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Research paper

Mechanical characteristics of coarse soil improved by fibre and cement additions

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Abstract: The study aimed to present the differences in the mechanical characteristics of gravelly sand after adding a small amount of cement and/or fibre reinforcement. The tests were conducted on compacted non-cohesive soil – the gravelly sand or gravelly sand improved with 1.5% cement addition. Polypropylene fibres of 18 mm length were used, added in amounts of 0.1%, 0.2% and 0.3% to the dry mass of the soil. Gravelly sand was compacted at the optimum water content to the maximum dry density using the standard Proctor energy. The soil samples were sheared under triaxial compression conditions. Adding fibres changed the behaviour of the sample towards plasticisation of the material. The fibre content increases the maximum shear strength, which is obtained under a greater relative deformation. The failure mode of the lightly cement-bonded soil is characterized as a semi-brittle material, whereas that of the uncemented gravelly sand is the ductile mode. The failure plane of the soil with added fibres is close to horizontal, which means that the fibre-reinforced material has entered the plastic zone.

Keywords: compacted soil, polypropylene fibres, cement addition, shear strength, triaxial tests

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1. Introduction

Stabilization with hydraulic binders is an effective way to increase the stiffness of base and subbase layers and improve the resistance to rutting of the subgrade. Another way to enhance the soil properties is to use fibre reinforcement. Researchers agree that fibre addition is a recognized method for improving the shear strength and ductility of the stress-strain response of unenhanced [1] or hydraulically bonded cohesive soils [2], but also uncemented [3] and cemented non-cohesive soils [4–6]. Cemented cohesive soil must be enhanced with fibre reinforcement due to its brittleness. Cohesive soil shows the possibility of cracking when drying, too. In the case of non-cohesive soils, silty sands are most often reinforced to improve their mechanical properties. In recent years, research has also been conducted on sands with poor grain size characteristics, which require improvement due to their low compaction possibilities.

Boutouba et al. [7] proved that the addition of cement has a significant effect on the increase of sand strength parameters. The stabilizer was mixed with the soil at the following percentages of the dry soil mass: 2.5%, 5%, 7.5%, and 10%. Shooshpasha and Shirvani [8] researched the effect of cement addition on the strength parameters of dune sand. Portland cement was used in amounts of 2.5%, 5% and 7% of the dry mass of the soil. In both papers, the tests were carried out in a direct shear apparatus. The greater the stabilizer addition, the higher the shear strength and strength parameters obtained. The cement content has a greater effect on the cohesion resistance than the angle of internal friction.

Haeri et al. [6] tested a kind of hydraulic agent added to coarse soil and found that the type of cementation (lime or Portland cement) was not important at low cement content. However, as the amount of cementing agent increased, the limiting stress ratio surfaces for the samples cemented with Portland cement are higher than those for lime cementing.

Studies of sand with fibre content were done by Yetimoglu and Salbas [9]. The sand was mixed with different amounts of 20 mm long polypropylene fibres. The researchers did not find a clear trend of increasing shear strength after adding fibres.

Michalowski and Čermák [3] tested fine and coarse sands reinforced by polyamide fibres with lengths ranging from 12 to 54 mm and a content from 0 to 2%. The tests were carried out in a triaxial compression apparatus under CD conditions. The results showed a significant increase in shear strength compared to unreinforced sands, especially at a fibre content of 2%, where the increase reached even 70%. For a fibre content of 0.5%, the reinforcement effect was much smaller and equaled about 20%. In fine sand, the improvement effect was more pronounced compared to coarse sand at low fibre percentage additions (0.5%), while at higher contents (2%), the relative increase in strength was more significant in coarse sand. It was found that the reinforcement is most effective when the fibre length exceeds the grain diameter by at least 10 times. Fibres with lengths comparable to the grain size do not provide effective interaction between fibres and sand. The fibres significantly increase the shear strength, but the initial stiffness of the material decreases. The peak strength is obtained at higher values of the relative strain, which indicates a change in the soil behaviour.

Anagnostopoulos et al. [10] tested sands with 12 mm polypropylene fibres in a direct shear apparatus. The fibres were added in the following amounts: 0.1%, 0.3% and 0.5%. The addition of fibres significantly increased the internal friction angle of fine sand, while in the case of coarse sand, this increase was insignificant. The researchers also checked the effect of the sand and fibre mix compaction on the shear strength results. In the case of medium-compacted sand, the impact of fibres was significant, while for well-compacted soil, this effect was insignificant.

