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Soil improvement by mixing: techniques and performances

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Abstract

Soil treatment and stabilization by mixing, an economic and eco-friendly method, is a technique that is increasingly being used worldwide in order to improve soft soils. A better understanding of the physical and mechanical properties and behavior of the final product is of vital importance for optimizing the design of the mixing process, thus for further development of the mixing methods, there is a need for more extensive laboratory research. The overall objective of the study presented in this paper is to improve the understanding of some of the important aspects of the strength behavior of stabilized soils. An experimental program was carried out in the laboratory on different artificial soils, comprised of clay and sand stabilized with cement, in order to determine the unconfined compressive strength, flexion strength, porosity, density and dynamic modulus. The results of the tests are presented in relation to results obtained by other researchers, available in the literature.

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Keywords: Soil stabilization; kaolin clay; binder; strength; porosity

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1. Introduction

The stabilization technology by Deep Soil Mixing is based on introducing and mixing additives (stabilizing agents) into the ground, as powder or as a suspension, using special equipment, with the main goal to improve volume stability, strength, permeability and durability of the soil. The development of better strengths than the initial ones is possible due to the reduction of the initial void volume, by replacing the fluid in the structure of the soil with the stabilizing agent used, so the particles and the aggregates get closer together, increasing the number of contact points and at the same time preventing the swelling.

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This soil treatment can be used as a practical, economic and environmental solution for a wide range of engineering applications. Some of the soil-mixing applications are road/rail embankments, lime, cement or lime/cement columns for excavation support, marine clays improvement for offshore platforms, shallow foundations, dam reinforcement, slope stability amelioration, silos foundations and reduction of seismic pile displacement.

The most used materials for this technology are cement and lime, but there are many other materials that can be used as stabilizing agents. The most used materials used in the stabilization by unique binder or mixed with other binders include: volcanic ash, bentonite, silica fume, bitumen, grinded furnace slag etc. These stabilizers are added either in dry form or in the form of a slurry in different proportions, these specifications being based on the study of the behavior of the mechanical parameters and of various complex mixtures by means of laboratory tests.

1. History of the Soil Mixing technologies

The basis of the soil mixing concept was laid over 50 years ago in the United States, but the main research, techniques and concept for the modern soil-mixing technology were developed and used in Japan and Sweden, over the last five decades. [1]

In 1954, Intrusion Prepakt Co. (United States) developed the Mixed in Place (MIP) Piling Technique. In the 1960's Japan and Sweden have developed research programs on deep soil-mixing, comprising laboratory and site tests. During the 1970's, several technologies were developed and used within projects, mainly in Japan and Sweden: Soil Mixing Walls (SMW), Deep Lime Mixing (DLM) and Cement Deep Mixing (CDM). The first European technology developed elsewhere than Scandinavia is the Colmix technology, introduced by Bachy Company in France, through which the cemented soil is both compacted and mixed in the same time [1]. The Deep Soil Mixing (DSM) and Shallow Soil Mixing (SSM) were brought to light in the end of the 1980's. Further development of the abovementioned technologies took place during the 2000's, and moreover, new technologies like Geomix, Trenchmix and Springsol, introduced by Soletanche Bachy opened the way to new applications [2].

2. The experimental program

In order to achieve a better understanding of the performances of soil-mix as a new material, a research program was conducted, comprising laboratory tests, for assessing the influence of the clay quantity over the physical and mechanical characteristics of stabilized soil. Artificial soils with different controlled clay content were used, mixed with different cement quantities. Several soil mixes with controlled clay content were created, containing 0, 10, 25, 40 and 50% kaolin clay, the rest of the volume being occupied by the Fontainebleau sand (Table 1).

The mixing process consisted in dry mixing the powder compounds (kaolin clay, cement, sand) in the first stage, then adding the dry mixture into the corresponding water quantity, followed by mixing all the ingredients in a mortar mixer for 10 minutes.

Then, the mixture ("soilcrete") was poured into cylinder shaped carton molds, having 4 and 5 cm diameter and 10 cm height, and rubber prism shaped molds of (4 x 4) x 16 cm. Between preparation and testing, the samples were stored in a controlled environment, with a constant temperature of 19 °C and with a relative humidity that prevents samples from drying. After 7 days, the mold was removed and the hardened samples were wrapped in wet cloth and stored again into closed plastic bags until the desired curing age (7 or 28 days).

