Strength increase in time of an alluvial clay, typical of the coast of Brazil´s Northeastern, mixed with different dosages of cement

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ABSTRACT

This study presents the increase over time of the strength of an alluvial clay, typical of the northeast coast of Brazil, mixed with different dosages of cement. In laboratory, water was added to samples obtained until the moisture content reached its liquid limit. Then the clay was homogenized using a planetary mixer with steel reservoir with a capacity of 5 lts and stainless steel beater. The following dosages of cement were used: 200, 400 and 600kg/m³. The cement used was of type Portland made with blast furnace slag (compressive strenght ≥32MPa for 28 days) and water /cement ratio of 0.8. After completion of mixing, the sample was homogenized during five minutes. The specimens were molded using a cylindrical steel mold with height and diameter of 50mm and 100mm, respectively. Soon after remoulded, they were immersed in water, and subsequently taken to failure in laboratory tests of uniaxial compression according to the recommendations of the Brazilian Association of Technical Standards (ABNT: NBR 14992/03 - "Determination of compressive strength). The tests were performed after 7, 28, 56 and 120 days. The soil samples were collected in an area located on the coast of Pernambuco State, northeastern Brazil. The site collection is characterized by a superficially homogeneous layer composed by highly organic clay-silts to very soft clays, with gray color and a thickness ranging between 12 and 15m. The groundwater level is found at 1.60m depth. Data analysis, determined by tests conducted, enabled the evaluation of the increase with time of the compressive strength of the soil-cement mixture, and the influence of dosage in the resistances values obtained

1. INTRODUCTION

1.1. Soft Soil stabilization by means of chemical elements addition

With the expansion of urban areas, increasing the necessity of occupation, sites that were not historically occupied due to geotechnical engineering, such as dominant soft soils, are now being increasingly occupied.

This situation concerns the technical means to find alternative solutions for mitigation of structural problems caused in the superstructures of the buildings by soil settlements.

One approach to this problem also includes, as an alternative for the treatment of these soils by means of chemical additives, the execution of pre-compaction, removal and replacement of material, among others (Nelson & Miller, 1992).

The soil stabilization by adding cement to improve the geotechnical characteristics of soft soil consists in a new technique, which has found wide acceptance in recent years by the improvement of technical means, with higher versatility and competitiveness compared to other more heavy classical solutions. (Hausmann, 1990).

The concept of using lime in marine organic clays stabilization was first published in technical journals written by PHRI (Port and Harbour Research Institute) in 1968 (Yanase, 1968).

The first studies carried out by PHRI aimed to pursue two main goals: a) to investigate how the lime reacts with Japanese marine clays; b) to develop equipment that would allow the constant supply of stabilizing agent and a proper and uniform mixing during the operation. These surveys also revealed that many Japanese marine clays showed strength gains in the order of the 100kN/m^2 to 1MN/m^2, in terms of unconfined compression strength.

In 1967 a new methodology for clay stabilization using active lime was developed by Kjeld Paus. The method was then called "Swedish Lime Column Method (SLCM)" (Broms & Boman, 1975).

Broms & Boman (1975) reported this new technique to the Geotechnical International Community at the 5th Asian Regional Conference of Soil Mechanics and Foundations Engineering. The first publication containing design recommendations was written by Broms & Boman was published in 1977 (Broms & Boman, 1977).

In Northern Europe countries, the main objective of improving soil using columns of soil-lime is to reduce the road settlements in landfills, to improve stability of compacted embankments, excavation slopes and other geotechnical structures. The mixing of lime and cement is also currently used to prepare columns with higher resistance (Rathmayer, 1996).
As an example of application of this technique, Rathmayer (1996) comments that in 1992 Sweden and Finland carried out more than one million linear feet of stabilized soil column. The author also reports that recently some new stabilizing agents, composed of ash and recycled residues, are being increasly used in the treatment of organic soils and saturated
The selection of the stabilizing agent and the sellection of the dosage will depend on the local ground conditions (soil type) and the level of improvement needed (Taki & Yang, 2005).
The concentration of stabilizing agents is usually expressed in weight per volume of soil mass to be treated. According to Bruce (2001) and Jacobson *et al* (2003) this value reaches 6 and 12% of the dry weight of soil under treatment.