Noorzad and Zarinkolaei [11] conducted the shear strength of uniform sand with added polypropylene fibres. The tests were performed in a direct shear apparatus and a triaxial apparatus. The addition of fibres with lengths 6, 12 and 18 mm to the soil was 0.25%, 0.5% and 1%. The fibres improve the strength parameters of the soil, which increase with the percentage reinforcement addition to the sand, for both test methods. Generally, the longer the fibres, the higher the strength parameters of the soil. The highest values of strength parameters were obtained for sand with 1% addition of 18 mm long fibres.

Kutanaei and Choobbasti [12] performed triaxial tests to investigate the effects of cement and polypropylene fibres on sand behavior. Fibres with a length of 18 mm were added at 0.6%, and the cement content was 5%. The fibres increased the shear strength, which was obtained at a greater relative strain. The highest value of the internal friction angle was stated for the soil with the addition of cement and fibres. Cement had a significant effect on cohesion resistance.

Consoli et al. [13] tested a uniform fine sand with 7% of Portland cement and 0.5% of fibres of various materials and lengths of 12 mm and 36 mm in a triaxial compression apparatus under CD conditions. Increasing the length of fibres from 12 mm to 18 mm had a negative effect on the soil shear strength parameters. Inclusion of polyester and glass fibres (both relatively stiff) slightly reduced the stiffness and increased the peak friction angle of both the cemented and uncemented sand. It also decreased the cohesive resistance. A relatively flexible polypropylene fibre dramatically reduced the brittleness, changing the failure mode of the cemented sand from brittle to ductile for 18 mm fibres, and stiffness, while increasing the ultimate strength of the cemented material.

Consoli et al. [14] also conducted tests of sand and its mixtures with cement and 24 mm long polypropylene fibres. The cement additions were: 1%, 4%, 7% and 10%, and fibres – 0.5%. The researchers showed that 4% of cement addition to the sand and fibre mixture was the optimal value that improves the shear strength of the soil. After exceeding 4% of cement addition, the added fibres caused lower shear strength values than those recorded for the soil with cement alone. A similar conclusion was found in the studies of Kutanaei and Choobbasti [12].

Uddin et al. [15] conducted tests on sand with the Portland cement (5%) and 22 mm long polypropylene fibres (0.5%). The samples were tested in a triaxial compression apparatus at significant confining pressures of 1, 4 and 10 MPa. The test results clearly showed that the cement and fibre additions significantly increased the peak strength and stiffness of the soil. The cement and fibres enabled the peak shear strength to increase by 40–60%. The tests showed that the effectiveness of fibre and cement improvement decreased for high effective confining pressure values, exceeding 10 MPa. This is due to the dominance of mechanical effects associated with high pressure, which reduced the influence of micromechanical interactions of fibres and soil grains on structural reinforcement.

Koutenaei et al. [16] investigated the effect of fibre and cement on the mechanical behaviour of sand by consolidated drained triaxial compression tests. Special fibres with a length of 10 mm and a diameter of 1.0 mm were added to sand and sand-cement mixtures at a weight ratio of 0.3% and 0.6%. The cement contents were 3% and 6%. The fibre addition to sand

and cement-stabilized sand increased the maximum deviatoric stress by 46% and axial strain at the failure point by 400%. The percentage reduction in the stiffness corresponding to 0.3% fibre content was 150%.

Summarizing, the most used fibre content concerning the dry soil mass is 0.1–0.6%, but in the literature, there are papers where the fibre content is 1% or even 2%. Binder additives are used in several proportions, and the most common content of cement or lime is 2.5–10%. In only one paper, researchers paid attention to the problem of compaction of the soil mixed with cement and/or fibres.

The study aimed to evaluate the effect of light hydraulic stabilization and/or dispersed reinforcement in the form of polypropylene fibers on the compaction and mechanical properties of compacted gravelly sand. Tests were performed on soil samples with 1.5% cement added to the dry soil mass and 0.1%, 0.2%, and 0.3% polypropylene fibres measuring 18 mm in length.

