Prediction of strength of lime columns

Prévision de la résistance des colonnes à la chaux

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SYNOPSIS: In the design of soil improvements with the lime column method, it is important to obtain a reliable prediction of column strength and strength increase with time after installation. This article deals with the effect of different curing conditions on the increase in strength of soils stabilized with quicklime and with cement. Especially the curing temperature has shown to have a large effect on the rate of strength increase. Results of both laboratory and field tests are presented and discussed.

INTRODUCTION

Lime columns have been used for deep stabilization of soft soils in Sweden since 1975. Since the mid -80s also cement has been utilized as a stabilizing agent. The total production of lime columns and cement columns in Sweden amounts to about 300,000 metres/year (1988). A continuing increase in production can be expected. The lime column method has proved to be technically and economically advantageous in several types of application. Today, there is an increasing use of the method in these established ways, as well as an increasing interest in using the method in new types of application.

For optimal design, it is essential to obtain a good estimate of column strength and strength increase with time after installation. A reliable prediction should preferably be made as early in design as possible. Prediction of in situ column strength has normally been based on unconfined compression tests on samples stabilized in the laboratory. To a lesser extent, test columns have been installed in situ to enable a better determination of strength for design. In Sweden, shear strength of stabilized soil in situ is normally evaluated from penetration tests using the lime column penetrometer, see Fig. 1. The shear strength is determined as 0.1 times the specific penetration resistance in accordance with Holm et al (1981).

Shear strength of stabilized soil is affected not only by type of soil and type and amount of stabilizing agent used. The influence of different curing conditions, such as temperature and stresses, should be taken into account when predicting strength and strength increase with time after stabilization. To enable better estimates of column strength, research has been carried out at the Swedish Geotechnical Institute (SGI) concerning the conditions in situ and their effect on the shear strength of the stabilized soil.

At present, other research projects are also being carried out at SGI in order to better estimate the soil-column interaction and behaviour for different types of applied loads. These projects aim at establishing an improved general soil/column model and design method.

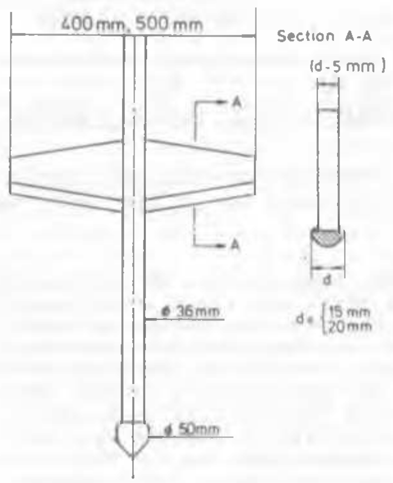

Figure 1. Lime column penetrometer.

CURING TEMPERATURE IN SITU

The chemical reactions that occur when lime or cement is mixed with saturated soil involve an increase in soil temperature. In Sweden, quicklime is used as stabilizing agent in lime columns. The slaking of lime and concurring lime-soil reactions create temperatures up to about a hundred degrees (Celsius) or more in the middle of the lime columns immediately after installation (Kujala, 1984) (Åhnberg & Holm, 1984). In cement columns the temperature also increases, due to hydration of cement and concurring cement-soil reactions. The generation of heat due to hydration is less than half of that of quicklime. On the other hand, it continues for a longer period. Examples of measured temperatures in lime columns and cement columns in situ are shown in Fig. 2.

