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Research paper

Effect of polypropylene fibres on the shear strength of fine-grained soil

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Abstract: This paper presents the results of shear strength tests of fine-grained soil reinforced by randomly oriented fibres. The tests were carried out in a direct shear apparatus on samples with a diameter of 100 mm and a height of 20 mm. The samples were formed directly in the apparatus box at a natural moisture content and two values of the degree of compaction (I_S = 0.79 and 0.90). The studies were carried out for samples of natural moisture content and for soaked ones. The two types of polypropylene fibres were used: monofilament and fibrillated (of traded names Fibermesh 300-e3 and SikaCem Fiber-12, respectively). The fibre content was 0.25; 0.50 and 1.00% by the weight of the dry soil. The results showed that the presence of fibre within the soil increased its the shear strength. The improvement of the shear strength was related to the type of reinforcement, its content and the soil parameters. The maximum increase in shear strength was 47% compared to the shear strength of the unreinforced soil. The increase in shear strength values were related mainly to the increase in the angle of internal friction of the soil. It was found that as the degree of compaction of the soil increases, the higher enhance of the shear strength of reinforced soil occurs. It was also found that the improvement of shear strength of reinforced soaked samples was more significant than for un-soaked ones.

Keywords: cohesive soil, polypropylene fibres, shear strength, soil reinforcement

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1. Introduction

The possibility of using soils in earthworks is mainly determined by their mechanical properties, which have an impact on the deformation, bearing capacity of the building ground or slope stability of excavation and embankment slopes as well as natural slopes. The development of the construction industry and the limited availability of areas characterised by favourable geotechnical conditions often result in the need to improve the geotechnical properties of the subsoil.

One of popular methods of soil improvement of geotechnical parameters of the soil is its reinforcement, which involves the inclusion of high tensile strength elements within the soil. The reinforcement is able to transmit tensile forces and as a result reduces deformation of earth-made constructions as well as improves their stability. Soil reinforcement was introduced into geotechnics in the 1960s and is now one of the commonly used methods of soil reinforcement in earth structures. This reinforcement is usually used in the form of systemically spaced sheets or strips of metal, geosynthetic materials or natural origin.

A relatively new and innovative technique of soil reinforcement is dispersed reinforcement, which consists in randomly placing short fibres of natural or synthetic origin in the soil. This solution is relatively often used in concrete to reduce shrinkage cracks, but there are also known cases of the use of these types of fibres for soil reinforcement in real earth-made structures [1, 2]. The effect of fibres use within the soil is similar to the behaviour of plant roots [3, 4]. The randomly oriented fibres enhance the soil strength isotropically, and thus prevents the formation of weakening planes that can develop in a plane parallel to the arrangement of reinforcement strips [5].

The reinforcing material can be monofilament or fibrillated fibres of varying structure, either of natural origin or made from plastic or metal. The first studies and theoretical basis for the description of soil-fibre interaction are provided by publications of Wu [6], Waldron [7] or Gray and Ohashi [8]. The latter work analysed the effect of natural and synthetic fibres, as well as their area ratio, stiffness or orientation relative to the shear plane, on the shear strength of loose and dense sand. Studies have shown that the presence of fibres in a soil can increase its shear strength and modify its stress-strain behaviour. Some studies (e.g. [5, 9–11]) refer to the role of fibres in granular soils and confirm the effect of fibre inclusions on increasing shear strength. Maher and Ohashi [5] tests revelead that the increase in strength and stiffness of sands is a function of their granulometry and fibre properties. They also showed, that sand-fibre composites can have either a curved linear or a bilinear failure envelope, with the breaking point occurring at a threshold confining stress. Michalowski and Cermak [11] proved, that the length of the fibres has to be at least 10 times larger than the size of the grains, otherwise the sand-fiber interaction is not activated.

Work showing the use of randomly oriented fibres to increase the shear strength of cohesive soils generally appears in the present century (e.g. [12–17]). The Casagrande et al. [13] have performed ring shear tests for a bentonite. They have shown that the inclusion of fibres increased the peak shear strength of the soil. On the other side, the increase in strength deteriorated at large displacements and the residual shear strengths of non-reinforced and fibre-reinforced bentonite were similar. Tang et al. [16] present the results of cohesive soil reinforced with propylene fibres subjected to a 14-day curation period. They showed that with the increase of reinforcement addition, the values of the angle of internal friction as well as cohesion increase, with the increase in the latter parameter being greater.

A significant increase in the number of publications on the use of randomly oriented fibres in cohesive soils occurred after 2010. In a significant proportion of these publications, the soil is reinforced by fibres of natural origin (e.g. [18–21]) and man-made fibres (e.g. [22–26]), mainly polypropylene. In a significant part of the research, soil samples are very often formed at an optimum moisture content close to or corresponding to the value of the its maximum dry density. In the literature, however, there is a lack of information on the properties of the shear strength parameters of cohesive soils determined at conditions where values of degree of compaction which are lower than those required for earth engineering structures (e.g. natural slopes or riverbanks) and the soil is saturated or close to saturation state.

The aim of this study was to determine the effect of the addition of two different types of polypropylene fibres and the soaking process on the shear strength of a typical cohesive soil found the Wielickie Foothills (the Outer Carpathians, Poland).