2. Materials and methods

The tested material is a Pleistocene glaciofluvial soil characterized by a large variation of the relief surface, which is connected with high dynamics of the sedimentary environment and the diversity of the mineral composition. It contains well-rounded quartz crumbles, as well as angular grains, with a significant addition of lytic particles and feldspars [17]. Following EN ISO 14688-1 standard [18], the tested soil is gravelly sand (grSa) with a median particle diameter D_{50} of 1.02 mm and a lack of fines ($f_C = 0\%$ under ASTM D653-11 [19]). Figure 1 shows the grain size distribution curve of the gravelly sand achieved by the sieve analysis performed according to the EN 933-1 [20]. The soil is a poorly graded material with uniformity and curvature coefficients equal to 5.27 and 0.87, respectively. The unit weight of solids, γ_s, is 26.0 kN/m^3.

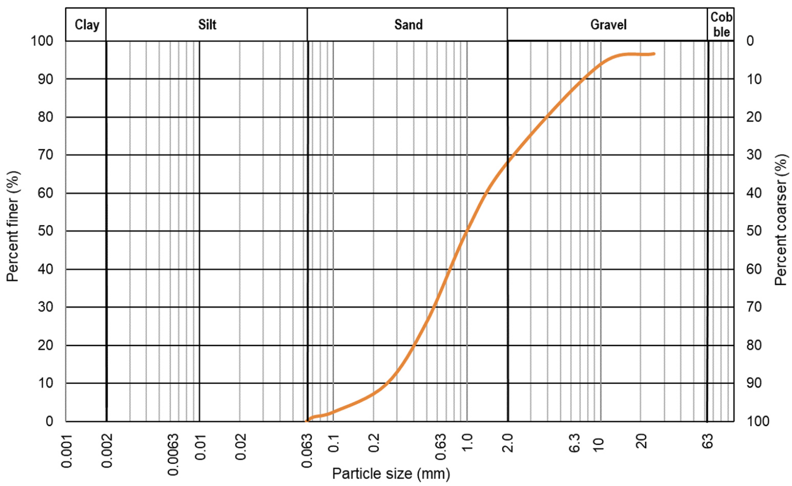


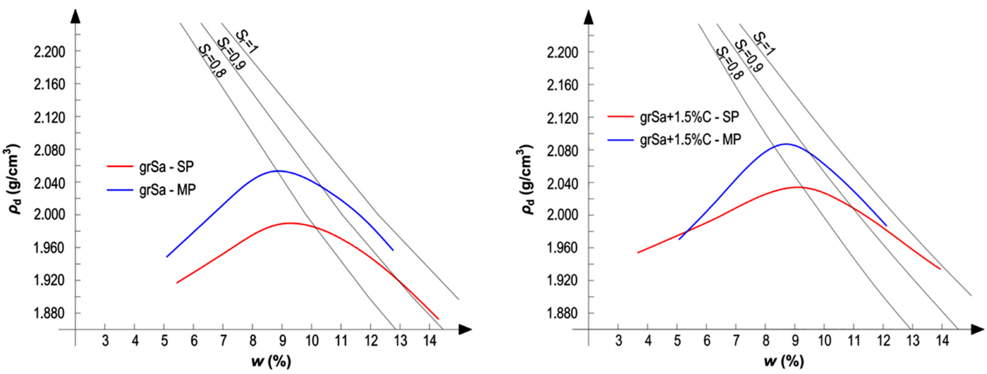
Fig. 1. Grain size distribution curve of the tested gravelly sand

Laboratory tests were performed on samples of gravelly sand and gravelly sand with the addition of 1.5% of Portland cement 42.5R to the dry mass of soil, and their mixtures with 0.1, 0.2 and 0.3% of the polypropylene fibres with a length of 18 mm. The fibres and a sample of soil mixed with 0.3% of fibres are shown in Fig. 2.

(a) (b) (c)

Fig. 2. The view of: (a) 18 mm-long polypropylene fibres, (b) a sample of soil mixed with 0.3% of fibres and compacted by the standard energy, (c) SEM image of gravelly sand mixed with 0.3% of fibres (×100)

Compaction parameters of gravelly sand and gravelly sand with 1.5% of cement, optimum water content, w_{opt}, and maximum dry density, ρd max, were obtained using the Standard and Modified Proctor methods (Fig. 3). Compaction results for soil and soil and cement mix with polypropylene fibres shown in the paper were limited to the standard test. The soil or soil and cement were mixed with polypropylene fibres using a laboratory mechanical stirrer, which is of great consequence for the homogeneity of the compacted samples [21, 22].



