Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v35i3.16042

Time-enhanced strength increase of an alluvial clay, typical of the northeastern region of Brazil, mixed with different cement dosages

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ABSTRACT. Time-enhanced strength increase of alluvial clay mixed with different cement dosages is provided. After clay collection, water was added to the soft clay samples until the moisture rate reached its liquid limit. Doses 200, 400 and 600 kg m^{-3} were used for the soil/cement mixture. The cement consisted of the Portland type with blast furnace slag (compressive strength ≥ 32 MPa for 28 days) and water/cement ratio was 0.8. After molding, specimens 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, 2003), after 7, 28, 56 and 120 days. Soil samples were collected on the coast of the state of Pernambuco, Brazil. The site is characterized by a surface homogeneous layer composed of soft organic clay-silt to very soft clay, with a gray color and a thickness ranging between 12 and 15m. The groundwater level is found at 1.60m depth. Parameters verified the compressive strength for each mixture under analysis and their time-enhanced resistance increase.

Keywords: alluvial soil, compressive strength, soil-cement.

Ganho de resistência com o tempo de uma argila típica do nordeste do Brasil misturada com diferentes dosagens de cimento

RESUMO. É apresentado o estudo do ganho de resistência com o tempo de uma argila aluvionar ao ser misturada com cimento Portland. Após coleta em campo, adicionou-se água às amostras de argila mole até teor de umidade equivalente ao seu Limite de Liquidez. Para a confecção da mistura de solo/cimento foram utilizadas as seguintes dosagens: 200, 400 e 600 kg m^{-3}. O cimento utilizado foi do tipo Portland feito com escória de alto forno (resistência a compressão ≥ 32 MPa em 28 dias) e a relação água/cimento de 0,8. Logo após a moldagem, estes foram imersos em água para cura, sendo posteriormente rompidos em ensaios laboratoriais de compressão simples de acordo com as recomendações da Associação Brasileira de Normas Técnicas (ABNT, 2003), depois de transcorridos 7, 28, 56 e 120 dias. As amostras de solo foram coletadas em uma área localizada no litoral do Estado de Pernambuco, Brasil. O sítio de coleta é caracterizado por apresentar superficialmente uma camada homogênea composta por uma argila-siltosa orgânica de consistência mole a muito mole e coloração acinzentada com espessura variando entre 12 e 15 m. O nível do lençol freático é encontrado superficialmente a uma profundidade de 1,60 m. Os parâmetros obtidos permitiram verificar a resistência à compressão de cada mistura utilizada, bem como o ganho de resistência destas com o tempo.

Palavras-chave: solo aluvionar, resistência à compressão, solo-cimento.

Introduction

Soft soil stabilization by the addition of chemical elements

With the expansion of urban areas, the need to occupy sites that, due to geotechnical engineering, were not historically inhabited, such as those with dominant soft soils, is currently on the increase. The above situation involves the technical means to find alternative solutions for the mitigation of structural problems caused to building superstructures by soil accommodation.

As an alternative for the treatment of soils by chemical additives, an approach to this problem has been pre-compaction, removal and replacement of material, among others. The main alternatives for the construction of embankments on soft soils are landfills supported on concrete or steel piles; landfills filled with lightweight materials (expanded clay, expanded polystyrene or EPS, and others); Deep Soil Mixing, Jet Cutter Soil Mixing and Grouting and others.

The methodology of Deep Soil Mixing is an example of an important technical improvement of soft soils that include expansive and marine clays. The advantage of this technique consists in greater execution speed and efficiency in soil and cement mixing (BRUCE; BRUCE, 2003).

Soil stabilization by adding cement or lime to improve the geotechnical characteristics of soft soil is an interesting technique, with a wide acceptance in recent years due to technical improvements, featuring higher versatility and competitiveness when compared to other more heavy classical solutions.

The selection of the stabilizing agent and dosage will depend on the local ground conditions (soil type) and the level of improvement needed. New stabilizing agents, some manufactured with recycled ash and residues, have been recently introduced in the treatment of organic or saturated soils.

The concentration of stabilizing agents is usually expressed in weight per volume of soil mass to be treated. According Jacobson et al. (2003), this rate ranges between 6 and 12% of the dry weight of soil under treatment.

Many physical factors may influence the behavior of treated soils. According to Shen et al. (2003), these factors may include the shape of the blade of the mixing equipment, the penetration and speed of the auger mixer and its speed rotation.