2. Methodology of tests

The study included the determination of the basic geotechnical properties of the soil (grain-size distribution, consistency limits, compaction parameters - Proctor method). In turn, the main scope of research were shear strength tests in direct shear apparatus. These tests were carried out on samples with a diameter of 100 mm and a height of 20 mm.

All samples were prepared at natural soil moisture and each sample was prepared separately. The fibre content in the soil was calculated as the ratio of fibre weight to dry soil weight. Fibres were added to the prepared soil sample and mixed by hand. The mixing process was carried out until a homogeneous distribution of fibres in the soil was achieved. The mixture was then poured into a shear box and compacted in one layer by tamping until the desired degree of compaction was achieved.

The samples were sheared at two degree of compaction index values (I_S = 0.79 and 0.90). Both values of degree of compaction values were in the range of dry density values of the soil samples determined in the field tests. In each series of tests, the specimens were consolidated for 60 min at a normal stress of 25, 50, 75, 100, 125 kPa and then sheared at a rate of 0.1 mm·min^{-1} until 18% relative strain was achieved. Tests were carried out for un-soaked and soaked samples. The fibres content was 0.25; 0.50 and 1.00%.

In analysis of the test results, the effect of fibre inclusion on the shear strength of the soil was evaluated using the shear strength ratio [25]:

$$R_{SP} = \frac{\tau_{pr}}{\tau_{ps}} \tag{2.1}$$

where: τ_{ps} – shear strength of unreinforced soil, τ_{pr} – shear strength of fibre-reinforced soil.

To analyse the influence of fibres on the post-failure of the soil, the modified form of Bishop's brittleness index [27] was used:

$$I_B = \frac{\tau_{\text{peak}}}{\tau_{\text{res}}} - 1 \tag{2.2}$$

where: $\tau_{\max}$ – peak (maximum) shear strength of the soil, τ_{res} – residual shear strength of the soil (obtained at 18% relative displacement).

The higher the value of the index, the higher reduction of the post-peak shear strength a soil presents. In turn, a parameter value equal to 0 means that the shear of the specimen corresponds to ductile behaviour and the peak shear strength is achieved at the end of the test.

For each series of tests, the values of the angle of internal friction and the cohesion were calculated using the least squares method. Data processing and visualisation of the test results were carried out in the Python programming language using the following libraries:

– *matplotlib* [28] and *seaborn* [29]; the libraries were used for visualization of data,
– *numpy* [30], *pandas* [31] and *Scipy* [32]; the libraries were used for data processing and computing of shear strength parameters.

A total number of 128 samples were tested; some samples were repeated, but all samples were included in the analysis of the test results.

3. Materials

The studies were carried out on soil coming from the surficial layer of slope located in Winiary near Gdów (małopolskie voivodeship). Numerous mass movements occurred in this locality in 2010, which caused damage to nearby residential buildings. In geotechnical terms [33], the studied soil (Table 1) can be classified as silty clay of an average plasticity.

The reinforcement of the soil were two types of polypropylene fibres (Fig. 1) of traded names: Fibermesh 300-e3 and SikaCem Fiber-12. Fibermesh fibres are fibrillated and form a mesh consisting of colourless fibres with lengths in the range 12.7–19 mm and diameters of 0.24, 0.40 and 0.64 mm. SikaCem fibres are 12 mm long monofilament fibres of white colour. The average residual strength of Fibermesh 300-e3 fibres is 0.35 MPa and the declared tensile strength of SikaCem Fiber-12 is 150 MPa.

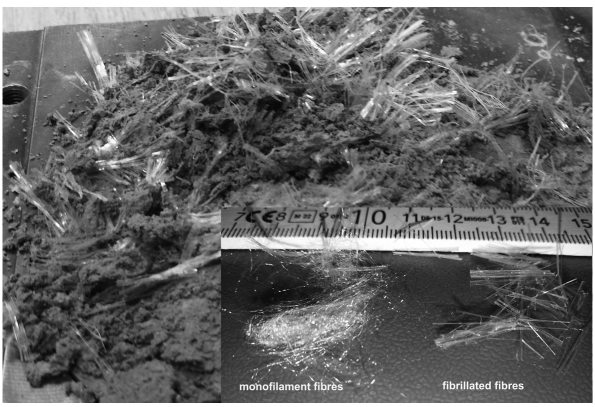

Fig. 1. The view of soil sample reinforcement with fibrillated fibres and the view of both types of fibres used in the tests

Table 1. Geotechnical parameters of soil

Parameter	Unit	Value
Fraction content: – gravel (> 2 mm) – sand (2–0.05 mm) – silt (0.05–0.002 mm) – clay (< 0.002 mm)	%	0.2 9.7 71.1 19.0
Symbol of soil acc. to PN-EN ISO 14688-2:2006	–	siCl
Type of soil acc. to PN-EN ISO 14688-2:2006	–	silty clay
Specific density	$g \cdot cm^{-3}$	2.69
Maximum dry density	$g \cdot cm^{-3}$	1.77
Optimum moisture content	%	15.50
Natural moisture content	%	16.6
Liquid limit	%	37.1
Plastic limit	%	15.3
Plasticity index	%	21.8

4. Test results and their analysis

4.1. The effect of soaking on shear strength of unreinforced soil

The test of unreinforced soil revealed that values of peak shear strength and shear strength parameters obtained for un-soaked soil were relatively high. The angle of internal friction and cohesion were 40.9° and 25.4 kPa, respectively.

