BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 62 (66), Numărul 4, 2016
Secţia
CONSTRUCŢII. ARHITECTURĂ

INFLUENCE OF THE WATER CEMENT RATIO ON THE UNCONFINED COMPRESSIVE STRENGTH OF A ROMANIAN SILT TREATED WITH PORTLAND CEMENT

BY

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Received: November 21, 2016
Accepted for publication: December 20, 2016

Abstract. A relatively new approach regarding the improvement of the geotechnical parameters consists of the *in situ* mixing of the soil with various stabilizing agents. A particular case of this treatment process is represented by the Cement Deep Soil Mixing methods. For the projects in which such a method is adopted, one of the main stages is the experimental laboratory program. Its purpose is to evaluate the applicability of the method and to determine the optimal formula of the stabilizing agent. This article focuses on a laboratory experiment aimed at investigating the influence of the water-cement ratio on the unconfined compressive strength of a powder mixed with cement slurry. In this respect, 155 samples prepared by mixing the soil with with three amounts of powder cement (150, 200 and 250 kg/m^3) and various water-cement ratios have been tested. The results allowed the identification of an optimal water-cement ratio for each of the three amounts of analyzed cement. An important aspect is that the increase of the water-cement ratio has led to the increase of the strength, a fact motivated by the low natural humidity of the analyzed powder.

Keywords: Romanian silt; cement sllury; water-cement ratio; unconfined compressive strength.

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1. Introduction

The surface stabilizing process of soils with mineral binders, especially with cement, has been used in Romania in order to improve their physical and mechanical characteristics since the 1950s. The main applications aim at stabilizing the soil layers included in road structures or earthworks e.g., dikes, dams, embankments (Lazăr, 1975). Although still not put into practice in Romania, deep soil stabilizing alternative is available, by mixing it with cement or with another stabilizing agent, known in the specialty literature as “Deep Soil Mixing Methods”. These technologies enjoy a multitude of applications worldwide, such as reducing the deformations manifested in the road or rail embankments, improving the bearing capacity of the foundation soil, ensuring slope stability, limiting the liquefaction potential, supporting deep excavations (EuroSoilStab, 2002; Kitazume &Terashi, 2013; Topolnicki, 2013). Regardless of the depth at which the intervention is carried out, the stabilizing of the soil by mixing it with cement is based on the chemical reactions and the physical processes that occur between the two components. Thus, the result is a geomaterial characterized by a heterogeneous structure, made out of products obtained by the hydration of cement, reaction products between cement and soil and, a mass of natural soil which remains unaltered and which depends on the quantity of used cement dosage. In order to assess the specific performances of the geomaterial, within the applications aiming at treating the soil by mixing it with stabilizing agents, it is necessary to conduct some rigorous laboratory and/or field analyses.

The laboratory tests and analyses are carried out initially on the soil in its natural state, in order to identify and classify it chemically, physically and mechanically. Subsequently to the mixing of the soil with the stabilizing agent, laboratory analyses which highlight the modifications in the resistance and deformability parameters of the new material are carried out once more. In this way, the results to be obtained following the ground application of this improvement process can be estimated. This paper presents the results of a laboratory study conducted on a silt soil type, mixed with cement. The main purpose of this article is to highlight the influence that the water-cement ratio has on the unconfined compressive strength of a soil-cement mixture. Within the study, more treatment recipes, which involved different powder cement quantities and water-cement ratios, have been analyzed. Several laboratory analyses, including unconfined compression tests after 7, 28, and 56 days following the curing of the mixture, have been conducted. In general, under normal humidity conditions, the water-cement ratio is expected to increase and the resistance value, to decrease (Bruce *et al.*, 2013; Filz *et al.*, 2005). The analyzed soil shows as feature the low humidity in its natural state by 15.81%. In this case, the results have highlighted the positive influence that the increased water-cement ratio has had on the resistance of the prepared mixtures. Thus, the strength has increased with the increased amount of water used in preparing the slurry, which can be justified as consequence of the fact that the soil in its natural state did not contain enough water, necessary for hydrating and binding the new chemical compounds. For each stabilizing recipe that implied a certain quantity of cement powder *e.g.*, 150, 200, and 250 kg/m^3, the optimal value of the water-cement ratio was considered the value beyond which the strength began to decrease.

2. Characteristics of the Used Materials

The materials used in the laboratory experimental program have consisted of: natural soil - silt, Portland cement, and distilled water.