(a) (b)

Fig. 3. Compaction curves of tested materials (where: SP – the Standard Proctor method, MP – the Modified method): (a) gravelly sand, (b) gravely sand with 1.5% of cement

Although the fibres were mixed with the soil using a planetary mixer, however, the analysis of SEM images (Fig. 2c) indicates that in some places the fibres may appear in clusters of small sizes. A similar phenomenon has been observed by other researchers [23, 24].

Mechanical characteristics were performed in the triaxial test apparatus supplied with a pneumatic way of applying the confining pressure and axial load. The diameters of the cylindrical reconstituted samples were about 70 mm, and the height was about 140 mm. The samples were prepared in a bipartite mould by dynamic tamping of the material at the w_{opt} in three layers to obtain the $\rho_{d\,\max}$ value from the compaction curve by the Standard Proctor method. The samples were tested directly after compaction (unstabilized hydraulically) and after 28 days of curing in constant temperature and humidity, wrapped in foil to avoid drying. All samples were assessed in the triaxial apparatus using the Consolidated Drained (CD) method with the 0.1 mm/min shearing ratio recommended for non-cohesive [25]. Samples were not saturated (because of the pneumatic system of applying load), and to rebuild the conditions existing in the pavement subgrade material. Saturation degree values of the materials were 70.92–77.55% for uncemented samples and 72.18–78.65% for cemented ones (Table 1). After isotropic consolidation, samples were compressed under confining pressure $\sigma_3' = 50$, 100 and 150 kPa.

Table 1. Properties of materials compacted by the standard Proctor method

C	F	w_{opt}	$\rho_{d\,\max}$	e	Sr	γs
(%)	(%)	(%)	(g/cm^3)	(–)	(%)	(kN/m^3)
0	0	9.3	1.990	0.33	73.31	26.0
	0.1	8.9	2.032	0.30	77.55	
	0.2	7.7	2.070	0.28	72.82	
	0.3	7.4	2.076	0.28	70.92	
1.5	0	9.1	2.034	0.31	78.65	26.1
	0.1	8.2	2.059	0.29	74.73	
	0.2	7.8	2.076	0.28	73.75	
	0.3	7.6	2.078	0.28	72.18	

3. Test results and analysis

3.1. Results of compaction

The compaction parameters, initial void ratio, e, saturation degree, S_r, and unit weight of solids, γ_s, values of the tested materials are presented in Table 1, where C and F are percentage cement and fibre additions, respectively. The cement addition to the gravelly sand increases the $\rho_{d\,\max}$ value while decreasing the w_{opt}, which is influenced by the slightly greater unit weight of solids of the bonded material. An analysis of the void ratio (Table 1) confirms better compaction after cement addition. It also indicates that the 0.1%–0.2% addition of fibres reduces the void ratio of the mixture to a constant value as the addition increases. The saturation degree values decrease with the percentage of fibre added. The fibre addition results in an optimum water content decrease and a maximum dry density increase in both uncemented and cemented samples (Fig. 4). Increasing fibre content from 0.2% to 0.3% practically does not affect the compaction parameters of gravelly sand and its mix with cement.

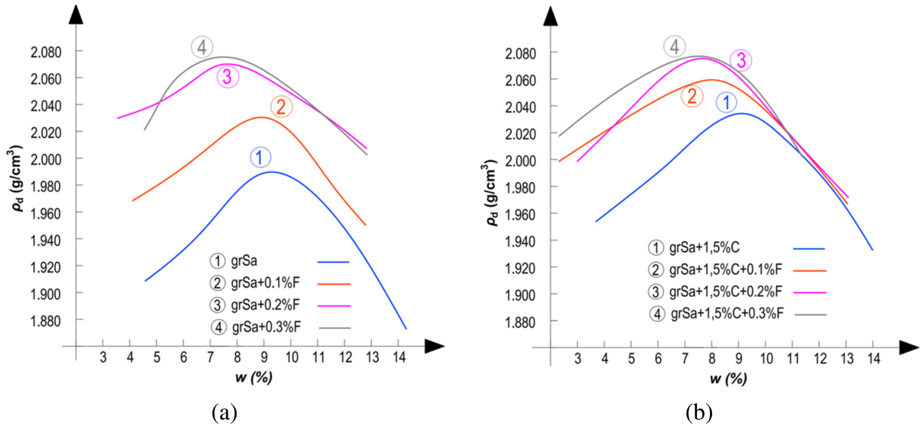


Fig. 4. Compaction curves of tested materials (SP method): a) gravelly sand with fibres, b) gravelly sand with 1.5% of cement and fibres