In turn, the shear strength of soaked samples at both values of degree of compactions (I_S = 0.79 and 0.90) were very similar; the relative difference was 3% per cent. As a result, the values of the internal friction angle and cohesion values received for both these test series also differed very slightly (33.3–34.2° and 8.3–8.6 kPa). It can be noted that shear strength obtained for the un-soaked samples with a degree of compaction of I_S = 0.79 was by 47–104% lower compared to the results of the soaked samples with a corresponding compaction. This relationship was probably due to the significant difference in moisture content of the soaked and un-soaked soil samples. The former ones had a moisture content close to 16.5% during the tests, while the final moisture content of the letter ones exceeded 24%.

4.2. The effect of fibre content and type on shear strength of the soil

The results of soil samples containing both types of polypropylene fibres showed that they have an effect on the shear strength of the soil and also that they change the stress-displacement behaviour of the soil (Fig. 2, 3).

Overall, the results showed that fibres had a positive effect on soil shear strength. The effect of fibre content on the increase in soil shear strength varied and depended on the content and type of fibre, as well as on the degree of soil compaction and soaking state of soil samples

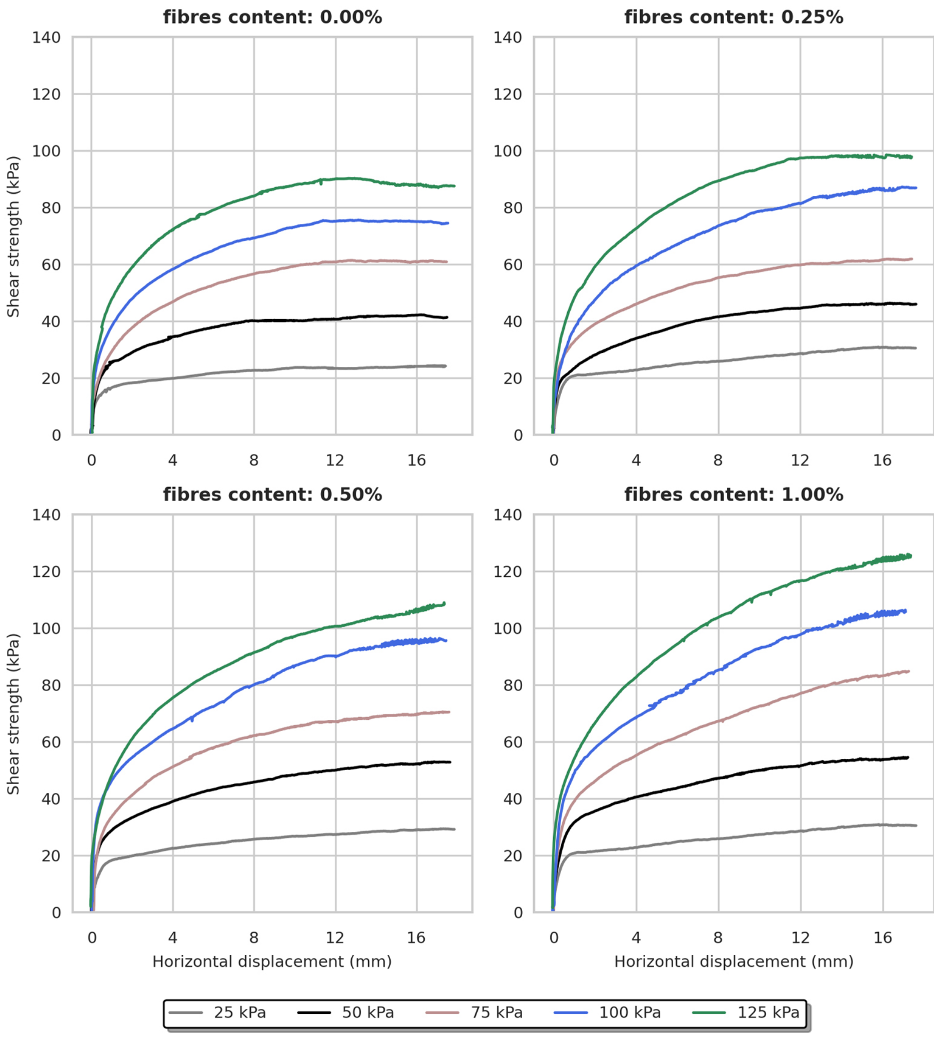

Fig. 2. Shear stress vs. horizontal displacement for unreinforced and reinforced soaked soil samples with a degree of compaction of $I_S = 0.90$ (results for monofilament fibres)