The tests carried out on the soil-mix samples were: determination of the density, porosity, unconfined compressive strength, flexion strength and dynamic modulus.

The porosity was studied after a curing time of 7 days and 28 days respectively. Specimens of 4 x 10 cm were endogenously cured for 7 and 28 days. When reaching the curing age, they were dried in an oven at 60°C. The dried samples were weighed each day, until a change in mass of less than 0.5% was observed, when they could be considered dry, then the samples were introduced in a plastic box inside a desiccator and subjected to a vacuum pressure of -0.92 bar. After several hours, de-aired water was poured into the desiccator. The samples were saturated for about 3 days and then were weighed. Before weighing, the superficial water on the surface of the samples was removed by wiping with a cloth.

Table 1. Summary of the soil-mixes used throughout the research

Formulation	Kaolin clay (%)	Cement (kg/m3 soilcrete)	Kaolin clay (kg/m3 soilcrete)	Sand (kg/m3 soilcrete)	Water (kg/m3 soilcrete)	Cement/Water ratio (Mixing)	Water content (%)
K0/C200	0	200	0	1534	352	0.57	20.29
K10/C200	10	200	125	1144	451	0.44	30.69
K25/C200	25	200	243	743	557	0.36	46.94
K40/C200	40	200	318	487	625	0.32	62.20
K50/C200	50	200	347	353	664	0.30	73.70
K0/C150	0	150	0	1589	349	0.43	20.07
K10/C150	10	150	128	1178	455	0.33	31.22
K25/C150	25	150	255	781	556	0.27	46.85
K40/C150	40	150	336	514	625	0.24	62.49
K50/C150	50	150	366	373	667	0.23	74.97

The press used for performing the unconfined compressive strength (UCS) tests and the flexion tests was an electro-mechanical control press. Before the test, the cylinder shaped samples were prepared by cutting and levelling the top and the bottom surfaces using sand paper. Each sample was measured, weighed and the dynamic elasticity modulus was determined by ultrasound device. The prism shaped samples were tested without any prior additional preparation. A speed of charge of 0.04 MPa/s was chosen for both types of tests.

In order to determine the longitudinal waves (P-waves) velocity, therefore the dynamic modulus, longitudinal vibrations pulse are generated by an electro-acoustical transducer held in contact with the surface of the soilcrete. The steel transducers were placed at the opposite sides of the sample, after being cut and surfaced. For coupling, silicon grease was used between the plates and the sample surface. After passing through the sample, the pulse of vibrations is captured and converted into an electrical signal by a second transducer.

2. Results of the tests and analysis of the results

2.1. Density

The density of the fresh and hardened material was measured in wet and dry state. The theoretic density, determined by the recipe of each formulation, therefore by the quantity of each compound material, was also taken into account.

A diminution in the difference between the density in fresh state and the density in hard state, as well as a growth in difference between the apparent density in wet state and the one in dry state, when increasing the kaolin clay dosage may be observed.

Even though the charts (Fig. 1) show a linear trend line for each of the four unit weights, a slight trend to a descending exponential curve trend line may be observed.

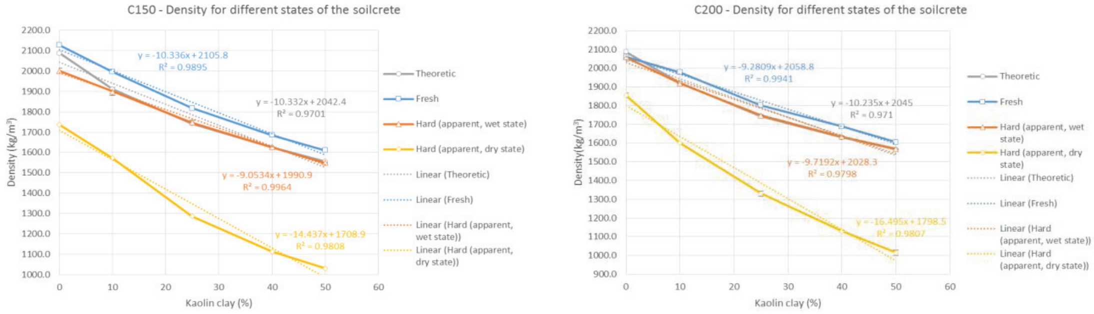

Fig. 1 – Variation of density of soilcrete in different states: (a) for 150 kg/m3 cement; (b) for 200 kg/m3 cement dosage