Curing temperature, curing time and moisture percentage are the major environmental factors that affect the strength of treated soils (LORENZO; BERGADO, 2004).

Basic mechanisms of soft soil stabilization

Although Portland Cement and Lime are the most commonly used stabilizing agents for many different types of soils, there are, however, other agents available that may be used successfully. In fact, the most common cement types used as stabilizing agent are 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 the minerals $3CaO.SiO_2$, $2CaO.SiO_3$, $3CaO.Al2O_3$, $4CaO.Al2O_3.Fe2O3$.

The cement-forming mineral 3CaO.SiO2, for example, reacts with water by hydrating the cement and is expressed by

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

Calcium hydroxide is released during the cement hydration. Cement hydration enhances its strength up to significant rates, while calcium hydroxide contributes to the pozzolanic reaction, occurring along lime stabilization.

The cement blast furnace slag is obtained by mixing Portland cement and blast furnace slag. Well-ground blast furnace slag will not react with water, but triggers pozzolanic reaction products under high alkalinity conditions.

In the cement blast furnace slag, SiO_2 and AlO_3, contained in the slag, are released by the stimulation of a large quantity of Ca^{2++} and SO_4^{2-} released by the cement. Consequently, a well-hydrated and abundant silicate aggregation is formed.

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 strength increase, following a reaction common to both stabilizing agents. This is due to a cation exchange that leads towards an improvement in soil plasticity.

Substantial hardening of the mixture starts after these reactions. In the case of lime treatment, the pozzolanic reaction between lime and clayey soils is slow and lasts for years. On the other hand, in the case of cement treatment, the formation of cement hydration product is relatively fast and most of strength increase, due to cement hydration, is completed within several weeks. The lime, liberated during cement hydration, also reacts with clayey soils, although strength increases very slowly and tends to do so for a long period.

The magnitude of 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 may be roughly divided into four categories: I) Characteristics of stabilizing agent, II) Characteristics and condition of soil, III) Mixing conditions and IV) Curing conditions.

The current paper aims at increasing technical knowledge about the mobilization of time-enhanced resistance of soft soil stabilized with cement. It 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 and the influence of different dosages of Portland cement on the increase of compressive strength. Research also discusses the influence of curing time on strength increase and thus how the technique of cement addition in a soft soil may increase its compressive strength and its behavior in time.

Material and methods

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

a) Soil samples collection: Soft clayey soil samples were collected to conduct the laboratory tests, using Shelby samplers, at depths 2.6 and 11 m.

b) Elemental geotechnical characterization tests: For the characterization of the collected soil samples, the following laboratory tests were carried out, complying with Brazilian Standards (ABNT:NBR): Liquid Limit, Plasticity Limit, Grain Size Distribution, Natural Moisture Content, and Particle Density.

c) Clayey samples homogenization: After collection, water was added to soil samples until the moisture content approached the Liquid Limit. The clayey samples were then homogenized by planetary mixer with 5L-steel tank and stainless steel beater.

d) Mixing procedures: Dosages 200, 400 and 600 kg m^{-3} were used for soil-cement mixture. The cement used was the Portland type made with blast furnace slag (compressive strength ≥ 32 MPa for 28 days) and water / cement ratio of 0.8. Ground granulated blast-furnace slag and carbonatic material, with a compressive strength of 32 MPa, were added to the cement. After mixing, the sample was homogenized for five minutes and then the mixture homogeneity was evaluated by verifying the occurrence of pellets and cement clumps.

e) Specimens and Curing Time: Cylindrical steel molds were used, height and diameter 50 and 100 mm, respectively, for molding the specimens. The cylindrical specimens were then immersed in water (temperature at 20°C) during 7, 28, 56 and 120 days for curing.

f) Determination of compressive strength: To obtain the specimens` compressive strength, laboratory tests were carried out according to the recommendations of the Brazilian Association of Technical Standards (ABNT, 2003) 'Determination of compressive strength'.

Characteristics of studied experimental site

The site where the soft soil samples were collected lies on the coast of the northeastern State of Pernambuco, Brazil, near the city of Goiania. Extending for 300 m, it is part of a project of enlargement of a national highway. The project involves many new embankments founded on deep layers of soft soil with low resistance and variable thickness.