1.2. Basic mechanisms of soft soil stabilization

For many different types of soils, Portland Cement and Lime are the most commonly used stabilizing agents, however there is a range of other agents available today that can be used with success.
The basic mechanisms of admixture stabilization using cement or lime were extensively studied for several decades in transport infrastructures' engineering. This is because lime or cement treated soils have been used for sub-base or base materials in road constructions for long (Ingless & Metcalf, 1972). In the following paragraphs, the basic mechanisms lime and cement stabilization are briefly reviewed.
The most common types of cement used as stabilizing agent are the following: Portland cement, cement made from blast furnace slag and special cements.
Portland cement is obtained by the addition of gypsum and clinker. The clinker is formed by minerals: $3CaO.SiO_2$, $2CaO.SiO_3$, $3CaO.Al2O_3$, $4CaO.Al2O_3.Fe2O3$.
The cementitious mineral 3CaO.SiO2, for example, reacts with water hydrating the cement in what follows, herein expressed by:

$2(3CaO.SiO_2)+6H_2O=3CaO.2SiO_2.3H_2O+3Ca(OH)_2$..............(1)

During the cement hydration, calcium hydroxide is released. The product of hydration of cement induces an increase of strength up to significant values, while the calcium hydroxide contributes to the pozzolanic reaction, occurring along the stabilization of lime.
The cement blast furnace slag is obtained by mixing Portland cement and blast furnace slag. When well ground, the blast furnace slag will not react with water, but has the potential to generate pozzolanic reaction products under conditions of high alkalinity.
In the cement blast furnace slag, SiO_2 and $AlO_{3,}$ contained in the slag, are released by stimulation of a large quantity of Ca^{2++} and SO_4^{2-} released by the cement, so that a well hydrated and abundant silicate aggregation is formed.
Special cement type stabilizing agents are cements that are specially prepared for the purpose of stabilizing soil or similar materials by reinforcing certain constituents of the ordinary cement, by adjusting the grain size or by adding other constituents more effective for particular soil types (*Japan Cement Association*, 1994). The improvement effectiveness of organic soils seems to be affected by the ratio $((SiO_2+Al_2O_3)/CaO)$) of the constituent elements in cement type stabilizing agents (Hayashi *et al*, 1989). The delay of stabilization or gain control of resistance over time can be obtained by adjusting the amount of ingredients such as gypsum and limestone.
Although the improvement by lime or cement is based on similar chemical reactions, the rate of strength increase differs.
In both cases, reduction of water content due to hydration precedes all other reactions if a dry-powder stabilizer is added. The reduction of water content leads to a slight increase of strength, following a reaction common to both stabilizing agents. This is due to a cation exchange, which leads to an improvement in the plasticity of soils.
After these reactions, substantial hardening of the mixture starts. In the case of lime treatment, the pozzolanic reaction between lime and clayey soils is slow but lasts for years. In contrast to this, in the case of cement treatment, the formation of cement hydration product is relatively rapid and most of the strength increase due to cement hydration is completed within several weeks. The lime liberated during the hydration of cement also reacts with clayey soils, although the strength increases very slowly, but it tends to last for a long time.
The magnitude of the strength increase of treated soil by lime or cement is influenced by a number of factors, because the basic strength increase mechanism is closely related to the chemical reaction between

the soil and the stabilizing agent. The factors can be roughly divided into four categories: I) Characteristics of stabilizing agent, II) Characteristics and condition of soil, III) Mixing conditions, and IV) Curing conditions, as show in Table 1 (Terashi, 1997).

Table 1: Factors affecting the strength increase (Terashi, 1997).

I- Characteristics of stabilizing agent	1- Type of stabilizing agent
	2- Quality
	3- Mixing water additives
II – Characteristics and conditions of soil (especially important for clays)	1-Physical chemical and mineralogical properties of soil
	2-Organic content
	3-pH of pore water
	4-Water content
III- Mixing Conditions	1- Degree of mixing
	2-Timing of mixing/re-mixing
	3-Quantity of stabilizing agent
IV- Curing Conditions	1-Temperature
	2-Curing time
	3-Humidity
	4- Wetting and drying/freezing and thawing, etc

The characteristics of stabilizing agent mentioned in Category I strongly affect the strength of the treated soil. Therefore, the selection of an appropriate stabilizing agent is, in a real sense, an important issue. (*Japan Cement Association, 1994*).

2. RESEARCH OBJECTIVES

This paper, aiming to contribute to the increasing technical knowledge about the mobilization of resistance with time of soft soil stabilized with cement, presents and discusses results from axial compression tests conducted on specimens manufactured in the laboratory using marine soft alluvial clay stabilized with Portland cement CPII-E-32, as well as the influence of different dosages of Portland cement on the increase of compressive strength. Finally, this paper will also discuss the influence of curing time on strength increase.

3. CHARACTERISCS OF THE EXPERIMENTAL SITE

The site where the soft soil samples were collected is located on the coast of Pernambuco, a state in Northeart of Brazil, near the city of Goinia and has 300m of extension, an is part of a project of enlargement of a national roadway.