2.2. Porosity

The value of the porosity is strongly related to the initial water quantity, as the water hydrating the cement creates voids. The porosity accessible to water varies between 25% and 61% (Fig. 2).The higher the dosage of kaolin clay, the higher water demand is, therefore the porosity is increasing.

The porosity also slightly tends to decrease with a higher cement quantity in a linear trend line. The change in the particle size distribution and a higher formation of hydrates can explain this trend. Nevertheless, at 28 days curing age, the porosity is approximately the same for the same percentage of kaolin clay, even though the binder dosage varies. A difference of maximum 4% was observed, however this was generally below 1%.

When relating to curing age the soil mixes, no rule was observed. There may be a slight diminution trend between the porosity at 7 days curing age and at 28 days curing age, but not confirmed for all the formulations (Fig. 2).

Relating the porosity to the apparent unit weight in wet state, the porosity decreases as the unit weight increases. However, no major trend seems to apply to different curing ages (Fig. 3).

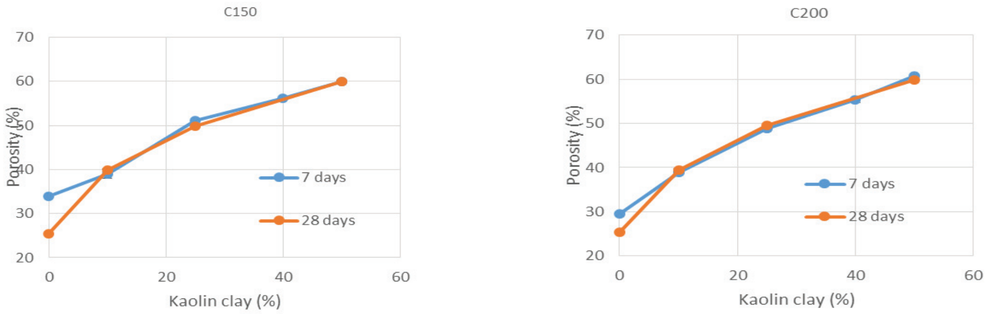

Fig. 2 – Porosity measured at 7 days and 28 days curing age: (a) for 150 kg/m3 cement; (b) for 200 kg/m3 cement dosage

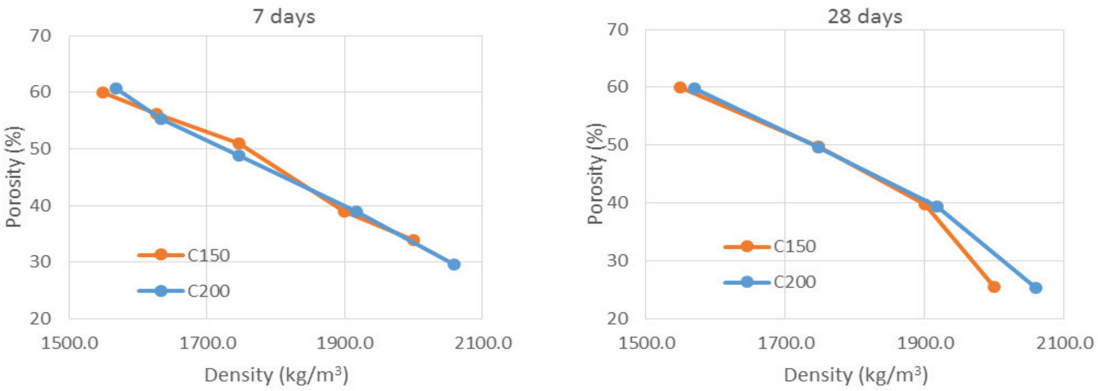

Fig. 3 – Porosity measured at different cement quantities, depending on the apparent density in hard wet state: (a) 7 days (b) 28 days

2.3. Unconfined compressive strength (UCS)

The best unconfined compressive strength values were obtained for samples with 10% kaolin clay (approximately 5.5 MPa for 200 kg cement dosage). When relating this study to the results of Helson [3] it can be confirmed that the ideal kaolin clay content for strength development is for approximately 10% kaolin clay dosage (Fig. 4).