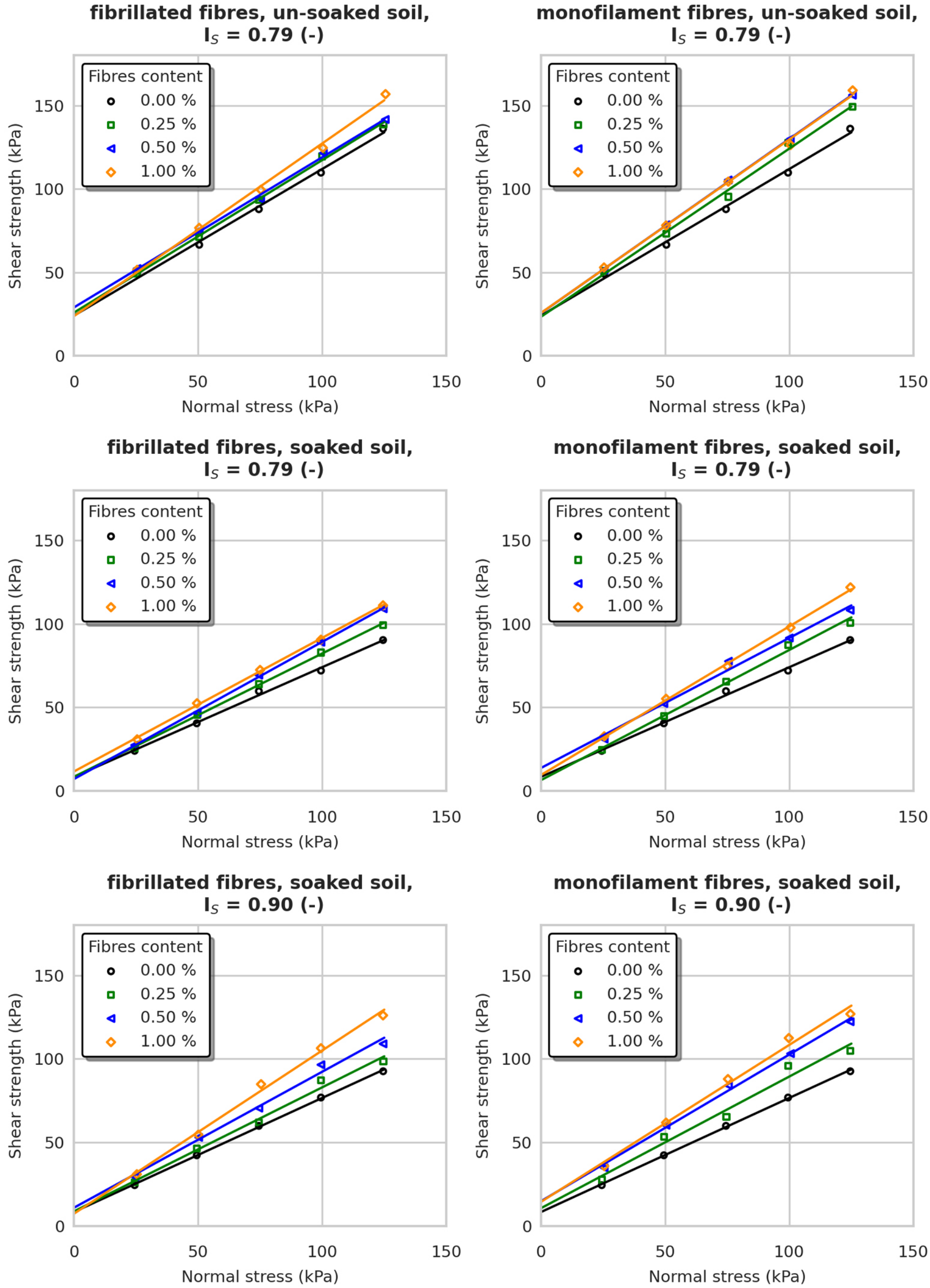

Fig. 3. Shear strength of tested soil vs. type and amount of reinforcement addition, test conditions and degree of compaction

(Fig. 3). The values of the shear strength ratio were in range of R_{SP} = 1.01–1.47 (Fig. 4). The highest increase in peak shear strength was obtained at a normal stress of 25 kPa for a soaked sample with a degree of compaction of I_S = 0.90 containing 1% monofilament fibres. Overall, for this series of tests, the average increase in peak shear strength was 45% (R_{SP} = 1.45). In contrast, the lowest value of shear strength ratio was obtained at 25 kPa normal stress for un-soaked soil sample with a degree of compaction of I_S = 0.79 containing 0.25% fibrillated fibres. In this series of tests, the shear strength of the fibre-reinforced soil was on average only 4.5% higher than that of the unreinforced soil.