This project involves a significant volume of new embankements founded over deep layers of soft soil with low resistance and variable thickness.

The subsoil is composed by a layer of sandy silt-clay of approximately 1.0 m of thickness followed by a layer of organic clay from 12.0 to 15.0 m, a layer of silty clay, 2.0m a layer of silt and clay. The water table level was detected at a depth of 1.60 m.

4. MATERIALS AND METHODS

The following activities and methodologies were carried out to develop this research:

a) Soil samples colection:

To conduct the laboratory tests soft clayey soil samples were collected, using Shelby samplers, in the following depths: 2,6 e 11m.

b) Elemental geothecnical characterization tests:

Aiming to characterize the collected soil samples, the following laboratory tests were carried out in accordance with their respective Brazilian Standards (ABNT:NBR): Liquid Limit (ABNT:NBR 6459/1984), Plasticity Limit (ABNT NBR 7180/1984), Grain Size Distribution (ABNT: NBR7181/1984), Natural Moisture Content, and Particle Density.

c) Clayey samples homogenization
After collecting, water was added to soil samples until the moisture content approached their Liquid Limit. Then the clayey samples were homogenized by planetary mixer with steel tank capacity of 5 litres and stainless steel beater.

d) Mixing procedures
To create the mixture of soil-cement the following dosages were adopted: 200, 400 and 600kg / m³. The cement used was of type Portland made with blast furnace slag (compressive strenght $\geq$32MPa for 28 days) and water / cement ratio of 0.8. This cement have adition of ground granulated blast-furnace slag and carbonatic material, reaching a compressive strenght of 32 MPa. After completion of mixing, the sample was additionally homogenized for five minutes. After this period the homogeneity of the mixture was evaluated verifying the occurrence of pellets and clumps of cement.

e) Specimens and Curing Time
For molding the specimens cylindrical steel molds were used, with height and diameter of 50 and 100 mm, respectively. Then, the cylindrical specimens were immersed in water (temperature of 20ºC) for 7, 28, 56 and 120 days on curing.

f) Determination of compressive strength
Aiming to obtain the compressive strength of the specimens, laboratory tests were carried out according the recommendations of the Brazilian Association of Technical Standards (ABNT: NBR 14992/03 - "Determination of compressive strength).

5. ACHIEVEMENTS AND DISCUSSIONS

Table 2 shows the geotechnical parameters obtained by the elemental characterization tests carried out. The grain size distribution of the studied soil is presented on Table 3.

Table 2: Geotechnical parameters obtained by simple characterization tests.

Depth (m)	Liquid Limit (%)	Plasticity Index (%)	Natural Moisture Content (%)	Volume Weight (kN/m^3)
2	64	25	120	13,8
6	65	26	126	13,9
11	71	30	100	14,4

Table 3: Grain Size distribution

Depth (m)	Sand (%)	Silt (%)	Clay (%)
2	10	28	62
6	2	20	78
11	6	20	74

Table 4 presents the compressive strength obtained for different curing times using cement dosage of 200kg/m^3. Figure 1 shows the values presented on Table 4.

Table 4: Compressive strength for different curing times using cement dosage of 200kg/m^3.

Compressive strength (MPa)				
Specimen	Curing time (days)			
	7	28	56	120
1	1.3	2.9	2.9	4.0
2	1.1	3.0	3.3	3.6
3	1.0	2.7	3.0	3.7
4	1.2	2.5	3.5	3.7
Average value (MPa)	1.2	2.8	3.2	3.8
Standard deviation (sd) (MPa)	0.1	0.2	0.3	0.2
Coefficient of variation (cv) (%)	11.2%	8.0%	8.7%	4.6%