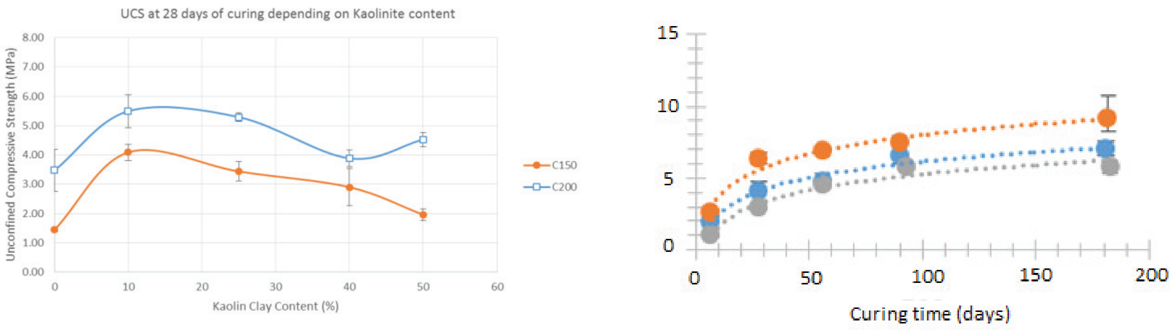

Fig. 4 – (a) UCS measured at 28 days curing age; (b) UCS for cement dosage 200 kg/m^3 by Helson [3]

It may be observed that the difference in strength between the two studied cement quantities, for the same kaolin clay percentage, is of approximately 2 MPa.

A linear relationship may be observed between the compressive strengths at 28 days for the cement quantities that were studied in this research (Fig. 5).

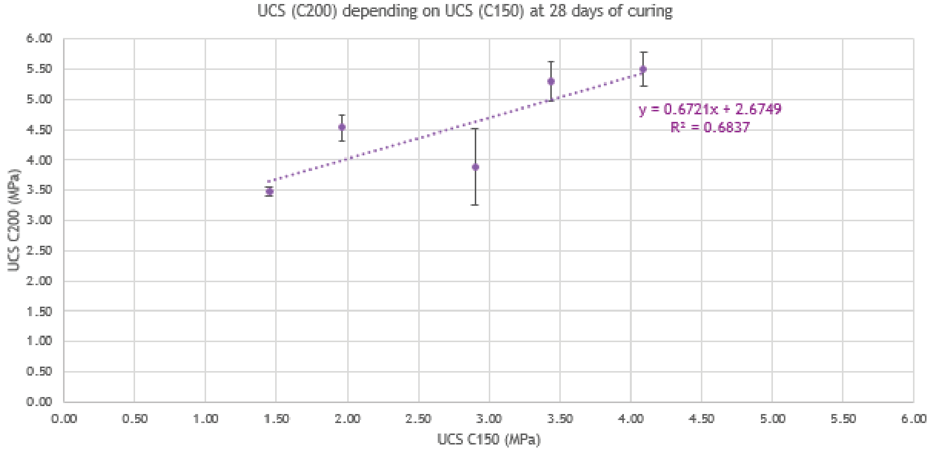

Fig. 5 – Relation between the UCS for 150 kg/m^3 cement and for 200 kg/m^3 cement

The compressive strength of a treated soil lies between UCS of the native soil and UCS of a concrete. When a binder added, the mechanical strength increases in time. In some cases, the mechanical strength of treated soils may decrease because of variable curing conditions (temperature, hygrometry, moisture content or other perturbations) [4].

The increase in strength of the soil after treatment over time is influenced by a series of factors. Depending on the soil, the type of binder will have a significant impact on the results. Some other factors that affect the increase of strength with time are the amount of binder, the mixing effort, the temperature and the stress during curing [5, 6].