3.2. Results of triaxial tests

Test results for uncemented (Fig. 5a) and cemented samples (Fig. 5b) show that a 1.5% cement addition about twice increases the strength of the tested samples, which rises with the increase in confining pressure for each material. The samples exhibit a gentle peak behaviour in relatively low values of confining pressure, 50–150 kPa. The test results, presented in Figures 5c–d, show that fibre addition changes the behaviour of the uncemented and cemented gravelly sand. The peak and ultimate strength values rise, whereas the initial strength is practically untouched. The fibre addition proportionally changes the sample characteristics to more plastic, and the values of maximum shear strength are gained at greater relative strains.

Stiffness estimated by the E_{50} module decreases evidently with fibre content (Table 2), for both uncemented and cemented samples. The 1.5% addition of cement practically does not enhance it, which was also stated in the case of the greater cement addition [26]. The cement and fibre additions increase shear strength parameters, both peak and residual. Fibre content (0.1–0.3%) affects an increase in the effective angle of internal friction, ϕ', of compacted grSa from 40.3° to 44.5°. In the case of stabilized soil, this increase is not so large and equals only 1.1°. Cohesion resistance, c', grows considerably with the fibre addition, both for natural and bonded materials. It increases respectively from 1.3 kPa to 12.9 kPa and from 49.3 kPa to 88.2 kPa. Adding 1.5% of cement improves the values of the angle of internal friction, but first of all, cohesion resistance. This causes the ϕ' value to increase by 4.4° and the c' value by 48 kPa. Similar results were obtained by Asghari et al. [5] for gravelly sand stabilized with 1.5% cement addition. The greater effect of cement addition on cohesive resistance than the angle of internal friction for sand was found earlier by Shooshpasha and Shirvani [8].

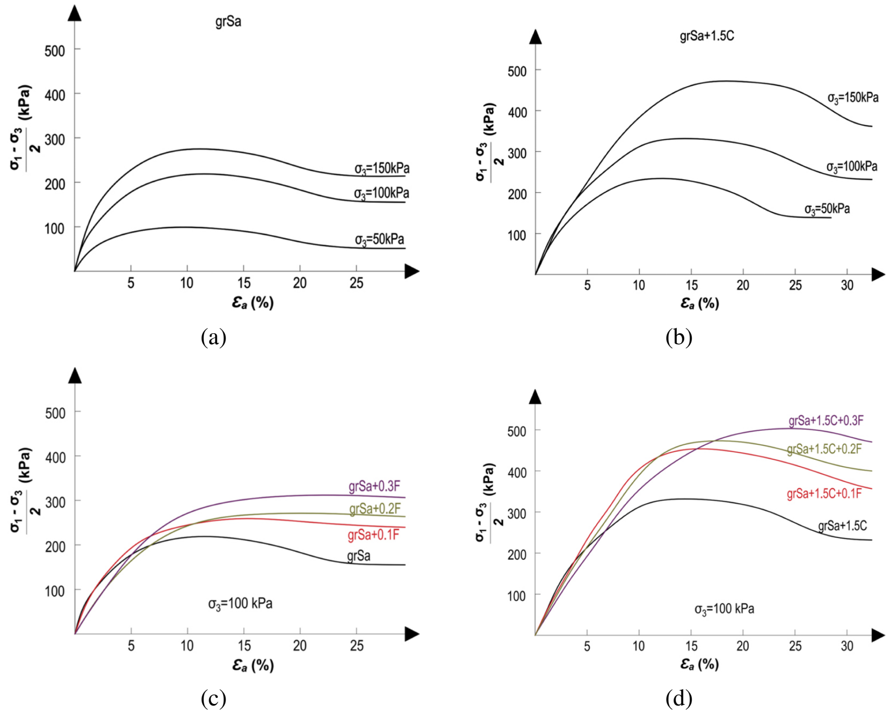


Fig. 5. Results of CD triaxial tests shown as half of the deviator stress- strain curves for: (a) gravelly sand at σ_3' = 50–150 kPa, (b) gravelly sand with 1.5% of cement addition at σ_3' = 50–150 kPa, (c) gravelly sand mix with fibres at 100 kPa, (d) gravelly sand/cement with 0.1, 0.2 and 0.3% of fibres at 100 kPa