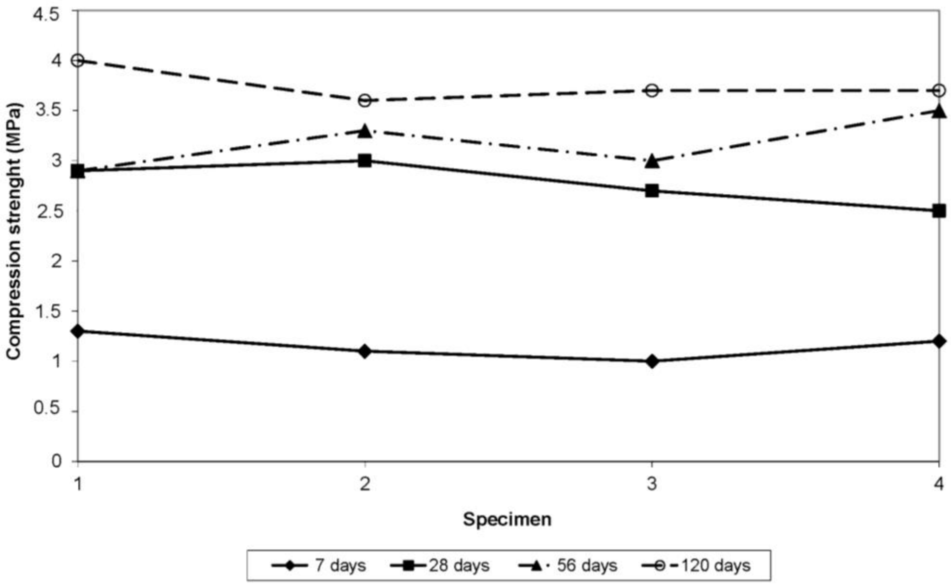

Figure 1: Compressive strength for different curing times using cement dosage of 200kg/m^3.

Table 5 presents the compressive strength obtained for different curing times using cement dosage of 400kg/m^3. Figure 2 shows the values presented on Table 5.

Table 5: Compressive strength for different curing times using cement dosage of 400kg/m^3.

Compressive strength (MPa)				
Specimen	Curing time (days)			
	7	28	56	120
1	1.5	4.7	5.2	9.3
2	1.5	4.7	6.0	7.0
3	1.4	4.4	5.9	7.0
4	1.4	4.5	4.8	7.0
Average value (MPa)	1.5	4.6	5.5	7.6
Standard deviation (sd) (MPa)	0.1	0.1	0.6	1.2
Coefficient of variation (cv) (%)	4.0%	3.3%	10.5%	15.2%

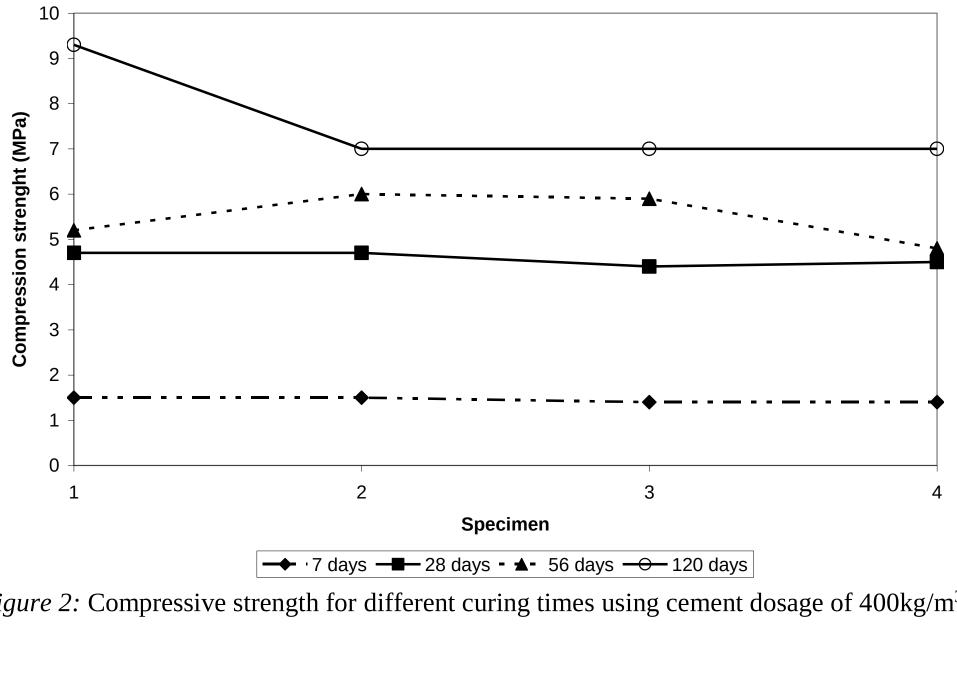

Figure 2: Compressive strength for different curing times using cement dosage of 400kg/m^3.

Table 6 presents the compressive strength obtained for different curing times using cement dosage of 600kg/m^3. Figure 3 shows the values presented on Table 6.

Table 6: Compressive strength for different curing times using cement dosage of 600kg/m^3.