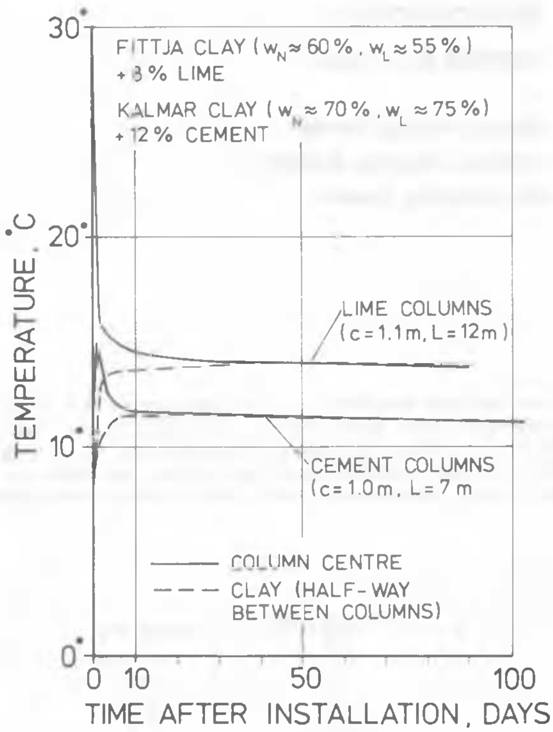

Figure 2. Examples of measured temperatures with time after installation in lime and cement columns.

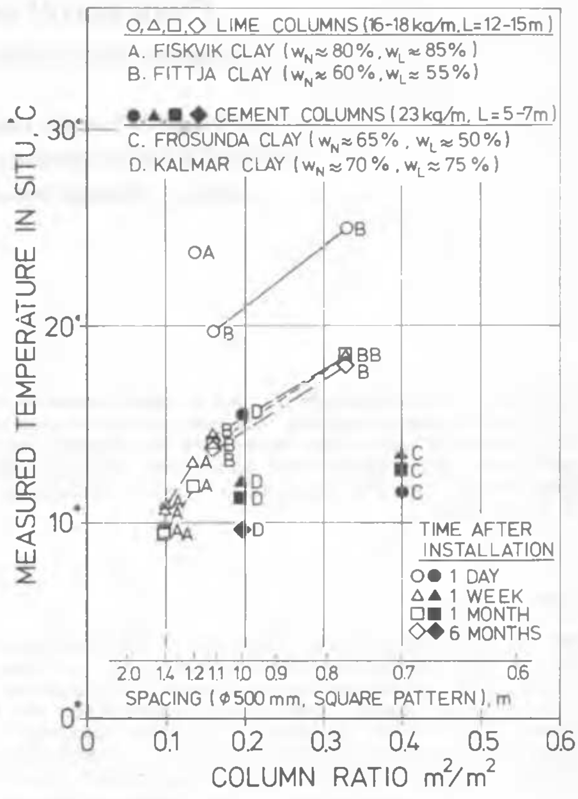

Figure 3. In situ temperatures measured in Sweden in the centre of columns at half length.

The curing temperatures of the stabilized soil in situ at different times after installation vary with the type and amount of stabilizing agent used in the columns, distances between the columns, type of soil, total area and depth of stabilized soil, and air and surrounding soil temperature.

Examples of temperatures measured in situ are shown as a function of column spacing in Fig. 3. The temperatures shown in the figure are measured at sites with about the same area and depth of stabilized soil, for the lime columns and cement columns respectively. The heat conductivity in clay decreases somewhat with increasing water content. This fact, however, probably does not affect the heat loss to any significant degree when the different sites are compared. The results indicate in situ temperatures of 10°-18°C one week after installation, decreasing to 8°-17°C six months after installation for lime columns with a spacing of 0.8-1.4 m. The corresponding temperatures for cement columns with a spacing of 0.7-1.0 m was 12°-14°C, decreasing to 10°-12°C. If the generated heat is the result of hydration of lime or cement and reactions produced by the stabilizing agent itself alone, the results would show general curing temperatures in Sweden. However, the chemical process involves soil-lime and soil-cement reactions as well. The extent of these soil reactions can be expected to vary considerably with type of soil and additive (Saitoh et al, 1985). The degree of heat generation from these reactions remains to be examined. One way of doing this could be to study the adiabatic rising temperatures at stabilization of a number of different types of soil, (Suzuki, 1982).

EFFECT OF CURING TEMPERATURE ON SHEAR STRENGTH OF STABILIZED SOIL

An increase in curing temperature results in a faster increase of shear strength. Effects of storing stabilized soil in the laboratory at curing temperatures corresponding to those of typical lime or cement columns in situ with spacing 1.0 m are shown in relation to results obtained on samples stored at a constant curing temperature of 8°C in Fig. 4. The relation is shown as the number of storing days required to obtain equal strengths. As a rule, a constant curing temperature in the laboratory, different from that in situ, results in a different rate of strength increase. In the case of lime stabilization, the differences may be extremely large depending on the type of soil. The development of shear strength with time after stabilization for a lime-stabilized clay from Fittja when stored at 8°C, at 20°C and at column temperature measured in situ is shown in Fig. 5.