Table 2. Mechanical parameters of materials

C	F	E_{50}	Shear strength parameters			
			Peak		Residual	
			ϕ'	c'	ϕ'	c'
%	%	MPa	°	kPa	°	kPa
0	0	10.39	40.3	1.3	38.5	0
	0.1	10.08	42.3	6.8	41.7	0
	0.2	7.84	43.5	8.8	43.2	5.1
	0.3	7.23	44.5	12.9	44.4	6.2
1.5	0	10.73	44.7	49.3	43.3	13.1
	0.1	9.33	45.0	82.6	45.7	45.9
	0.2	8.43	45.6	87.2	45.9	50.2
	0.3	7.51	45.8	88.2	46.5	60.6

Figure 6 shows various failure modes of samples damaged during the compression triaxial test.

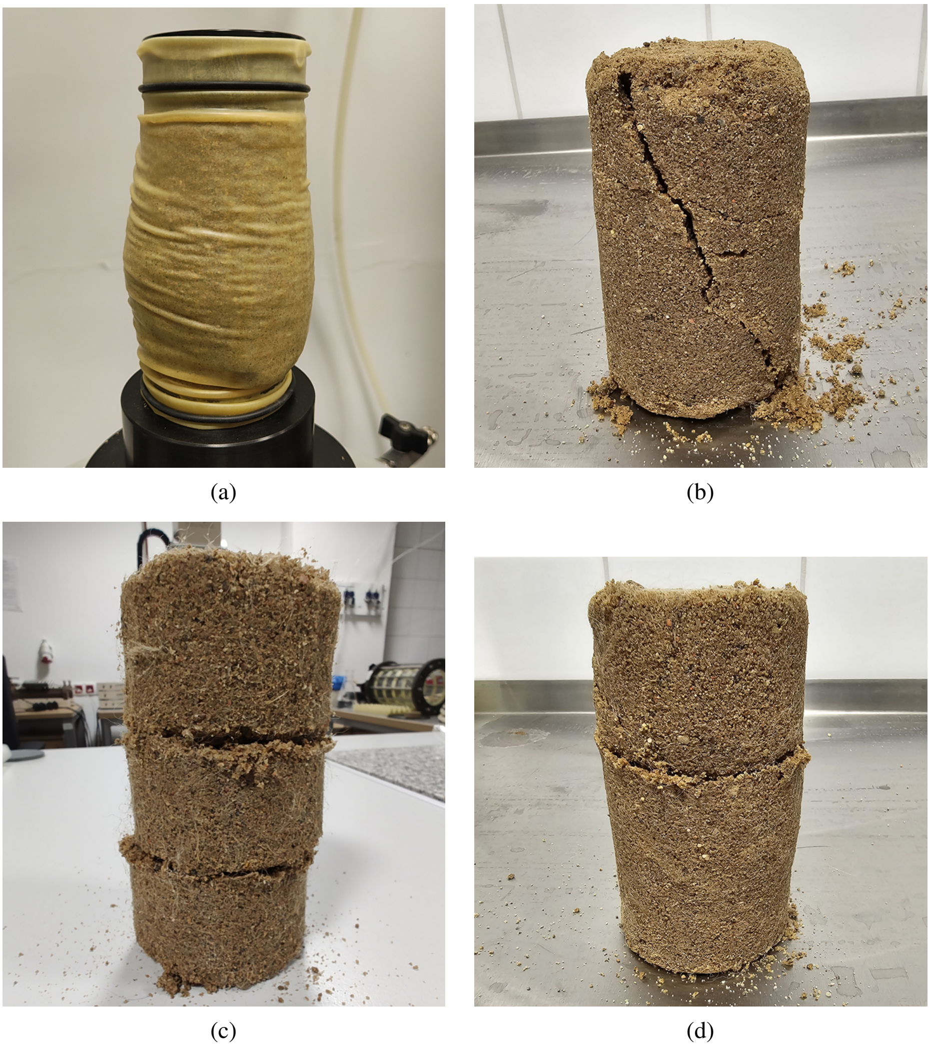


Fig. 6. Views of samples under $\sigma_3' = 100$ kPa: (a) grSa, (b) grSa + 1.5C_28 days, (c) grSa + 0.3F, (d) grSa + 1.5C + 0.3F_28 days

