Mechanical performance of different stabilised soils for application in stratified ground

Accomplissement mécanique des différents sols pour appliquer aux couches de terre

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ABSTRACT

To achieve homogeneity in soil mixing along the depth of a column in a non-homogeneous layered soils, it is necessary to understand the effect of soil type on the treatment and to adapt the treatment for the different soil strata. For this purpose, an extensive laboratory testing programme was carried out to examine the effect of different soils and cement content on the mechanical and physical properties of the resulting treated soils. Four different soils, namely gravely sand; silty clayey gravely sand, silty clay and a pure clay were tested. Different grout constituents, constituent ratios, dosages and water content were used in order to improve the performances of the mixes using Portland cement as the main binder. The tests performed included unconfined compressive strength, from which the elastic stiffness was also calculated, and permeability at 28 days. The results show that relatively homogenous results in terms of compressive strength and permeability may be reached by modifying the cement-bentonite ratio in granular soils and the binder dosage in fine-grained soils. The results constitute a preliminary useful guide to adapt in the construction techniques in field applications.

RÉSUMÉ

Pour appliquer l'homogénéité de sol mélangé au long de la profondeur d'une colonne dans les couches des sols non homogènes, il est nécessaire de comprendre l'effet du genre de sol sur le traitement et d'adapter le traitement sur les différents couches. Pour ce but un programme étendu des essais laboratoires a été développé pour examiner l'effet des différents sols et la quantité de lieur sur les propriétés mécaniques et physiques des sols traités. Quatre genres de sol différent ont été utilisés comme exemple sable graveleux, sable limon argileux avec gravier, limon argileux, et gravier. Des différents constituants de mortiers, constituants de rapports, proportions, et contenu d'eau ont été utilisés pour améliorer les exécutions des mélanges utilisant le béton Portland comme un lieur principal. Les essais exécutés comprenaient la force de compression libre de laquelle la dureté élastique et la perméabilité à 28 jours ont été aussi calculés. Les résultats montrent que des conséquences homogènes relatives en terme de force de compression et perméabilité peuvent être atteindre en modifiant le rapport béton : bentonite dans les sols graviers, et la quantité de lieur dans le sable graveleux. Les résultats constituent un guide préliminaire utile pour adapter dans les constructions techniques des applications aux champs.

Keywords: deep soil mixing, laboratory tests, optimisation, mechanical properties, bentonite, layered soils.

1 INTRODUCTION

Deep mixing is a relatively new in-situ treatment technology which improves the mechanical and hydraulic properties of soils with the introduction and mixing of an additive with the soil. In many practical applications it is necessary to obtain a uniform behaviour of treated soils in terms of strenght ad permeability. In the case of non-homogeneous layered soils, such as alluvium deposits, it is then necessary to adapt the treatment to the different particle size and other properties of the different layers. The work presented in this paper forms an initial part of an extensive study aimed at developing simple operative criteria to optimise the deep mixing process and resulting treated soil properties in the presence of geotechnical complex formations (e.g. layered subsoil with high variability of mechanical and hydraulic properties). This work has been carried out as part of a large international collaborative study with the objective of comparing the effect of treatment parameters on the geotechnical properties of cement-stabilised soils.

2 EXPERIMENTAL WORK

The work consisted of a laboratory investigation which studied the effect of the binder content on the mechanical properties, namely unconfined compressive strength, secant modulus and permeability, of different stabilised soils. A total of about 300 tests were conducted to achieve this task.

2.1 *Test Programme*

The testing programme consisted of four test series that covered the effect of soil type and binder content on the mechanical properties of the four soils studied. Each soil type was mixed, moulded, cured and tested using the same methodology. The details of the soil types and binder contents utilised are summarised in Tables 1 and 2. Duplicate samples were used for permeability testing and triplicate samples for the unconfined compression strength (UCS) test.

2.2 *Materials and equipment*

Four different soil types were modelled: Soil I is a gravely sand with an initial water content of 8%, Soil II is a silty clayey gravely sand with an initial water content of 14%. Soil III is a silty clay, a representative of a natural clay, with an initial water content of 50%. This soil has liquid and plastic limits of 40% and 28% respctively. Soil IV is a pure clay and was produced using two water contents of 50% and 100% to produce the medium stiff and very soft clay respectively.