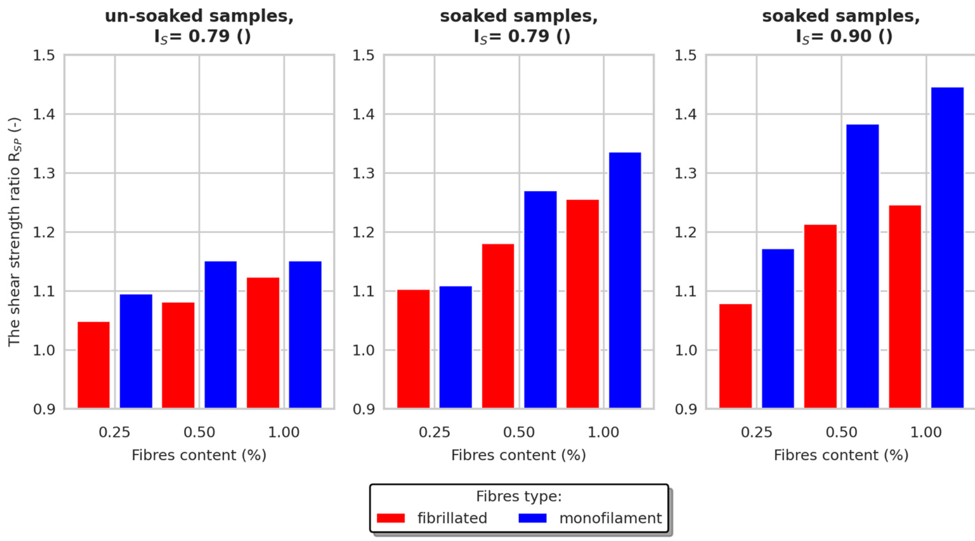

Fig. 4. Values of the shear strength ratio of tested soil

The effect of the addition of randomly oriented fibres on increasing the shear strength of the soil is well known and widely discussed in the literature. It can be generally stated, that values of the increase in peak shear strength of fibre-reinforced soils are within a wide range. However, the results of Qu and Sun [34] and Anagnostopoulos et al. [35] showed that, at low normal soil stresses, fibres can have a negative effect on the shear strength of the soil. The cited authors studied wheat straw and carbon fibres, respectively. The studies, which used polypropylene fibres, generally showed that these materials improve the shear strength of both granular and cohesive soils. A study by Shao et al. [36] of sand with 0.1–0.9% content of Fibermesh 150 showed that the increase in peak value of shear strength depends on the magnitude of the normal stress. At a stress of 50 kPa, cited authors obtained maximum a 2.6-fold increase in shear strength of reinforced soil, while at a stress of 150 kPa the increase in the shear strength was less than 50% as regards unreinforced soil. Fibermesh fibres (6 and 12 mm in length) were also used by Dafalla et al. [37], who carried out shear strength tests of the clay. The results of these tests showed, that at 0.6% fibre content the maximum increase in shear strength of soil was 30% for the longer fibres and 14–21% for the shorter fibres. Shear strength results of soil with polypropylene fibres were also conducted by Pradhan et al. [38], Anagnostopoulos et al. [35], Noorzad and Zarinkolaei [5], Benziane [39], among others. The results of Pradhan et al. [38] carried out for clay showed that a content of fibres up to 0.5% results in up to a 2.7-fold increase in peak shear strength. In addition, these studies have shown that the value of the shear strength ratio decreases (from 1.5 to 1.2) as the density index of the soil increases (from 30 to 80%). Interesting results are provided by Anagnostopoulos et al. [35] and Noorzad and Zarinkolaei [3], who investigated sandy soils. Anagnostopoulos et al. [35] were carried out tests in direct shear box using two rates of displacement for two cohesive soils and two types of fibre with content up to 0.9%. They showed that there is an optimum fibre content, above which the shear strength decreases or remains constant. The increase in peak shear strength at low rate of displacement (R_{SP} = 1.19–1.93) was greater than at low rate (R_{SP} = 1.13–1.62). In contrast, Norzad and Zarinkolaei [3] carried out tests of a sand in both triaxial and direct shear apparatus at fibre contents up to 1.0%. These tests showed that the maximum value of the shear strength ratio in the direct shear tests was 1.76, while the values of this parameter in the triaxial tests were much higher, with a maximum as high as 6.7.

The results of the present study indicate that the presence of fibres within the soil altered its stress-strain relationship, primarily resulting in an increase in the shear strength at high soil strains (residual shear strength). The residual shear strength values of soil samples with fibres were 1–50% (average 22%) higher than the residual shear strength values corresponding to unreinforced ones.

The other parameter, that is commonly used to assess the post-peak shear strength of soil, is the brittleness index. The results of the calculations showed that the highest values of the brittleness index were obtained for the series of tests in which the soil samples were not soaked (Fig. 5). The brittleness index values obtained for unreinforced and un-soaked soil were I_B = 0.0–0.31 (average 0.10). In the case of reinforced samples, values of the index were significantly lower (I_B = 0.0–0.19, average 0.04), whereas values did not differed significantly among the both types of fibres. It is noticeable that with the increase in fibre content and normal stresses, the values of the brittleness index decreased significantly. Tests on the soaked samples showed that they exhibited a ductile behaviour. Consequently, the values of the brittleness index were generally close to 0.0.

In many publications, in which cohesive soils are tested, the inclusion of fibres usually increases the plasticity of the soil, especially as the fibre content and normal stress increase. For an example, Freilich et al. [17] testing clay in a triaxial apparatus (CIU test) showed that the brittleness index for unreinforced soil samples ranged from I_B = 0.61 to 0.35, while for reinforced soil samples it ranged from I_B = 0.26 to 0.01. However, there are examples that the addition of fibres can change the behaviour of the soil making it brittle [22, 38], mainly if the low values of normal stress are used in the tests.