The effect of temperature on the rate of strength increase varies with the type of soil. The shear strengths at various curing temperature are most accurately estimated by testing samples stored at the particular temperatures. A relatively good estimate of strength increase at varying curing temperatures can also be made by usin

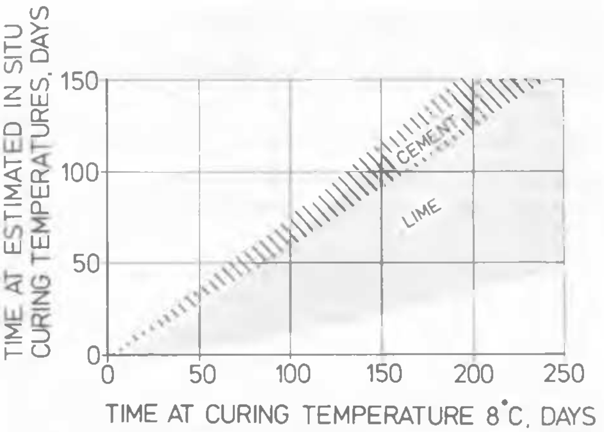

Figure 4. Example of number of days required to reach equal strength at different curing temperatures. Results from unconfined compression tests.

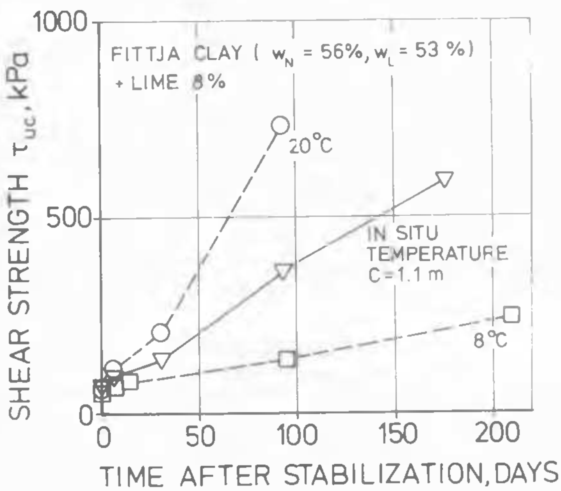

Figure 5. Example of differences in strength increase due to curing temperature.

the maturity number M_T (Åhnberg & Holm, 1984)

$$M_T = [20+(T-20)K]^2 \sqrt{t}$$

where T = curing temperature, °C
t = time after stabilization, days
K = factor varying with type of additive, soil and temperature

In Sweden, empirical values of K for quicklime or cement have been found to be about 0.5 at temperatures higher than 20°C and 0-0.5 at temperatures from 8°C up to 20°C. In normal procedures, samples are stored at two or three different temperatures e.g. 8°C, 20°C and 30°C. They are then tested at adequate times to obtain values of K that give a unique curve for the results when plotted in a diagram with shear strength versus M_T. The strength with time after stabilization can then be estimated for any curing temperatures by using this diagram.

The effect of curing temperature on the strength of lime columns is considered also in the standard testing procedure in Finland. The method of handling the temperature effects here is to store all samples at specified temperatures decreasing with time (Kalkkipilariohjeet, 1986).

ESTIMATE OF COLUMN STRENGTH

An exact prediction of shear strength in situ cannot be expected from unconfined compression tests on samples stabilized in the laboratory. The methods used when stabilizing the soil and circumstances such as surrounding soil conditions, stresses and temperature at curing and testing are different in the laboratory compared to the in situ conditions. The relation between shear strength evaluated from laboratory tests compared to in situ tests is, of course, also affected by the differences in testing methods used.