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

Results and discussion

Table 1 shows the geotechnical parameters obtained by the elemental characterization tests carried out. The grain size distribution of the studied soil is presented on Table 2.

Table 1. 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 2. Grain size distribution.

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

Table 3 presents the compressive strength obtained for different curing times using cement dosage of 200 kg m^{-3}. Figure 1 shows the rates presented on Table 3.

Table 3. Compressive strength for different curing times using cement dosage of 200 kg m^{-3}.

Specimen	Compressive strength (MPa) 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%

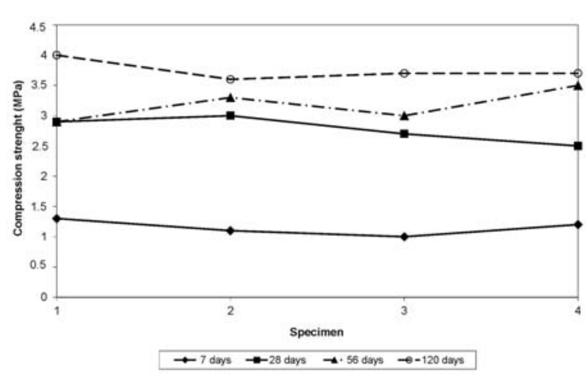

Figure 1. Compressive strength for different curing times using cement dosage of 200 kg m^{-3}.

Table 4 presents the compressive strength obtained for different curing times using cement dosage of 400 kg m^{-3}. Figure 2 shows the rates presented on Table 4.

Table 4. Compressive strength for different curing times using cement dosage of 400 kg 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%

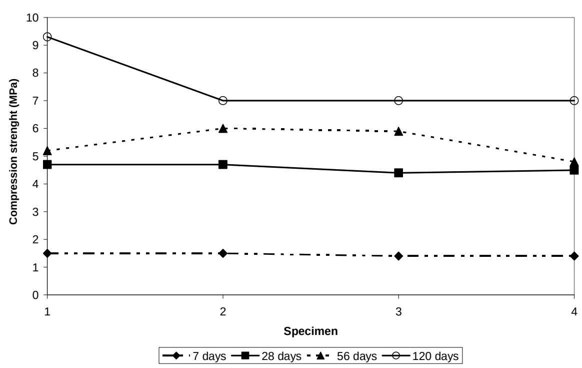

Figure 2. Compressive strength for different curing times using cement dosage of 400 kg m^{-3}.

Table 5 presents the compressive strength obtained for different curing times using cement dosage of 600 kg m^{-3}. Figure 3 shows rates presented on Table 5.

Table 5. Compressive strength for different curing times using cement dosage of 600 kg 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%

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

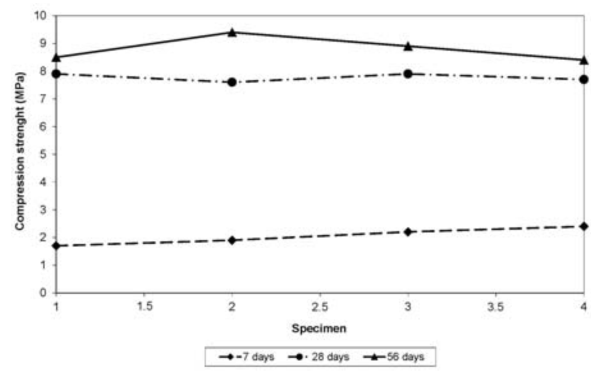

Figure 3. Compressive strength for different curing times using cement dosage of 600 kg m^{-3}.

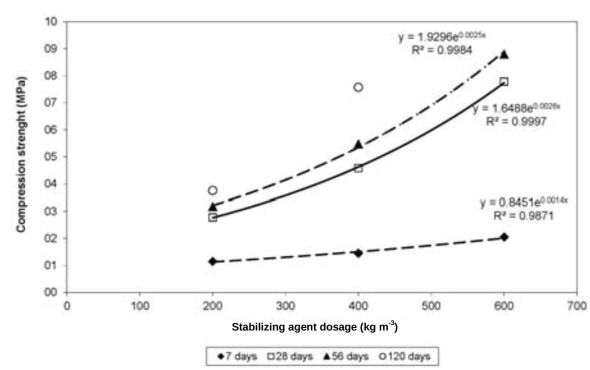

Figure 4. Compressive strength versus cement dosages.