Compressive strength (MPa)			
Specimen	Curing time (days)		
	7	28	56
1	1.7	7.9	8.5
2	1.9	7.6	9.4
3	2.2	7.9	8.9
4	2.4	7.7	8.4
Average value (MPa)	2.05	7.78	8.8
Standard deviation (sd) (MPa)	0.31	0.15	0.45
Coefficient of variation (cv) (%)	15%	2%	5%

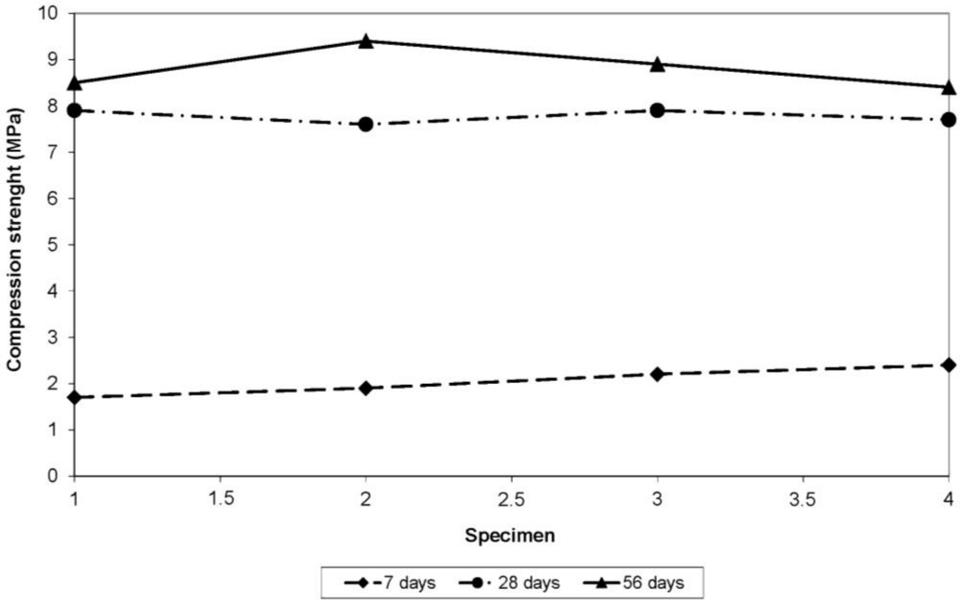

Figure 3: Compressive strength for different curing times using cement dosage of 600kg/m^3.

As shown in the previous tables, the compressive strengths for 7 days curing time considering cement dosages of 200, 400 e 600kg/m^3 are, respectively: 1.2MPa *(sd=0.1MPa, cv=11.2%); 1.5MPa (sd= 0.1MPa, cv=4%)* and *2.05MPa (sd=0.31MPa, cv= 15%).* The compressive strengths for 28 days curing time considering cement dosages of 200, 400 e 600kg/m^3 are the respectively: 2.8MPa *(sd=0.2MPa, cv=8%), 4.6MPa (sd=0.1MPa, cv=3.3%)* and *7.8MPa (sd=0.1MPa, cv= 2%)*. The compressive strengths for 56 days curing time considering cement dosages of 200, 400 e 600kg/m^3 are, respectively: 3.2MPa *(sd=0.3MPa, cv=8.7%), 5.5MPa (sd=0.6MPa, cv=10.5%)* and *8,.8MPa (sd=0.45MPa, cv=5%).* The compressive strengths for 120 days curing time considering cement dosages of 200, 400 e 600kg/m^3 are, respectively: 3.8MPa *(sd=0.2MPa, cv=4.6%)* and *7.6MPa (sd= 1.2MPa, cv=15.2%).* The low values observed of *cv* and *sd* indicate the good homogeneity of the mixture.

Figure 4 presents the variation of compressive strength with the different used cement dosages for different curing times (7, 28, 56 and 120 days).