Simulating stresses and loading conditions in situ by triaxial tests appears to be the most suitable testing method for use in the laboratory. However, unconfined compression tests are much simpler and cheaper to perform and have therefore been used in the standard procedure for testing stabilized soil in Sweden. These tests have also been found to be useful for determining the type and amount of stabilizing agent that should be used in production.

The effect of temperature on strength of stabilized soil is fairly well established. However, the effect of different stresses during curing has not yet been sufficiently examined. Test series being carried out, have so far shown no significant differences in shear strength in unconfined compression tests on samples stored in triaxial cells at stresses and pore pressures of the same magnitude as those in situ, compared to those stored in ordinary sampling tubes. Previous test series have, for some soils, shown an increased shear strength at an increased pressure during curing, while no such effect could be seen in other stabilized soils (Tränk, 1988). The relevance of these laboratory tests may also be questioned. In the field, the stabilizing agent and soil are mixed and then probably cured at about the same stresses as those prevailing before installation of columns. In the laboratory, standard preparations of samples are made by compacting stabilized soil in sampling tubes with a vertical pressure of 100 kPa. This precompaction probably balances to some extent the effect of different curing stresses.

In situ column strength is most adequately tested by using test columns and test fills or excavations. These tests, however, are quite costly and time-consuming. In Sweden, test fills and excavations have so far been used only in research projects. Tests with the lime column penetrometer are used as a standard procedure for examining columns in Sweden. This continuous testing method has made it possible to check the homogeneity of the columns and to obtain a rough estimate of strength and strength increase in the columns.

Relations between shear strengths determined by unconfined compression tests compared to results from penetration tests in situ are shown in Fig. 6. The differences in design strength

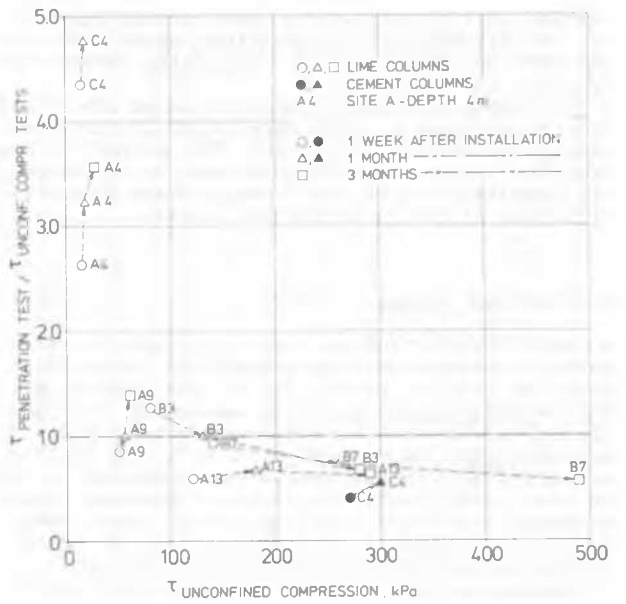

Figure 6. Relations between shear strength obtained in unconfined compression tests on samples stabilized in the laboratory compared to results from in situ penetration tests.

have in most cases been much less. The design strength based on unconfined compression tests has normally been maximized to 150 - 200 kPa. On the other hand, very low values obtained in the laboratory have often resulted in installation and penetration testing of test columns.

Practical experience shows that design based on unconfined compression tests, in some cases combined with penetration tests on test columns, has provided effective soil stabilizations. Measured settlements for applied loads have tended to be smaller than expected. This implies that a somewhat conservative estimate of strength for the soil-column model is used in the present design method.

CONCLUSIONS

Shear strength of chemically stabilized soil is affected by a number of different factors. In deep stabilization with the lime column method, the effect of different curing temperatures has proved not to be negligible. However, a relatively good estimate of this effect can be made.

Confining stresses and pore pressures may also affect the column strength. Further investigations should be made concerning these effects.

The use of unconfined compression tests in the laboratory and penetration tests with the lime column penetrometer in situ for determination of design strength of lime or cement columns has shortcomings. This seems to have resulted in somewhat conservative designs. The increasing use of lime and cement columns for various types of application calls for more accurate tests to better predict the behaviour of soil/columns under different types of loadings.

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