Experimental and numerical study on weathered soil improvement by fiber/cement inclusions

Weathered soil, cementation,

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1. Introduction

Soil improvement is an important aspect of geotechnical engineering aimed at enhancing the mechanical properties and stability of soils for various construction applications. Cement is commonly used in soil stabilization due to its ability to enhance load-bearing capacity and reduce susceptibility to factors as erosion and weathering. Recently, fibers are often considered as an additive to the soil-cement mixture to further enhance mechanical properties of soils and improve durability of structures. In this study, unconfined compression and undrained triaxial compression tests were conducted on weathered soils treated with cement and short fibers. Also, a numerical analysis utilizing a constitutive model based on soil skeleton concept super/subloading yield surface cam-clay model (SYS Cam-clay) was performed to describe and reproduce experimental results.

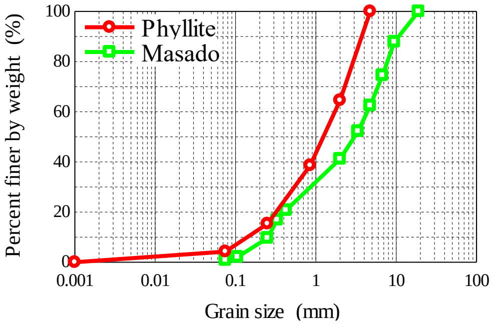

Fig. 1. Grain size distribution of weathered soils in this study

Table 1. Physical properties of weathered soils

Property	Weathered phyllite	Masado
Specific gravity, G_s	2.70	2.65
Plastic limit, w_P (%)	NP	NP
Coefficient of uniformity, C_u	22.12	26.9
Coefficient of curvature, C_c	1.34	1.18
Maximum dry density, (g/cm^3)	2.053	2.013
Optimum moisture content, (%)	9.04	10.5

2. Materials and methods

Two types of weathered soils, phyllite and Masado, were used in this study. The grain size distribution of soils is shown in Fig. 1, and main properties of soils are summarized in Table 1. As for the reinforcing materials, 12mm lengths discrete polyvinyl alcohol fibers (PVA) with d=0.04mm and rapid-hardening Portland cement were utilized. Fiber-treated soils contained 0.25% and 0.50% fiber, while cement-treated soils prepared with 1% and 3%.

Unconfined compression (UC) and consolidated undrained triaxial compression ($\overline{\text{CU}}$) tests were conducted on untreated and cement/fiber treated samples prepared at different compaction degrees (D_c=85%, 90%, 95%).

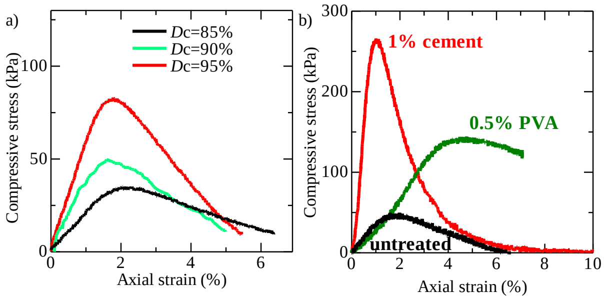

Fig. 2. UC test results: a) untreated phyllite (dif. D_c) and b) cement/fiber treated phyllite (D_c=90%)

3. Results and discussion

UC test results performed on untreated and cement/fiber treated phyllite and masado samples are presented in Figs 2-3, respectively.

Both untreated phyllite (Fig. 2a) and Masado (Fig. 3a) samples showed increase in unconfined strength with the increase in compaction degrees. However, Masado soil which contains smaller percentage of fine particles showed only about 35kPa of unconfined compression strength even for a densely compacted sample with D_c=95%. Referring to an observed behavior of both weathered soils, various treatments to enhance performance of soils was considered.

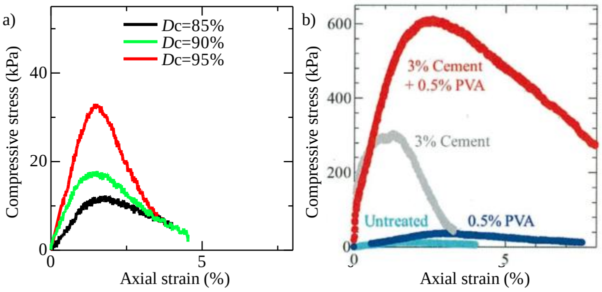

Fig. 3. UCT results: a) untreated Masado (dif. D_c) and cement/fiber treated Masado (D_c=85%)

In Fig. 2b results of UC test are shown, performed on untreated and treated phyllite samples prepared with 0.5% PVA fiber and 1% cement at D_c=90%. Cement addition led to significant increase of unconfined compression strength (q_{max}>250kPa), however, a brittle behavior of weathered phyllite was not improved with almost a full drop of compressive stress within 5% axial strain. In turn, 0.5% fiber-treated phyllite also showed a noticeable increase in unconfined compression strength (q_{max}>140kPa), while also maintaining quite high strength at higher axial strains, i.e., a fiber-treated phyllite sample showed more ductile behavior. Compared with cementation, addition of fibers did not improve initial stiffness and/or even reduced value of initial stiffness attributed with the

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interaction mechanism of fibers and soil particles. Based on these results, mixed effect of cement/fiber was considered for Masado soil (Fig. 3b), which showed more brittle behavior compared to phyllite. Indeed, even adding only cement or fiber improves strength of Masado soil, while mixed effect of cement and fiber was significantly high, with two times increase in q_u than only cementation and prolonged ductile effect of improvement that maintained at higher axial strains.