4.3. The effect of content and type of fibre on angle of internal friction and cohesion values

The results of shear strength tests were reflected in the values of the angle of internal friction and cohesion (Fig. 6). In general, for both types of fibres, the value of the angle of internal friction increased (5.1° on average) as the fibre content enlarged. Such relationships were

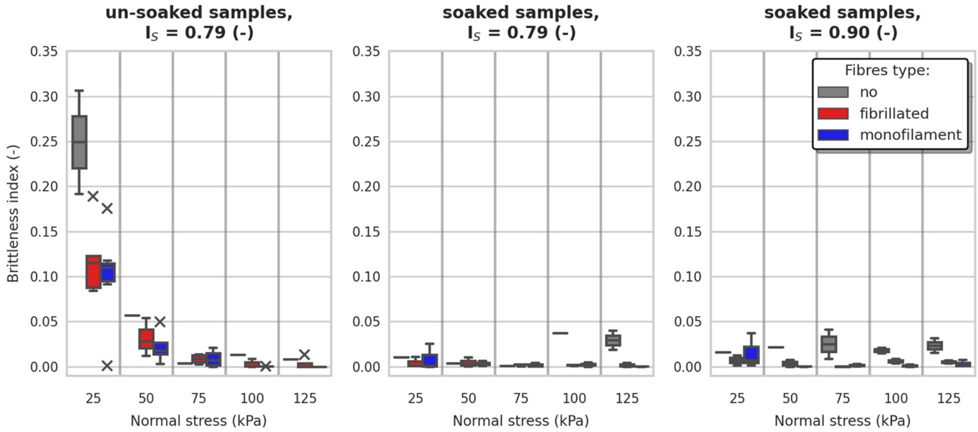

Fig. 5. Values of brittleness index

obtained for each test series, irrespective of the degree of compaction and the test condition. In turn, the effect of fibres on the change in cohesion values was not so clear. Overall, the average increase in peak cohesion was 14% (1.3 kPa), similar to the peak internal friction angle values (15%), but for some part of the tests there were obtained lower cohesion values than for unreinforced soil. In general, only for tests performed for sample of relatively high degree of compaction values soil reinforced by monofilament fibres exhibited an increase in cohesion. In general, the smallest changes in internal friction angle and cohesion values were obtained for un-soaked samples and less favourable shear strength parameters were obtained for samples with fibrillated fibres. On the other hand, when testing un-soaked samples, more favourable values of both parameters were obtained for soil with higher degree of compaction.

In the literature, the effect of the addition of randomly oriented fibres on the values of soil shear strength parameters varies. Theoretical analysis and experiments conducted on sand reinforced with reed fibres, plastic fibres, Palmyra palm fibres and copper wire by Gray and Ohashi [8] showed that the inclusion of fibres within the soil has no effect on the values of the angle of internal friction. On the other hand, they highlighted that there is a threshold below which the fibres tend to slip or pull out of the soil. Maher and Ohashi [5] stated that the fibre reinforced sands have a curved linear or a bilinear failure envelope, with the break occurring at a threshold confining stress. The magnitude of the critical confining stress decreases with an increase in sand granulation, particle angularity, and fibre aspect ratio, and increases with an increase in fibre modulus. So that, the relationship between change in the angle of internal friction and cohesion of reinforced soil can be to some extent related to range of the values of normal stress (or confining pressure) applied in the experiments. It can be also noted that soil's shear strength and its parameters improve with increase in fibres content up to the certain (optimum) dose and then can drop or remain nearly the same e.g. [22, 35, 38].

Some test results indicate presence of fibres in the soil improves mainly cohesion [22,23,40], but some others revealed that reinforcement effect corresponds to the increase in the angle of internal friction value [18, 19, 41–43]. The results of Anagnostopoulos et al. [35] obtained