2.4. Dynamic (Young) Modulus

For the dynamic elasticity modulus, the same trend as the unconfined compressive strength measured at 28 days curing age may be observed, excepting the samples for the formulation K0/C200. The values (Fig. 6) decrease with the kaolin clay percentage, having a maximum for 10% of kaolin clay. The difference between the dynamic Young modulus for the two studied cement quantities is in general less than 2 GPa, and most likely below 1.5 GPa.

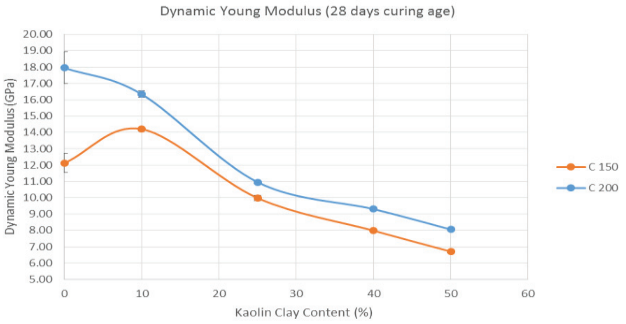

Fig. 6 – Dynamic Young Modulus determined at 28 days curing age for different cement quantities

As it may be observed in Fig. 7, the relation between the UCS and the P-waves velocity determined at 28 days, the trend line is ascendant, as shown by previous research conducted by Åhnberg and Holmen [7] (Fig. 8), for the cement dosage of 150 kg/m3, but slightly descendent for the cement dosage of 200 kg/m3. This fact is probably due to the low number of tested specimens, so to the unevenness of the results.

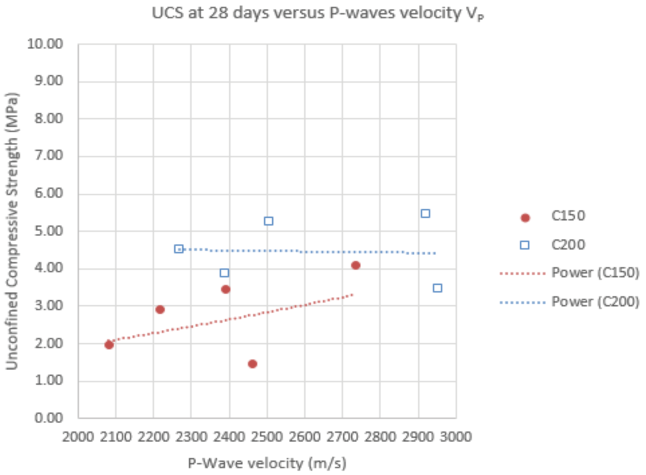

Fig. 7 – Unconfined compressive strength determined at 28 days curing related to the P-wave velocity

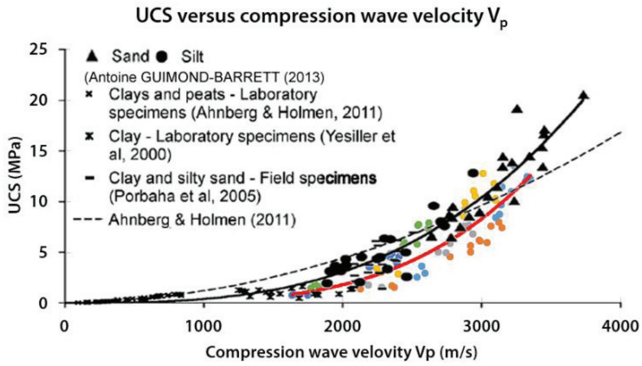

Fig. 8 – UCS related to wave velocity, literature survey comparison [7]

2.5. Flexion strength

The best flexion strength values were obtained for samples with 10% kaolin clay for 150 kg cement dosage and for samples with 25% kaolin clay for 200 kg cement dosage (2.1 MPa, respectively 2.6 MPa) (Fig. 9).