$\overline{\text{CU}}$ test results performed on untreated and cement/fiber treated phyllite samples with D_c=90% is presented in Fig 4. For the weathered phyllite, which contained higher percentage of fine particles, cementation was relatively more effective than fiber treatment. In contrast, in case of Masado soil (Fig. 5, thick lines), 0.5% fiber additions showed relatively better performance than 1% cementation compared with the behavior observed in phyllite soil. Possible mechanism is that the bonding between bigger particles and cement was not strong enough, while fibers worked as a better agent to improve performance of Masado soil. Moreover, both fiber-treated weathered soils experienced increase in deviator stress even until axial strain of 20% (peak strength not yet reached), whereas untreated and cement-treated samples had steady or post-peak reduction at the end of shearing. Based on the above results, depending on soil, percentage of fiber or cement inclusions should be properly considered, with additional attention on proportion of cement/fiber in case of a mixed usage.

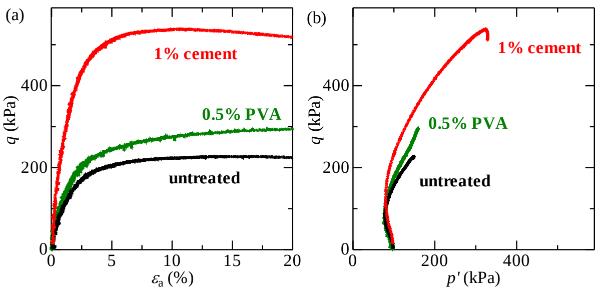

Fig. 4. $\overline{\text{CU}}$ test results performed on untreated, and cement/fiber treated phyllite (D_c=90%, p'_0=100kPa)

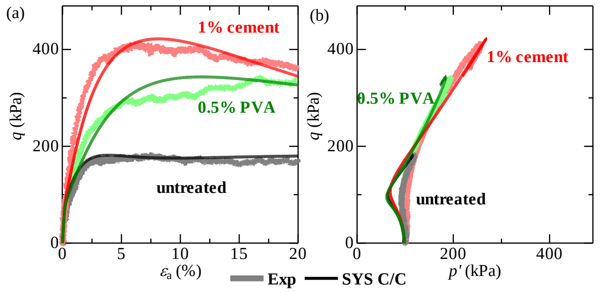

Fig. 5. Experimental and calculation results of $\overline{\text{CU}}$ test performed on untreated, and cement/fiber treated Masado (D_c=85%, p'_0=100kPa)

In the same Fig. 5, SYS Cam-clay model calculation results (thin lines) are shown only for Masado soil due to a space limitation. SYS Cam-clay model parameters are summarized in Table 2. Elasto-plastic parameters for all samples was set to be similar, and the effect of cementation and fiber treatment was mainly controlled through evolution rule and initial state parameters. Calculation results were in good agreement with the mechanical behavior of the untreated and cement/ fiber treated Masado by SYS Cam-clay model along the whole shearing process.

Table 2. SYS Cam-clay model parameters for Masado soil

Material	Untreated	0.5%PVA	1% cement
Elasto-plastic parameters			
Compression index, λ	0.052	0.052	0.052
Swelling index, κ	0.003	0.003	0.003
Critical state index, M	1.540	1.540	1.540
Normal consolidation line intercept (at p' = 98.1 kPa), N	1.552	1.552	1.552
Poisson's ratio, υ	0.350	0.350	0.350
Evolution rule parameters			
Degradation index of overconsolidation, m	0.350	0.350	0.350
Degradation index of structure, a (b=c=1)	1.000	0.150	0.100
The ratio of plastic volume strain to plastic deviatoric, c_s	0.800	0.800	0.800
Rotational hardening index, b_r	1.190	0.800	1.190
Limitation of rotational hardening, m_b	0.270	0.900	0.270
Initial state parameters			
Confining pressure, p'_0 [kPa]	100.0	100.0	100.0
Specific volume, v	1.540	1.550	1.570
Degree of structure, $1/R^*$	2.810	2.000	9.400
Degree of anisotropy, ζ_0	0.000	0.000	0.000
Degree of overconsolidation, $1/R$	21.90	11.20	30.00

4. Conclusions and discussions

Results of experimental work showed that both cementation and fiber-addition have a positive effect on improving performance of weathered soils. Particularly, a cementation significantly increased initial stiffness and compressive strength, but kept brittleness. In contrast, fiber additions improved brittle behavior with also significant increase in compressive strength, however there was no effect on initial stiffness improvement. Furthermore, $\overline{\text{CU}}$ test results were well-captured by SYS Cam-clay model along the whole shearing process for untreated, cement and fiber-treated soils.

Overall, soil improvement with cement and fibers represents a versatile and effective solution for enhancing engineering properties of soils with greater stability, strength, and durability for a wide range of construction projects. Through careful selection of materials and optimization of mix designs, soil stabilization techniques can be further advanced to meet specific project requirements and achieve long-lasting, sustainable infrastructure solutions.