The analyzed soil was sampled from a site characterized by instability phenomena – settlements, located in Galați Municipality, Romania. In order to identify the soil, granulometric analyses using the aerometro method, which revealed a percentage of silt of 60%, granulometric majority fraction, have been carried out. Consequently, the analyzed soil was classified, according to SR EN ISO 14688/2-2005, as belonging to the silt category. The results of the laboratory investigations carried out on the soil in natural state were centralized in Table 1.

Table 1
Chemical, physical, and mechanical characteristics of the silt

<table>
<tr><td rowspan="9">Silt (cf. SR EN ISO 14688 -2:2005)</td><td colspan="2">Chemical and physical characteristics</td><td colspan="3">Mechanical characteristics (measured average values)</td></tr>
<tr><td>pH</td><td>7.5</td><td>Unconfined compression strength, [kPa]</td><td colspan="2">66.51</td></tr>
<tr><td>Organic matter content, [%]</td><td>0,…,1</td><td>Edometric deformation modulus Eoed 200-300, [kPa]</td><td colspan="2">7,625.04</td></tr>
<tr><td rowspan="2">Unit weight, [kN/m^3]</td><td rowspan="2">16.45</td><td rowspan="2">Shear strength parameters under consolidated and undrained conditions</td><td>Φ, [°]</td><td>17.18</td></tr>
<tr><td>C, [kPa]</td><td>36.30</td></tr>
<tr><td>Humidity, [%]</td><td>15.81</td><td rowspan="4">Index of the additional settlement by humidification i_{m3}, [%]</td><td rowspan="4" colspan="2">6.73</td></tr>
<tr><td>Porosity, [%]</td><td>48.30</td></tr>
<tr><td>Plasticity index, [%]</td><td>12.88</td></tr>
<tr><td>Consistency index</td><td>1</td></tr>
</table>

The used cement was a common Portland one, CEM I 42.5R, characterized by an unconfined compressive strength at 28 days, between 42.5 and 62.5 MPa.

3. Preparation, Storage and Sample Testing Procedure

In order to prepare the soil-slurry cement mixture, the specifications listed in the Standard of the Japanese Geotechnical Society were followed. This procedure is detailed by Kitazume and Terashi in the book entitled "The Deep Mixing Method" and in other scientific papers (Grisolia *et al*., 2013; Kitazume *et al*., 2015).

For the preparation of the samples, the following equipment and tools were used: balance with a minimum of 0.01g accuracy, electric mixer, cylindrical plastic molds, compacting tool and other accessories, such as spatulas and forks. After weighing the materials, in order to prepare the samples, the following stages were completed: initial disintegration of the natural soil, cement slurry preparation, soil and slurry 10 minute mixing and, finally, mold arrangement, and static compacting in successive layers of the mixture. The plastic, disposable molds had a diameter of 50 mm and a height of 100 mm (Fig.1.). After the actual mold mounting, the samples were sealed, weighed, labeled according to the composition, and stored so that they cure at a constant temperature. In order to obtain the relevant results that show as accurately as possible the time evolution of strength in accordance with the actual ground conditions, during the curing period, the samples were stored, until testing time, at a temperature of 7°C,...,8°C, temperature which corresponds to depths greater than 3 m and which is recommended in the sample storage specialty literature (SGF 4:95E, 1997; Ignat 2015; Åhnberg & Andersson, 2015).

Fig. 1 – Stabilized soil samples after curing.

155 samples were prepared following the preparation and storage procedures described above, within the experimental program. The main differentiating element of the samples was the recipe of the stabilizing agent e.g. the quantities of cement and water, shown in Table 2. According to the European Standard EN 14679-2005, the binder content expressed in kg/m^3 (column 1 of Table 2) is defined as the weight of the dry binder introduced in the unit volume of the soil that stabilizes, and the water-cement ratio (column 2 of Table 2) is defined as the weight of the water needed to prepare the slurry, divided to the weight of the dry binder.

In order to investigate the impact that the water-cement ratio has on the strength of the soil mixed with cement slurry, unconfined compression tests were carried out (STAS 8942/ 6-75; ASTM D2166/D2166M, 2013). For each slurry recipe, 9 cylindrical specimens, corresponding to the three test periods at 7, 28, and 56 days, were prepared. The unconfined compression tests were performed on stabilized soil samples, with the aforementioned curing ages, with an upload speed of 1 mm/min (Fig. 2). The value of the normal stress corresponding to the breaking or yielding time of the sample was considered the unconfined compressive strength of the tested material.