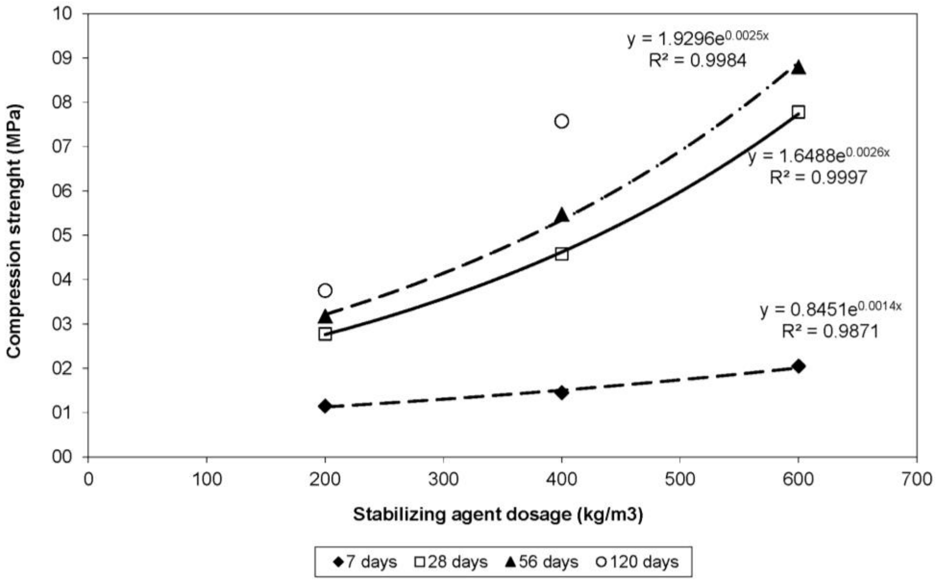

Figure 4: Compressive strength *versus* cement dosages

All curing times revealed the same trend of increasing compressive strength with the cement dosage. The exponential regressions showed good correlations between compressive strength and stabilizing agent dosages ($R^2 > 0.98$).
Figure 5 shows correlations between differents compressive strengths (q_u) obtained for different dosages of stabilizing agent in different curing times.

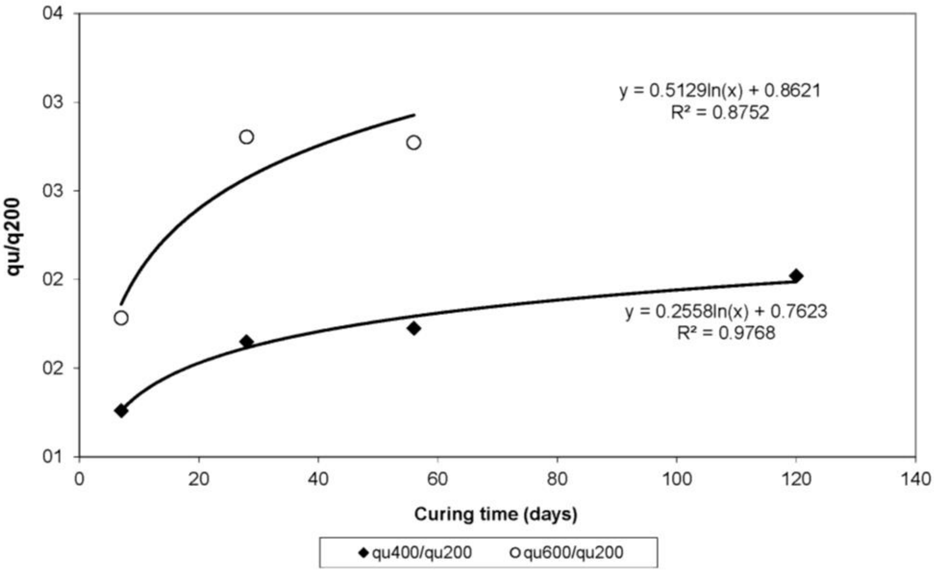

Figure 5: Correlations between different compressive strengths and curing time

As shown in Figure 5, the values of q_u obtained considering dosage of 600kg/m^3 and 7 days of curing time were $1.8 \cdot q_{u200}$, increasing to $2.8 \cdot q_{u200}$ for 28 days of curing time and keeping the same value for 56 days.
The values of q_u obtained considering cement dosage of 400kg/m^3 and 7 days of curing time were 1.3xq_{u200}, increasing to $1.65 \cdot q_{u200}$ for 28 days, $1.72 \cdot q_{u200}$ for 56 days and $2.0 \cdot q_{u200}$ for 120 days of curing time.
Figure 5 also shows that the obtained correlations (q_{u600}/q_{u200} and q_{u400}/q_{u200}) present an increase of 50% between the first controlling date of curing time (7 days) and the last one (120 days). This fact shows that the compressive strength results obtained in early ages may not represent the real difference between the stabilizing agent dosages and compressive strength. In these very early days the sensitivity of these mixtures to the difference in the cementing agent is not sufficient.

Figure 6 shows the average increase of the compressive strength with curing time, considering the studied cement dosages.