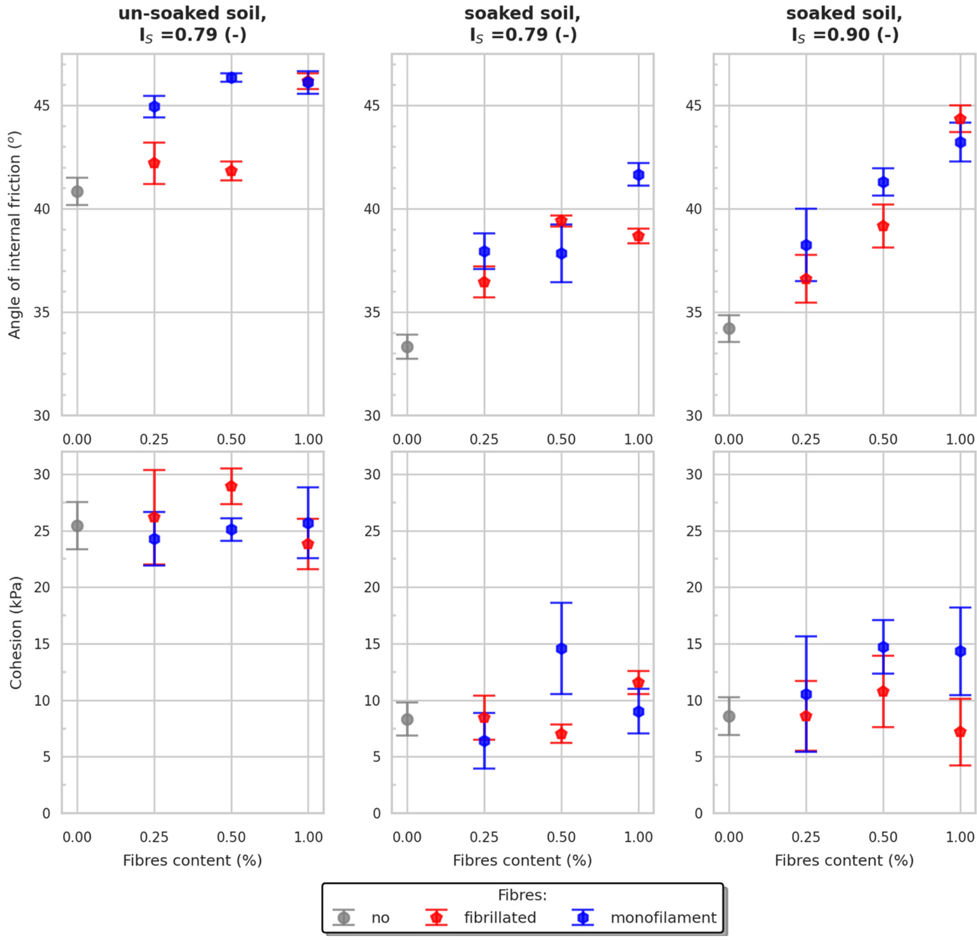

Fig. 6. Values of peak shear strength parameters of tested soil with the addition of polypropylene fibres (vertical bars represent standard deviation of parameter)

for cohesive soils (sandy silt and silty clay) showed that the effect of reinforcement on the change in shear strength parameters values can be varied and depends on the fibre content and type, the soil type and the rate of sample displacement used in the tests. It was showed that the addition of fibres within soil resulted in an increase in both internal friction angle and cohesion values and a slightly larger increase in shear strength was obtained for sandy silt. The results of silty clay tests revealed, that greater changes in the values of the internal friction angle of the soil with the addition of fibres were obtained using the slower rate of displacement, as opposed to the test at faster rate which had greater impact on cohesion's rise. A study of Arabani and Haghsheno [25] that were carried out for a clay reinforced with acrylic fibres showed that the effect of reinforcement on the values of shear strength parameters depends on the moisture content of the soil. At moisture contents lower than the optimum moisture content, the fibres inclusion has no effect on the values of the angle of internal friction, but causes an increase in the cohesion value. On the other hand, at moisture content equal to or greater than the optimum moisture content, as the content of fibres increased, the cohesion decreased and the angle of internal friction increased. These tests were carried out in direct shear box at similar values of normal stresses that were used in the present study. The influence of fibre content at relatively high moisture content on the changes of angle of internal friction and cohesion correspond well the relationship between were obtained in this study. It should also be mentioned that, at low confining stress, the main interaction mechanism between fibres and soil is fibre slippage (or pullout), and the failure envelope may be different from that in the stress range where fibre breakage dominates. The results of Heineck and Consoli [44] showed that the increase in shear strength at low confining stress corresponded mainly to an increase in the angle of internal friction, while the change in cohesion was neglected. This relationship may partly explain why the presence of fibres within the soil in this study had significant impact on internal friction angle values, but not on the cohesion.

4.4. The effect of test parameters on reinforcement of the soil

The results showed that monofilament fibres have a greater effect on the increase in shear strength of the soil than fibrillated ones, regardless of degree of compaction and test conditions. There is lack of publications where the fibres in form of grid within the soil are tested. The similar type of fibres was used by Shao et al. [36], Dafalla and Moghal [37]. The latter studies revealed that fibrillated fibres possess a rough surface with protrusions (branching extrusions) which is beneficial to the soil shear strength. The piece of information provided by the producer of both types of fibres used in the present study does not enable to compare their mechanical properties directly and use it to explain the obtained differences in results.

As regards the test conditions, a greater increase in shear strength was obtained for soaked samples. This relationship may have been partly an effect of the volumetric changes (settlements) caused by the soaking of the soil samples during the tests. On one hand, results of some tests [44] indicate that the increase in moisture content of the soil reduces the benefits coming from the presence of the fibres within the soil. On the other hand, Murray et al. [12] stated that strength losses associated with saturation of the soil are significantly reduced with fibre reinforcement. Soleimani-Fard et al. [46] found that the fibre inclusion reduced the shear strength of samples with suctions higher than air entry values (AEV), while the opposite effect was observed for samples with suctions lower than AEV.

As regards the impact of degree of compaction on reinforcement of the soil, we compared the results obtained for the soaked samples. The tests revealed that a greater effect on shear strength and its parameters were obtained for the soil with a higher degree of compaction. This relationship is in opposition to results of Javdanian et al [47] or Anagnostopoulos et al [48]. Javdanian et al [47] stated that as soil density increases, the soil further contributes to the carrying load while the fibres play a less significant role in the peak shear strength. On the other hand, results of Consoli et al. [48], Develioglu and Pulat [43], Patel and Singh [49], Ganiev et al [50] indicate that the increase in compaction of the soil has neutral or positive effect on the increase in peak shear strength of reinforced soil. Diambra et al. [51] indicate that dense samples of sands tend to dilate more than loose ones. As a result it induces a greater desire for radial strain and therefore greater potential tensile stresses in the fibres. Consequently, this phenomena increases confinement on the sand in the dense samples and hence a much larger increase in shear strength than observed for loose samples.