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Table 1. Soil constituents

Soil type.	Kaolin (%)	Silt (%)	Sand (%)	Sharp sand (%)	Gravel (%)	Water content (%)
I	-	-	60	-	40	8
II	15	20	-	40	25	14
III	60	40	-	-	-	50
IV	100	-	-	-	-	50 and 100

Table 2. Details of the soil – grout mixes

Mix no.	Soil type	Initial water content %	Soil:grout ratio	Soil constituents					Grout constituents		Water %
				Kaolin %	Silt %	Sand %	Sharp sand %	Gravel %	Cement %	Bentonite %	
1	I	8	10:1	-	-	50.5	-	33.7	4.0	-	11.3
2	I	8	5:1	-	-	46.3	-	30.9	8.0	-	14.5
3	I	8	3.3:1	-	-	42.7	-	28.5	11.0	-	17.2
4	I	8	3.3:1	-	-	42.7	-	28.5	13.0	-	13.4
5	I	8	10:1	-	-	50.5	-	33.7	2.07	0.03	12.8
6	I	8	10:1	-	-	50.5	-	33.7	2.04	0.06	12.8
7	I	8	10:1	-	-	50.5	-	33.7	2.01	0.09	12.8
8	II	14	10:1	12.0	15.9	-	31.9	19.9	4.0	-	15.7
9	II	14	5:1	11.0	14.6	-	29.2	18.3	8.0	-	18.6
10	II	14	3.3:1	10.1	13.5	-	27.0	16.9	11.0	-	21.0
11	II	14	10:1	11.2	14.9	-	29.9	18.7	10.0	-	15.4
12	III	50	1.5:1	24.0	16.0	-	-	-	20.0	-	40.0
13	IV	50	1.5:1	40.0	-	-	-	-	20.0	-	40.0
14	IV	50	3:1	50.0	-	-	-	-	12.5	-	37.5
15	IV	100	3:1	37.5	-	-	-	-	12.5	-	50.0
16	IV	50	1.5:1	40.0	-	-	-	-	18.0	2.0	40.0

Kaolin clay (Polywhite China clay), frequently utilised in laboratory testing, was used to produce the clay. Silica flour was used for the silt component in the soils. Gravel with a maximum particle size of 10 mm, sand, 150-300μm particle size, and sharp sand used for construction in the UK (D60 = 1.25 mm) were used to produce the granular soils. Portland cement was used as the main binder at different percentage additions by weight which ranged from 4-13% for the granular soils and higher percentages of 12.5-20% for the fine-grained soils. The cement was applied at two different water:cement ratios of 1:1 and 1:2. Bentonite was also used in some cases at different bentonite:cement ratio. For the grouts with bentonite, the latter was mixed using a high shear mixer prior to the introduction of cement to guarantee homogeneous mixing. The grouts and the soils were first prepared separately and then mixed together for 10 mins using a high power food mixer to produce the stabilised soil. The same mixing blade ('K' shape), time of mixing and spin velocity were always used in order to ensure the same mixing conditions for each soil. A higher range of soil:grout ratios from 3.3:1 to 10:1 were used for the granular soils while two different lower ratios of 3:1 and 1.5:1 were used for the fine-grained soils.

The stabilised soils were then placed into plastic moulds 100mm in diameter and 100mm in height for permeability samples and 50mm in diameter and 100mm in height for strength samples in three layers compacted to 30 blows with 8 mm diameter steel rod each. The treated soil specimens were then cured in 20^{o}C and 95% relative humidity in curing tanks. Once the samples developed sufficient strength, which was usually after between 1 and 2 weeks of curing, the specimens were removed from the moulds.

3 RESULTS AND ANALYSIS

The results obtained from the experimental work are presented in three sections to demonstrate the effects of the soil type, binder constituents and content on the UCS, stiffness (E_{50}) and permeability. In each section are presented indications to address the operative parameters of the deep mixing treatment, in presence of geotechnical complex formations.

3.1 *UCS*

Fig. 1 shows the average UCS values for the mixes studied while Figs 2 and 3 show the relationship between the UCS and the cement and water contents respectively. Fig. 1 clearly shows the wide range of UCS values that can be obtained for different soil types and cement content. It is also clear from Fig. 1 that the rate of increase in the UCS of soil I (purely granular) is greater than that of soil II. This is also clear when comparing soils II and IV. It is evident from Fig. 2 that an increase in the cement content results in an increase in the UCS values for all soil types.