Table 2

Cement Slurry Recipes Used Within the Experimental Program

Stabilizing agent type	Cement content, [kg/m^3]	Water-cement ratio
CEM I 42.5 R Cement slurry	150	0.8
		1.3
		1.5
		1.8
		2.3
		2.5
	200	1.3
		1.5
		1.6
		1.8
		2.3
	250	1.3
		1.5
		1.6
		1.8
		2.3

Fig. 2 – Stabilized soil samples during the unconfined compressive assay.

4. Result interpretation

The unconfined compression test is carried out all over the world, on stabilized soil samples, to assess the strength and stiffness characteristics (Grisolia *et al*., 2013; Ignat, 2015; Kitazume *et al*., 2015). The unconfined compressive strength value measured at 28 days is the key parameter in designing (Kitazume & Terashi, 2013 Topolnicki, 2013). Regardless of the number of days after which the testing was carried out, the maximum unconfined compressive strength value, q_u, was obtained for the samples prepared using the biggest quantity of cement, respectively 250 kg/m^3 (Fig. 3). Considering the maximum unconfined compressive strength value, depending on cement quantity α and the W/C water-cement ratio, the following combinations were considered optimal variants: for α = 150 kg/m^3, the optimal W/C ratio = 2.3; for α = 200 kg/m^3, the optimal W/C ratio = 1.8; for α = = 250 kg/m^3, the optimal W/C ratio = 1.5 (Fig. 4).

The first slurry cement formula analyzed within the experimental program consisted of a powder cement quantity equal to 150 kg/m^3 and a W/C ration equal to 0.8. Following the unconfined compressive tests performed 7 days after sample preparation, a normed strength value equal to 57.59 kPa lower than the average measured value of the strength of the soil in natural state equal to 66.51 kPa (Table 1) resulted. This situation can be justified by the insufficient amount of water contained in the soil in natural state, required in the first stage of cement hydration reactions and, subsequently, in the long term pozzolanic reactions, in creating cementation compounds. This argument is based on the fact that, as the W/C ratio was increased, the resistance value increased.

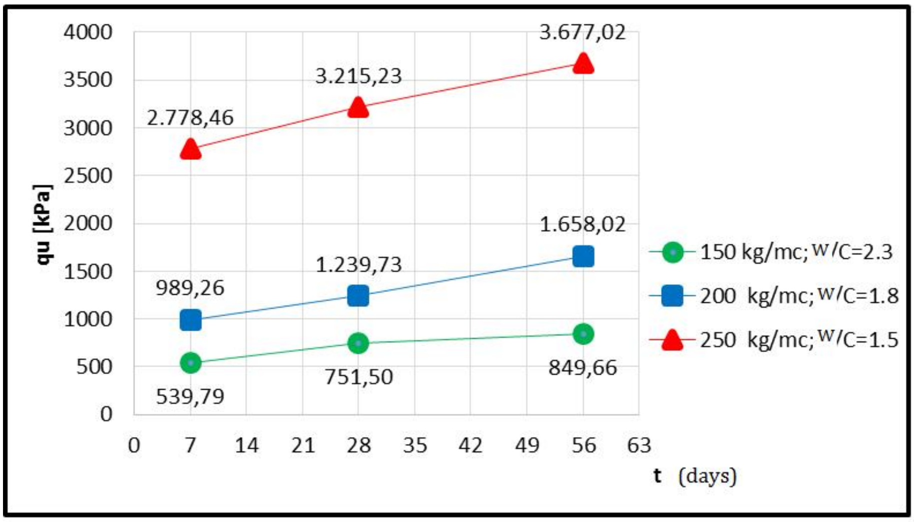

Fig. 3– Unconfined compressive strength depending on the curing time.

Taking as starting point the W/C water-cement ratio = 0.8, by the gradual increasing of its value, it was found that, for the 150 kg/m^3 cement quantity, the maximum unconfined compressive strength values were obtained for the 2.3 water-cement ratio. Beyond this value, for the W/C ratio C = 2.5, a decrease of resistance is found (Fig. 4). Therefore, for the 150 kg/m^3 cement quantity, for the powder type analyzed soil, the optimal value of the water-cement ratio has been found to be 2.3. For α = 150 kg/m^3 and W/C = 2.3, the maximum resistance value $q_{u,}$ which is approximately 8, 11, and 13 times bigger than the strength of the natural soil at 7, 28, and respectively 56 days following the mixing, was obtained.