An important influence on soil reinforcement is the orientation of the fibres relative to the failure plane. Gray and Ohashi [8] found that an orientation of 60° relative to the shear plane is optimal for peak shear strength. Furthermore, they found that with a fibre (or a root) orientation of 120°, the shear strength of the soil may even deteriorate. In this case, the root (the natural equivalent of a fibre) is compressed and, as Thomas and Pollen-Bankhead [52] found, the soil has to displace enough distance to allow these roots to first buckle and then tension to allow these roots to enhance the shear strength of the soil.

As stated by Diambra et al [53] and Ekinci and Ferreira [54], the use of the tamping method for sample preparation tends to create a preferred sub-horizontal fibre orientation. As stated by Diab et al. [45], this fibre orientation is favourable in triaxial tests because it does not coincide with the plane of maximum shear strain. On the other hand, Mui Wood et al. [4] state that there is no method of sample preparation which produces an isotropic distribution of fibres within the soil. In the present study, the soil degree of compaction values were relatively low, so the tamping of samples was limited as compare to test in which degree of compaction is close to maximum dry density.

5. Conclusions

In this paper, a series of direct shear strength test were carried out on soaked and unsoaked silty clay without and with fibrillated, and monofilament fibres of 0.25, 0.5, and 1.0‰ content. The following conclusions are drawn from the study:

1. The presence of both types of fibres within the soil increase its shear strength up to almost 50‰. The enhance of the shear strength improvement is proportion to the fibres content. The results indicate that the use of monofilament fibres to reinforce the soil is more effective than the fibrillated ones.
2. The failure envelope obtained for each series of reinforced soil has been linear and the improvement of shear strength is generally related to the increase in the angle of internal friction, whereas the impact of the fibres' addition on the values of cohesion was ambiguous.
3. The increase in the shear strength of reinforced soil was also related to the to the degree of compaction and moisture content of the soil. The effect of degree of compaction on the shear strength of unreinforced soil was not clear, while it was significant for reinforced soil. As regards moisture content, a benefit of the use of fibres within the soil was higher exhibited for soaked samples than for un-soaked ones. This relationship implies that the randomly oriented fibres in geotechnical practice can be used to the improve geotechnical parameters of the cohesive soils of high moisture content.

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Wpływ włókien propylenowych na wytrzymałość na ścinanie gruntu drobnoziarnistego

Słowa kluczowe: grunt spoisty, włókna polipropylenowe, wytrzymałość na ścinanie, zbrojenie rozproszone

Streszczenie:

W pracy przedstawiono wyniki badań wytrzymałości na gruntu drobnoziarnistego z dodatkiem zbrojenia rozproszonego. Oznaczenie parametrów wytrzymałości na ścinanie przeprowadzono w aparacie bezpośredniego ścinania na próbkach o średnicy 100 mm i wysokości 20 mm. Próbki były formowane bezpośrednio w skrzynce aparatu przy wilgotności naturalnej, zbliżonej do optymalnej, oraz dwóch wartościach wskaźnika zagęszczenia ($I_S = 0,79$ i 0,90). Próbki konsolidowano przez 60 min przy naprężeniu normalnym 25, 50, 75, 100, 125 kPa, a następnie ścinano z prędkością 0,10 mm·min^{-1} do momentu uzyskania 18% względnego odkształcenia. Badania przeprowadzono dla zawodnionych nieza-wodnieniem próbek gruntu. Zbrojenie rozproszone stanowiły dwa rodzaje włókien polipropylenowych (monofilamentowe i fibrylowane o nazwach handlowych odpowiednio Fibermesh 300-e3 oraz SicaCem Fiber-12), które dodawano w ilości 0,25; 0,50 i 1,00% w stosunku do masy szkieletu gruntu. Wyniki badań wykazały, że zastosowanie zbrojenia rozproszonego wpływa pozytywnie na wytrzymałość na ścinanie gruntu, przy czym wpływ ten jest zależny od rodzaju zbrojenia, jego dodatku, a także parametrów geotechnicznych gruntu. Maksymalny wzrost wytrzymałości na ścinanie gruntu ze zbrojeniem wyniósł 47% w stosunku do wartości wytrzymałości na ścinanie gruntu bez dodatku zbrojenia. Stwierdzono, że dodatek zbrojenie wpłynął zasadniczo na wartości kąta tarcia wewnętrznego, a w przypadku spójności był niejednoznaczny. Wyniki badań wykazany również, że włókna monofilamentowe mają bardziej korzystny wpływ na wzmocnienie gruntu niż włókna fibrylowane. Wykazano również, że wpływ zbrojenia na wzmocnienie gruntu jest bardziej efektywny przy wyższym wskaźniku zagęszczenia gruntu, a większe przyrost wytrzymałości na ścinanie gruntu uzyskano w przypadku badań próbek zawodnionych.

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