m^3$) as determined from the standard Proctor test. To achieve the same dry unit weight and thus the same void ratio in all three samples as precisely as possible, compaction of samples was divided into 5 layers. Compaction of the last (topmost) layer was further divided into 4 sub-stages to prevent the soil from falling out of the mould. In the first stage of tests, samples were saturated firstly by water percolation than followed by a gradual increase of back-pressure. After completing the saturation, the samples were consolidated in two steps to effective mean stress $p' = 150 kPa$. Displacement controlled loading was applied during shearing. The strain rate was determined according to ČSN EN ISO 17892-9 and further reduced to 0.025 mm/min. Lower than required displacement rate allowed better equalizing of pore pressures and thus maintaining the effective stress uniformity during shearing. Volumetric changes of the sample were recorded via the volumetric changes of water in the backpressure pump. The area correction according to (12) was applied instead of the more standard assumption that sample deforms as a right cylinder. $A_0$ is the initial cross-sectional area, $\varepsilon_a$ and $\varepsilon_v$ are the axial and radial strain, respectively. The equation (12) is valid for complete fixity at the ends of the sample and parabolic lateral strain profile.
\[ A = A_0 \frac{1-\varepsilon_f}{1-\varepsilon_a} \left( 2 - \frac{1-\varepsilon_a}{1-\varepsilon_f} \right) \] (12)

5. Results and discussion
The results of tests are presented in form of axial strain – stress deviator curves (figure 6a), effective stress paths with corresponding secant peak angles of internal friction (figure 6b), axial strain – volumetric strain curves (figure 6c).

(a) sample preparation  (b) sample after failure

**Figure 5.** Drained triaxial tests of fibre-reinforced soils
The improvement in shear strength due to the inclusion of synthetic fibres is quantified in table 2 according to [3] in terms of the following variables:

- Deviator stress improvement factor at failure $I_{df}$ (13), where $(\sigma_1 - \sigma_3)_{pu}$ and $(\sigma_1 - \sigma_3)_{pR}$ are the peak (failure) deviator stress of the unreinforced and reinforced soil specimen, respectively.

$$I_{df} = \frac{\Delta (\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)_{pu}} = \frac{(\sigma_1 - \sigma_3)_{pu} - (\sigma_1 - \sigma_3)_{pR}}{(\sigma_1 - \sigma_3)_{pu}} = 1$$ (13)

- Deviator stress ratio at failure $DSR_f$ (14).

$$DSR_f = \frac{(\sigma_1 - \sigma_3)_{pR}}{(\sigma_1 - \sigma_3)_{pu}}$$ (14)

- Brittleness index $I_b$ (15) which is a measure of the post-peak strain-softening rate. The ultimate deviator stress $(\sigma_1 - \sigma_3)_{ult}$ corresponds to the axial strain $\varepsilon_a = 9\%$ due to membrane puncture in the second test shortly after reaching this strain level.

$$I_b = \frac{(\sigma_1 - \sigma_3)_{pu} - (\sigma_1 - \sigma_3)_{ult}}{(\sigma_1 - \sigma_3)_{ult}} = \frac{(\sigma_1 - \sigma_3)_{pR}}{(\sigma_1 - \sigma_3)_{ult}} - 1$$ (15)

The addition of straight fibres led to an increase in the peak deviator stress by 63%. Modification of the shape of fibres from straight to the profiled ones further increased the improvement factor $I_{df}$ by 25%. Compared to the unreinforced sample, the total increment in the peak shear strength when using profiled fibres is 88%. No fibre ruptures were detected during the post-inspection of the samples. The second positive effect of fibre reinforcement is the reduction of the rate of post-peak softening quantified by the brittleness index $I_b$ from 0.15 (unreinforced) to 0.04 (straight reinforcement) and 0.02 (profiled reinforcement). The addition of fibres had an adverse effect on the initial stiffness. This phenomenon is being further studied and must be confirmed by additional tests. Similar behaviour was however observed in the case of fine sands reinforced by polyamide fibres [8]. No stiffness reduction was recorded when steel fibres were used. Thus, the initial stiffness of composite is probably significantly affected by the stiffness properties of fibres. Differences in the initial stages of stress-strain behaviour might also be caused by the lower local degree of compaction in the vicinity of

![Figure 6. Results of drained triaxial tests](image)
fibres. This assumption is supported by the fact that higher positive volumetric compression (contraction) during shearing was detected in the case of reinforced samples. The rate of negative volumetric changes (dilatation) of the sample with profiled fibres is higher compared to that with straight fibres. A certain analogy to this behaviour might be found in the shear-strength behaviour of rock joints [14] which is strongly dependent on the roughness of the joint surface given by height and length of asperities on it. The higher the roughness is, the higher the dilatancy angle and the shear strength of the joint is reached. The difference between these two cases is that fibres have significantly lower Young modulus and higher ductility compared to rock asperities and thus they might be strained (reshaped) during loading.

| Table 2. Drained triaxial tests results |
|----------------------------------------|
| ID          | Reinforcement | $p^*_{v,f}$ [%] | $(\sigma_1-\sigma_3)_p$ [kPa] | $(\sigma_1-\sigma_3)_\%$ [kPa] | $I_{df}$ [-] | DSR$_f$ [-] | $I_b$ [-] |
| Tr-I        | -             | 0              | 572.6                          | 496.3                          | -           | -           | 0.15   |
| Tr-II       | straight      | 4              | 932.2                          | 893.4                          | 0.63        | 1.63        | 0.04   |
| Tr-III      | profiled     | 4              | 1075.6                         | 1052.1                         | 0.88        | 1.88        | 0.02   |

6. Conclusions
A novel application of the fusion deposition modelling (3D printing) for the fabrication of fibres with variable shapes was presented in the paper. The series of drained triaxial tests revealed that the variation of the shape of fibres led to a further increase in the soil shear strength and reduction of the rate of the post-peak strain softening compared to the soil reinforced with straight fibres. The initial stiffness of the soil-fibre composite was lower compared to the unreinforced soil. This is due to the lower stiffness of the fibre material compared to the soil itself and probably due to the lower degree of compaction in the vicinity of fibres. Further mechanical tests with other shapes, contents of fibres and test settings are being carried out.

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