Fig. 3 implies that the UCS is inversely proportional to the clay content of the soil. By comparing the results of mixes 3, 10 and 14 (with cement content of approximately 12%) one can see that the soil type significantly affects the final UCS of the treated soil. This should be taken into account when deep mixing treatment is used in layered soils. In fact if an homogeneous UCS of 2000 kPa is needed, it can be achieved by using a cement content of about 8%, 12% and 20% for soil I, II and IV respectively. The higher cement content should be used in the overlapping depth zones of the different soils layers.

The results also show that the water:cement ratio has a considerable impact on the UCS results. When comparing mixes 3 and 4 (Soil I) and mixes 8 and 11 (Soil II), it is evident that by decreasing the water:cement ratio from 1:1 to 0.5:1 (at constant soil:grout ratio) the measured UCS significantly increases. These results are consistent with the conclusions deduced from a related study on cohesive soils (Marzano et al. 2009).

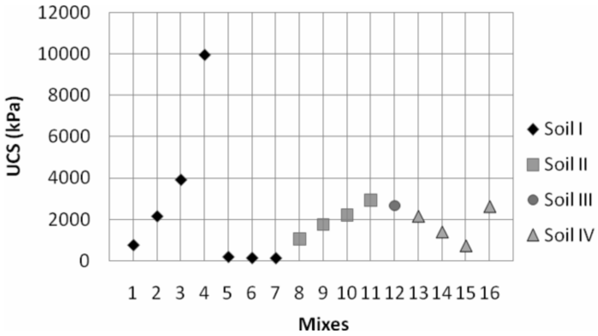

Figure 1. The UCS values for the mixes investigated.

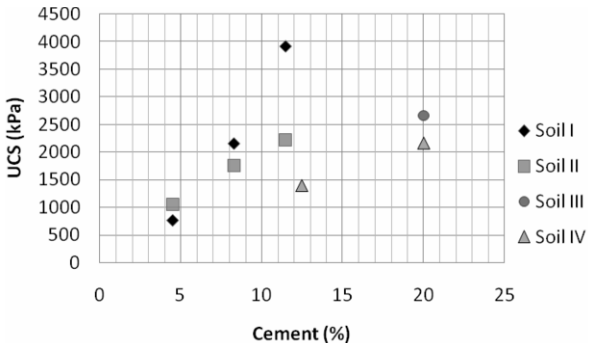

Figure 2. Relationship between the UCS of the stabilised soils and their cement content.

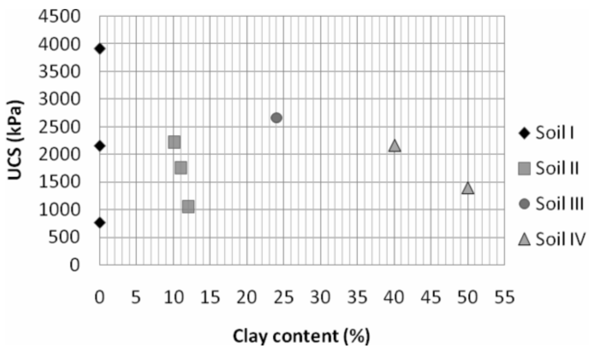

Figure 3. Relationship between the UCS of the stabilised soils and their clay content.

3.2 E_{50}

Fig. 4 shows the average E_{50} values for the mixes investigated while Figs. 5 and 6 show the effects of the cement and clay contents on the stiffness of the treated soils respectively. Similar to the UCS results, the E_{50} is significantly affected by the soil type and cement and clay contents. It is evident from Fig. 5 that the stiffness is directly proportional to the cement content for soils I, II and IV. By comparing the E_{50} results of soils I and II, it is clear that soil I with a higher gravel content produced generally higher stiffness values than Soil II with lower gravel content and higher silt content. On the other hand, the E_{50} results for soil IV (pure clay) were higher than those of soils I and II which is an unexpected result. This however can be accounted for by the higher cement content in the former mixes.