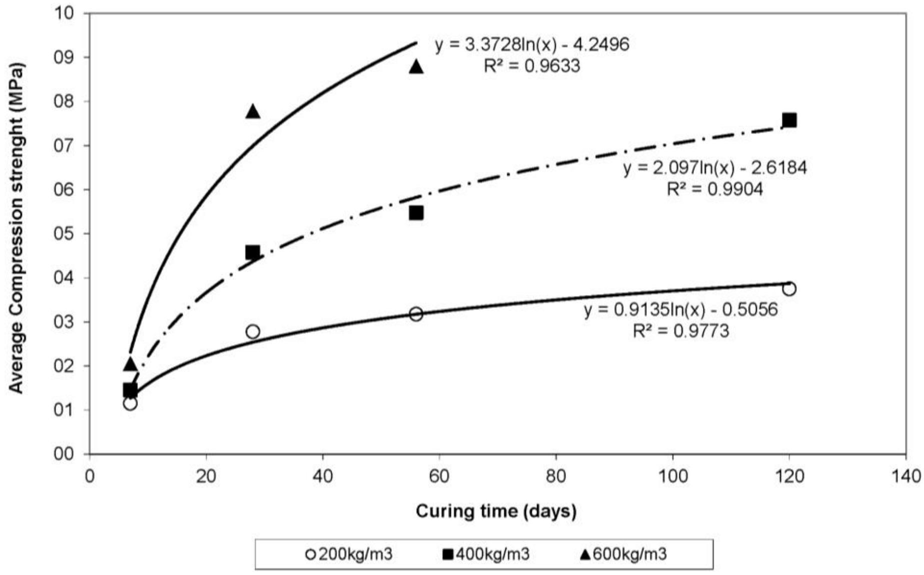

Figure 6: Increase of average compressive strength *versus* curing time

As shown in Figure 6 the compressive strength increasing in the first curing days can be represented by a logarithmic curve. The compressive strength increases fast in the first days, however decreases gradually with time. The logarithmic regressions showed correlations presenting $R^2 > 0.96$.
Figure 7 presents compressive strength *versus* curing time, however the horizontal axis (curing time) time is represented by a logarithmic scale.

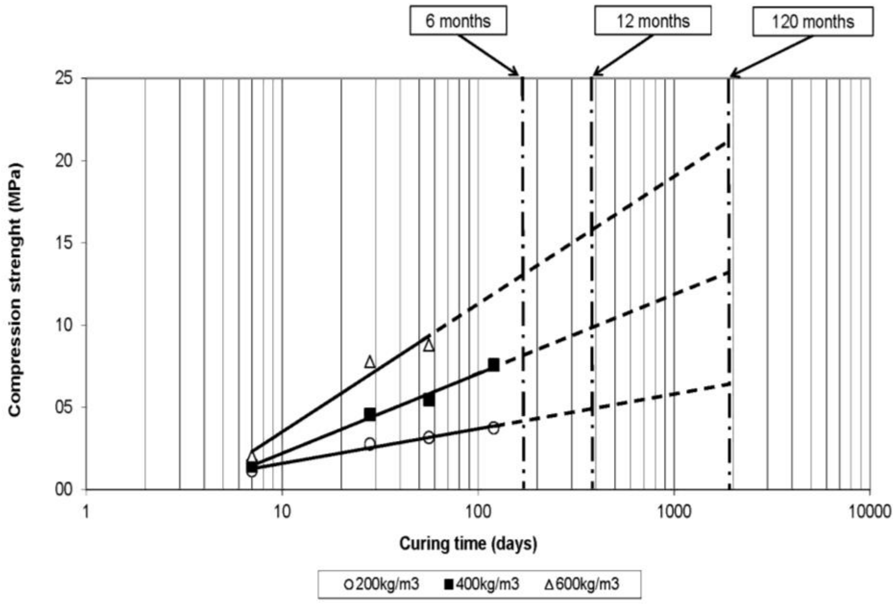

Figure 7: Compressive strength *vsversus* curing time

As presented in Figure 7, assuming that the best relationship between the compressive strength *versus* curing time is logarithmic (*as seen in Figure 6*) considering a period of 10 years it is estimated that qu could reach approximately the double of the maximum value obtained for 120 days of curing time.

6. CONCLUSIONS

The following conclusions can be drawn from the work presented above:

a) The homogenization procedures used to stabilize with the clayey soil involved in this project were satisfactory. This fact can be based in the low coefficients of variation obtained, ranging between 2% and 15% within the same group of samples (samples molded with the same dosages and tested in the same curing time).

b) The curves that represented the gain of compressive strength, obtained for the tested samples in the same curing time within the adopted cement dosages ranges, showed a exponential variation law with high adjustment (R^2 values between 0.98 and 0.99).

d) The relationship between the compressive strength obtained for different stabilizing agent dosages in the same curing time varied considerably, increasing when the tests were carried out with 7 days or 28 days. Considering the two studied relationships, for the dosages of 400 and 600kg/m³ in relation to the one of 200kg/m³ (q_{u600}/q_{u200} and q_{u400}/q_{u200}), the observed strength gain was about 50% between tests performed with 7 days and 28 days, respectively. After this period the samples increased in strength, however, their relationship did not vary significantly. Thus, it is concluded that controlling tests should be performed with a curing time of no less than 28 days, as there is the risk of assuming inaccurate trends for the variation of strength in mixtures studied with samples cured with lower times.

e) The values of compressive strength obtained for each cement dosage in different curing times, showed that the increase is logarithmic type. In the first curing days, the gain of strength was faster, decreasing gradually in time. The logarithmic regressions obtained showed R^2 values ranging between 0.96 and 0.99. Thus it can be concluded that the adoption of a logarithmic law to represent the gain in strength with time is appropriate when soft soils stabilized with Portland Cement.