The same procedure was followed to establish the optimal water-cement ratio and for the other cement quantities of 200 kg/m^3 and 250 kg/m^3 analyzed. Taking into account the previous experience related to the water-cement ratio equal to 0.8, in these two cases, the first analyzed report was of 1.3. For α = = 200 kg/m^3 and W/C = 1.8, the maximum resistance value qu, which is approximately 15, 19, and 25 times bigger than the resistance of natural soil at

7, 28, and respectively 56 days after mixing, was obtained, and for α = = 250 kg/m^3 and W/C= 1.5, the maximum resistance value qu, which is approximately 42, 48, and 52 times bigger than the resistance of natural soil at 7, 28, and respectively 56 days.

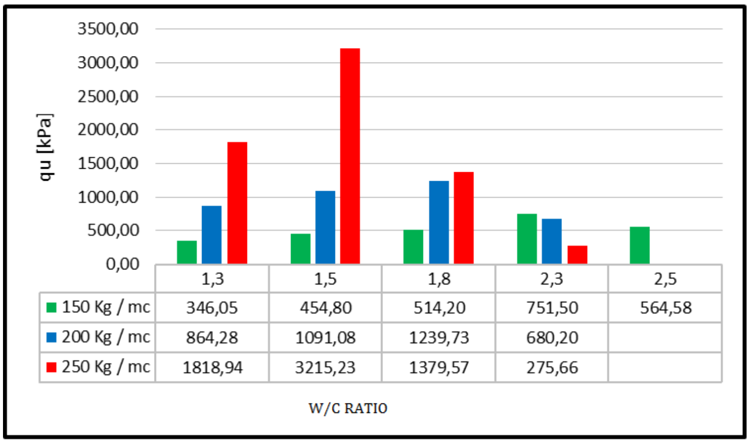

Fig. 4 – Unconfined compressive strength at 28 days, depending on the cement quantity and the water-cement ratio.

5. Conclusions

This article presents the results of an experimental laboratory program, conducted on a silt sampled from Galați Municipality, Romania. The natural soil was mixed with various cement slurry recipe, prepared by varying the amount of powder cement and the water-cement ratio. Within the experiment, 155 cylindrical samples with a diameter of 50 mm and a height of 100 mm were analyzed. In order to assess the influence of the water-cement ratio on the strength characteristics, unconfined compressive tests were performed on the samples with a curing age of 7, 28, and 56 days. The results of the carried out showed that, for the analyzed soil, characterized by a natural humidity of 15.81%, the hypothesis according to which the unconfined resistance strength decreases as the water-cement ratio increases, is not valid. This fact is argued by the need for a sufficient amount of water, be it contained in the soil pores, be it added to the preparation of the suspension that allows the occurrence of chemical reactions between the soil and the stabilizing agent. Thus, for the analyzed situation, by increasing the water-cement ratio used in sample preparation, the testing revealed the increase of resistance up to a point, beyond which it began to drop. This resistance peak was considered the optimal value for the water-cement ratio.

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INFLUENŢA RAPORTUL DE APĂ-CIMENT ASUPRA REZISTENŢEI LA COMPRESIUNE MONOAXIALĂ A UNUI PĂMÂNT ROMÂNESC DE TIP PRAF TRATAT CU CIMENT

(Rezumat)

O abordare relativ nouă în ceea ce priveşte îmbunătăţirea paramerilor geotehnici constă în malaxarea terenului in situ cu diverşi agenţi de stabilizare. Un caz particular al acestui procedeu de tratare il constituie metodele de stabilizare a terenului in adâncime prin malaxare cu suspensie de ciment (Cement Deep Soil Mixing). Pentru proiectele în care este adoptată o astfel de metodă, una dintre etapele principale constă în programul experimental de laborator. Scopul acestuia este de a evalua aplicabilitatea metodei şi de a stabili reţeta optimă a agentului de stabilizare. Acest articol este axat pe un experiment de laborator ce vizează investigarea influenţei pe care raportul de apă-ciment o are asupra rezistenţei la compresiune monoaxială a unui praf malaxat cu suspensie de ciment. În acest sens au fost testate la compresiune monoaxială 155 de probe pregătite prin amestecatea prafului cu trei cantităţi de ciment pulbere (150, 200 şi 250 kg/m^3) şi diverse rapoarte de apă-ciment. Rezultatele au permis identificarea unui raport optim de apă-ciment pentru fiecare dintre cele trei cantităţi de ciment pulbere analizate. Un aspect important îl reprezintă faptul că majorarea raportului de apă-ciment a condus la creşterea rezistenţei fapt motivat de umiditatea naturală scăzută a prafului analizat.