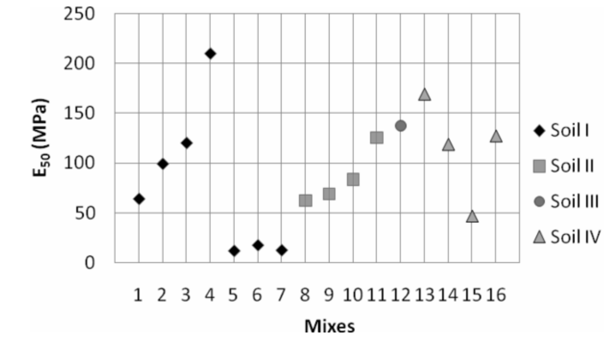

Figure 4. The elastic stiffness values for the mixes investigated.

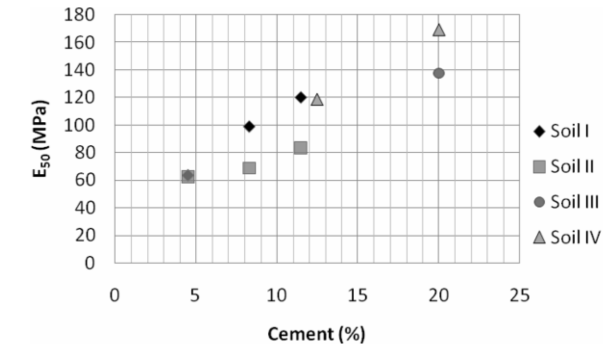

Figure 5. Relationship between the E_{50} of the stabilised soils and their cement content.

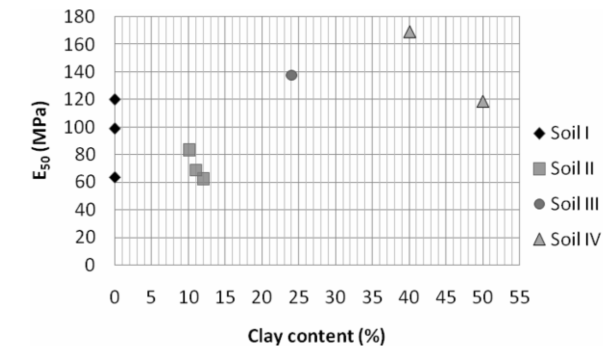

Figure 6. Relationship between the E_{50} of the stabilised soils and their clay content.

By comparing mixes 3 and 4, the effect of the water:cement ratio on the E_{50} of the stabilised soils can be seen. Similar to the UCS results a decrease in the water:cement ratio results in a great increase in the E_{50} value.

3.3 *Relationship between UCS and E_{50}*

The E_{50} value of stabilised soils is generally found to be proportional to the UCS. The results obtained from this study are plotted in Fig. 7 From the figure the following two relationships are obtained:

$$25\ \text{UCS} < E_{50} < 130\ \text{UCS} \quad \text{for soils I and II}$$
$$35\ \text{UCS} < E_{50} < 100\ \text{UCS} \quad \text{for soils III and IV}$$

The latter relationship is consistent with that proposed by O'Rourke et al. (1998). It is evident from the E_{50} and UCS relationships above that a wider range is obtained for the granular soils when compared to the cohesive soils.

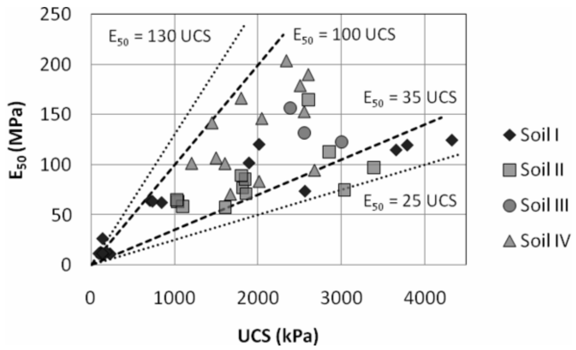

Figure 7. The relationship between the E_{50} and UCS.

3.4 *Permeability*

Fig. 8 shows the average permeability values for the mixes studied while Figs. 9 and 10 show the effect of the cement and clay contents respectively. Fig. 9 shows that an increase in the binder content results in a reduction in the permeability of the stabilised soils and on this semi-log scale it appears that this relationship is almost linear. It is also evident from the figure that the rate of decrease of the permeability for soil I is higher than that of soil II and IV. Similarly the permeability of soil II reduces faster than that of soil IV. It is also clear from the graph that Soil I (gravely sand) exhibits higher values of permeability, around one order of magnitude, in comparison with the soil II (containing 25% of silt and clay). It is obvious that the soil type has a great influence on the permeability of stabilised soils and that the presence of clay and silt, in the treated soil, results in lower permeability values. Similarly to the UCS and E_{50} the permeability is also influenced by the water:cement ratio. A reduction in the permeability, of two orders of magnitude, was evident when comparing mixes 3 and 4 due to the reduction in the water:cement ratio.