REFERENCES

Brazilian Association of Technical Standards (ABNT). ABNT:NBR-6459/1984. Soil-Determination of Liquid Limit. Rio de Janeiro, 1984. 6p. In Portuguese.

Brazilian Association of Technical Standards (ABNT). ABNT: NBR-7180/1984. Soil- Determination of the Plasticity Limit. Rio de Janeiro, 1984. 3p. In Portuguese.

Brazilian Association of Technical Standards (ABNT). ABNT:NBR-7181/1984. Soil- Grain Size Distributio Analysis. Rio de Janeiro, 1984. 13p. In Portuguese.

Brazilian Association of Technical Standards (ABNT). ABNT:NBR-7215/196. Portland Cement - Determination of Compressive Strength. Rio de Janeiro, 1996. 8p. In Portuguese.

Babasaki, R. M., Terashi, T., Suzuki, A. Maekaea, M. (1996) JGS TC report: Factors influencing the strength of improved soil. Proceedings 2and International Conference on Ground Improvement Geosystems, Grouting and Deep Mixing, Vol. 2, Balkema, Tokyo, pp913-918. 1996.

Broms, B., Boman, P. (1979) Lime columms – a new foundation method. Journal of Geotechnical Engineering, ASCE, Vol. 105, GT4, pp. 539-556

Bruce, D. (2001) An introduction to deep mixing methods as used in geotechnical applications, volume 3, the verification and properties of treated ground. Report No FHWA-RD-99-167 U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Enami, A., Hibino, S. (1991) Improvement of foundation ground using a deep mixing blender with free blades.

Journal of Japanese Society of Soil Mechanics and Foundation Engineering, N 39, Vol.10, pp 37-42.

Hayashi, H.S., Noto.,Toritani, N. (1989) Cement improvement of Hokkaido peat. Proceedings. Symposioum on High Organic Soils: pp101-106. 1989

Hausmann, M.R. (1990) Engineering principles of ground modification, McGraw Hill. New York, 320p.

Ingless, O.G., J.B., Metcalf. (1972) Soil stabilization, principles and practice. Butterworth.pp120-135.

Jacobson, J. R., Filz, G.M., Mitchell, J. K. (2003) Factors affecting strength gain in lime-cement columms and development of a laboratory testing procedure. Report No. VTRC 03-CR16, Virginia Transportation Research Council, Charlottesville, Va.

Japan Cement Association. (1994) Soil improvement manual using cement stabilizer. pp15-30.

Lorenzo, G.A, Bergado, D.T. (2004). Fundamental parameters of cement admixed Clay-New approach. JGGE, n.130, vol.10,pp.1042-1050.

Nelson, J.D., Miller, J. D. (1992) Expansive soils: Problems and Practice in foundation and pavement engineering. John Wiley and Sons, Inc., New York.

Puppala, A.J, Bhadriraju, V., Porbaha, A. (2005) Quality assurance practices and protocols for in-situ testing of deep mixed columns. Proceedings of International Conference on Deep Mixing: Best Practice and Recent Advances, Swedish Deep Stabilization Research Centre, Stockholm, Sweden, pp 613-619.

Rathmayer, H. (1996) Deep mixing methods for soft subsoil improvement in the Nordic Countries. Proceedings 2and International Conference on Ground Improvement Geosystems, IS-Tokyo 96, Balkema, Rotterdam, The Netherlands, 869-878.

Taki, O, Yang, D.S. (2005) Soil-cement mixed wall technique. Geotechnical Engineering Congress, ASCE, Reston, Va., 298-309.

Terashi, M., H. Tanaka & T. Okumura. (1979) Engineering properties of lime treated marine soils and the DSM method. Proceedings of the 6th Asian Regional Conference on Soil Mechanics and Foundation Engineering, vol.1, pp. 191-194.1979

Terashi, M. Theme Lecture: (1997) Deep Mixing Method-Brief State of the Art. Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, vol.4, pp.2475-2478.

Yanase, S. (1968) Stabilization of marine clays by quicklime. Report of the Port and Harbour Research Institute, n.7, vol.4, pp.85-132.