All curing times revealed the same trend in 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 different compressive strengths (q_u) obtained for different dosages of stabilizing agent at different curing times.

As shown in Figure 5, q_u rates for dosage 600 kg m^{-3} and 7 days curing time were $1.8 \cdot q_{u200}$, with an increase to $2.8 \cdot q_{u200}$ for 28 days of curing time while maintaining the same value for 56 days. The rates of q_u for cement dosage 400 kg m^{-3} and 7 days of curing time were $1.3x q_{u200}$, with an increase 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.

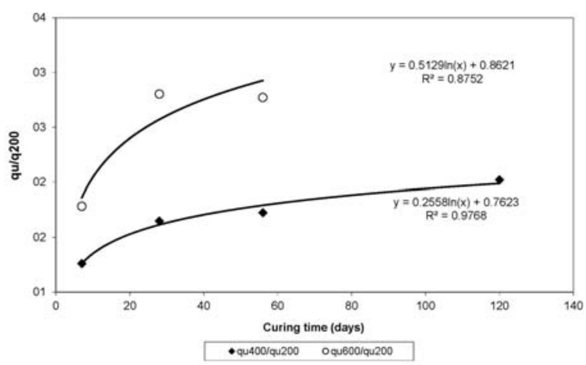

Figure 5. Correlations between different compressive strengths and curing time.

Figure 5 also shows that correlations (q_{u600}/q_{u200} and q_{u400}/q_{u200}) present a 50% increase between the first control 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.

During the initial days, the sensitivity of these mixtures to the difference in the cementing agent was not sufficient. Figure 6 shows the average increase of the compressive strength with curing time, taking into consideration the cement dosages under analysis.

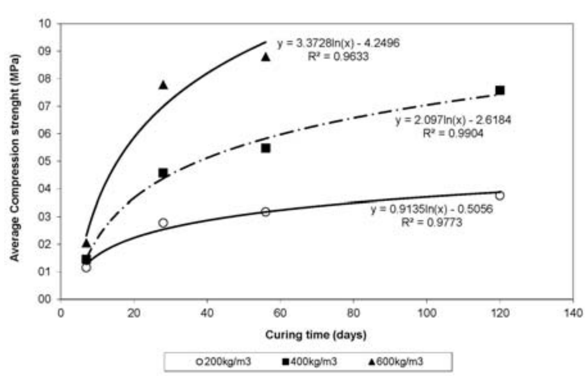

Figure 6. Increase of average compressive strength versus curing time.

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

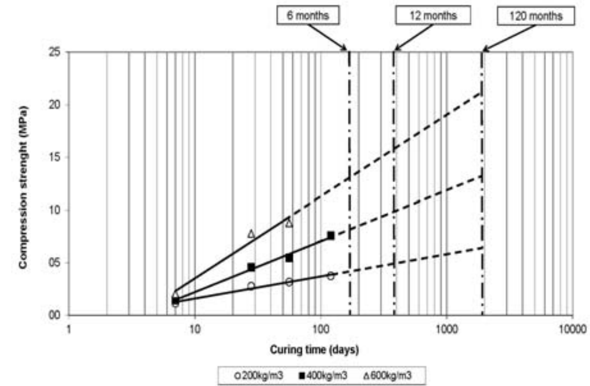

Figure 7. Compressive strength versus curing time.

As Figure 7 shows, since the best relationship between the compressive strength versus curing time may be logarithmic (as seen in Figure 6), it is estimated that for a 10-year period the compressive strength (q_u) could reach approximately the double of the maximum rate obtained during 120 days of curing time.

Conclusion

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 an exponential variation law with high adjustment.

The relationship between the compressive strength obtained for different stabilizing agent dosages in the same curing time varied considerably. It may be concluded that controlling tests should be performed with a curing time of no less than 28 days. In fact, there is a risk of assuming inaccurate trends for the variation of strength in mixtures studied with samples cured at shorter times.

The values of compressive strength obtained for each cement dosage in different curing times showed that the increase is logarithmic. It can be concluded that the adoption of a logarithmic law to represent gain in strength with time is appropriate when soft soils were stabilized with Portland Cement.

Acknowledgements

The authors wish to thank Moretti Engenharia Consultiva Ltda, Universidade do Porto/Portugal, Universidade Nove de Julho/Uninove (FAPIC).

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Received on February 14, 2012.
Accepted on July 18, 2012.