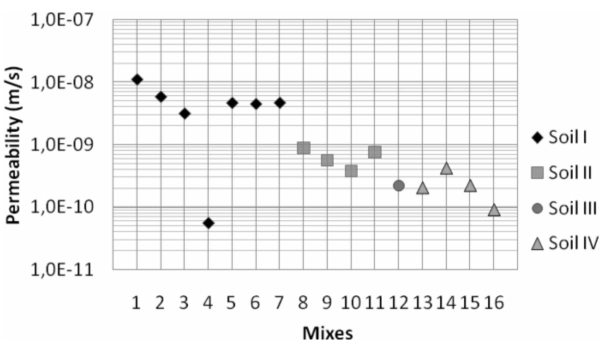

Figure 8. The permeability values for the stabilised soil mixes investigated.

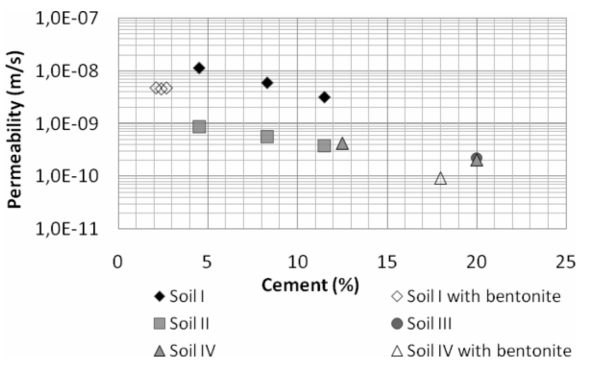

Figure 9. Relationship between the permeability and the cement content.

To study the effect of the bentonite addition, the results of mixes 5, 6 and 7 (named "soil I with bentonite" in Fig. 9) are compared with those of mixes 1, 2 and 3 (soil I) treated only with cement. It is clear that the presence of bentonite in the grout leads to lower values of permeability being reached even with a lower amount of cement. This fact can be relevant in practical applications if reducing the cement usage is needed. The permeability for the three mixes 5, 6 and 7 (Fig. 8) is almost the same which is due to the small variation of the amount of bentonite used between mixes. Similar considerations can be done also for the Soil IV (pure clay) if compared in Fig. 9 with the "soil IV with bentonite (mix 16).

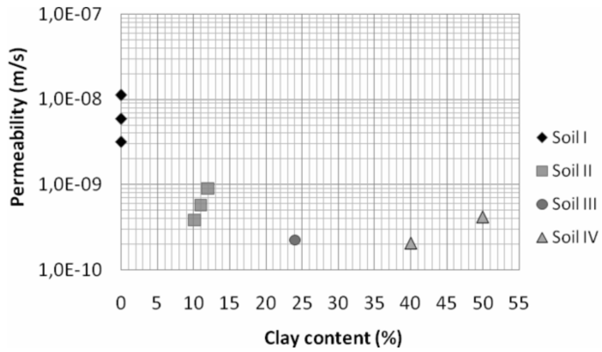

Figure 10. Relationship between the permeability of the stabilised soils and their clay content.

A coefficient of permeability of 1.0E-8 m/s or less is usually required for permanent seepage control (i.e. waste and contaminant containment to prevent groundwater pollution). Fig. 9 shows that in order to obtain such value it is necessary a cement amount of about 10% for the soil I and about 5% for the others. This can be achieved by the modification of the grout flux and/or penetration (or retrieval) speed. If operating with the cutter soil mixing technique, where the use of bentonite is needed to the process, the permeability required can be achieved with a sensible reduction of the cement amount (from Fig. 9).

4 CONCLUSIONS

The laboratory study presented here suggests some important clues to obtain, with soils stabilisation and in particular using the deep mixing method, reliable average performances in layered soils with different mechanical and physical characteristics. Homogeneous geotechnical characteristics in terms UCS and permeability can be achieved in layered soils by modifying the main treatment parameters for single layer unit. The results suggest useful indications to address control techniques for the deep mixing treatment processing of geotechnical complex formations.

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