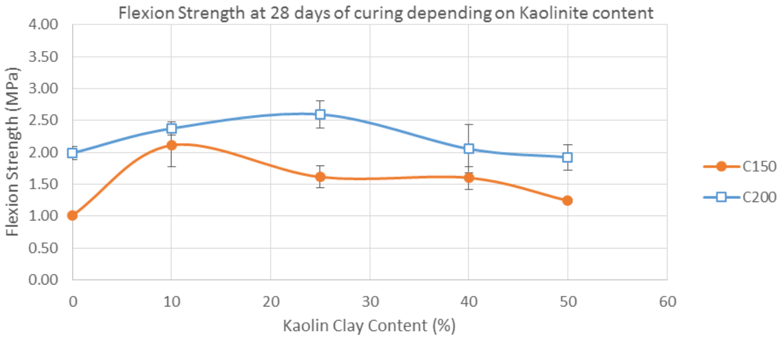

Fig. 9 – Flexion strength measured at 28 days curing age for different cement quantities

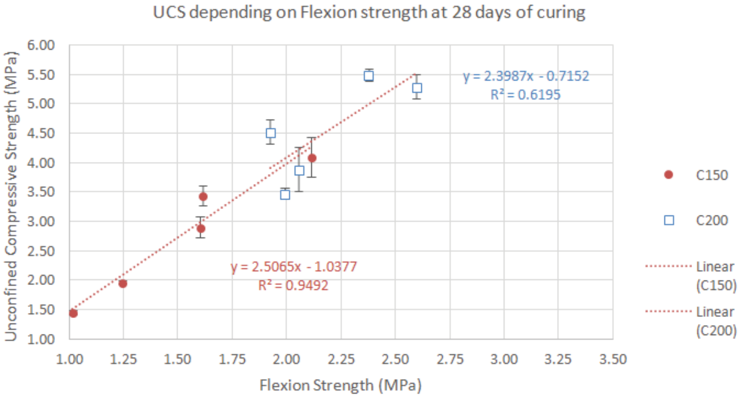

Fig. 10 – Unconfined compressive strength in relation to flexion strength at 28 days curing age for different cement quantities

A linear relationship between the flexion strength and the unconfined compressive strength at 28 days (Fig. 10) may be observed. The ratio value is between 0.42 and 0.64, in general being around 0.50. However, this ratio was not obtained for all the formulations.

3. Conclusions

The experimental program consisted in unconfined compressive strength tests, flexion strength tests and wave velocity measurements. In addition, on the hardened material the density, porosity, and permeability and their influence over the final material behaviour were studied. The data presented in this report follows the same trend as the other available data from other studies, confirming a certain repeatability.

The density in all the states decreases when increasing the kaolin clay quantity. It can be observed a diminution in the difference between the density in fresh state and the density in hard state, as well as a growth in difference between the apparent density in wet state and the one in dry state, when increasing the kaolin clay dosage.

The porosity accessible to water varies between 25% and 61%. The higher the dosage of kaolin clay, the porosity is increasing. The porosity slightly tends to decrease with a higher cement quantity in a linear trend line. The change in the particle size distribution and a higher formation of hydrates can explain this trend. Nevertheless, at 28 days curing age, the porosity is approximately the same for the same percentage of kaolin clay, even though the binder dosage varies. A difference of maximum 4% was observed, however this was generally below 1%.

The best unconfined compressive strength values were obtained for samples with 10% kaolin clay (approximately 5.5 MPa for 200 kg cement dosage). The difference in strength between the two studied cement quantities, for the same kaolin clay percentage, is of approximately 2 MPa.

For both P-Wave velocity and dynamic elasticity modulus, it may observed the same trend as the unconfined compressive strength measured at 28 days curing age. The values for both parameters decrease with the kaolin clay percentage, having a maximum for 10% of kaolin clay. The difference between the dynamic Young modulus for the two studied cement quantities is in general less than 2 GPa, and most likely below 1.5 GPa.

The best flexion strength values were obtained for samples with 10% kaolin clay for 150 kg cement dosage and for samples with 25% kaolin clay for 200 kg cement dosage (2.1 MPa, respectively 2.6 MPa). A linear relationship between the flexion strength and the unconfined compressive strength at 28 days. The ratio value is between 0.42 and 0.64, in general being around 0.50.

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