After shearing, the gravelly sand sample is characterized by the barrelling ductile mode with a diagonal failure plane. The failure mode of lightly cement-bonded soil with only 1.5% of cement is a typical single failure plane (shear failure), obtained for semi-brittle material, whereas the plane of destruction in the majority of uncemented and cemented samples, improved with cement or/and fibre addition, is close to horizontal. The horizontal failure plane indicates that the fibre-reinforced material entered its plastic zone. Such a horizontal failure mode was achieved only for samples containing 0.2–0.3% of fibres, where for uncemented samples a bilinear mode was obtained, and for lightly cemented samples a single-linear mode was found. Samples with 0.1% of fibres were sheared by a similar failure mode as those without fibres – ductile or brittle. This failure mode was also obtained in the case of cyclic loading. Marri et al. [27] stated the layering effect after isotropic compression of highly cemented fibre- reinforced sand at high confining pressures. The researchers explained this phenomenon by compacting in layers, but it was probably the plasticizing effect. They did not notice it at conventional pressure. The authors tested samples at σ'_3 = 50–150 kPa, and it was noticeable in all values of confining pressure. In earlier authors' research [28] carried out on grSa + 1.5C compacted by the modified method, so characterized by larger density, the failure mode was vertical through the failure plane like splitting failure, as in the case of brittle material, like in [26] where vertical failure modes of cement-stabilized organic sand was stated.

4. Conclusions

1. Cement and polypropylene fibre additions impact the compaction characteristics of gravelly sand. The 1.5% of cement improves its compaction characteristics. The 0.1–0.2% of fibres also improve the gravelly sand compaction, both uncemented and cemented. Increasing the fibre addition to 0.3% does not change the compaction parameters of gravelly sand and its mix with cement.
2. The 1.5% cement addition to gravelly sand increases peak and residual shear strength parameters and practically does not influence the material stiffness estimated by the E_{50} module. Adding cement improves the values of the angle of internal friction, but most considerably, cohesion resistance.
3. Polypropylene fibre addition modifies the characteristics of uncemented and lightly cemented gravelly sand. The peak and residual shear strengths get stronger while the initial strength becomes similar. The peak and residual strength parameters increase, but the stiffness modulus, E_{50}, decreases.
4. The 0–0.3% addition of fibres increasingly changes the behaviour of gravelly sand and its mix with cement towards plastic characteristics, where the peak strength is gained at a greater relative strain. Fibre addition changes the failure mode of sheared samples in the triaxial apparatus for both uncemented and bonded samples from ductile or brittle shear failure mode to a horizontal one.

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Właściwości mechaniczne gruntu gruboziarnistego ulepszonego dodatkami włókien i cementu

Słowa kluczowe: zagęszczony grunt, włókna polipropylenowe, dodatek cementu, wytrzymałość na ścinanie, badania trójosiowego ściskania

Streszczenie:

Celem pracy jest przedstawienie zmian w charakterystyce piasku ze żwirem po dodaniu małej ilości cementu i/lub zbrojenia rozproszonego w postaci włókien polipropylenowych. Badania przeprowadzono na zagęszczonym niespoistym gruncie – piasku ze żwirem lub zagęszczonym piasku ze żwirem ulepszonym dodatkiem cementu w ilości 1,5%. Użyto włókien o długości 18 mm, które dodano w ilościach 0,1%, 0,2% i 0,3% do suchej masy gruntu. Piasek ze żwirem zagęszczano przy wilgotności optymalnej do maksymalnej gęstości szkieletu gruntowego za pomocą metody standardowej Proctora. Próbki gruntu ścinano w warunkach trójosiowego ściskania metodą CD. Dodanie włókien zmieniło zachowanie próbki w kierunku uplastycznienia materiału. Zawartość włókien zwiększa maksymalną wytrzymałość na ścinanie, ale uzyskuje się ją przy większym względnym odkształceniu. Tryb zniszczenia lekko związanego cementem gruntu przebiega jak w przypadku materiału półkruchego, natomiast niezwiązanego piasku ze żwirem ma charakter plastyczny. Płaszczyzna zniszczenia gruntu z dodatkiem włókien jest zbliżona do poziomej, co oznacza, że materiał wzmocniony włóknami wszedł w strefę plastyczną.

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