Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

Arbetsrapport 31
2004-10

A laboratory model study on the transition zone and the boundary layer around lime-cement columns in kaolin clay

Mirja Kosche

Svensk Djupstabilisering

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Verksamheten finansieras av medlemmarna samt genom anslag från Byggforskningsrådet/Formas, Svenska byggbranschens utvecklingsfond och Kommunikationsforskningsberedningen.

Svensk Djupstabilisering har sitt säte vid Statens geotekniska institut (SGI) och leds av en styrgrupp med representanter för medlemmarna.

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Swedish Deep Stabilization Research Centre

The Swedish Deep Stabilization Research Centre coordinates research and development activities in deep stabilization of soft soils with lime-cement columns. A joint research programme based on the needs stated by the authorities and the industry is being conducted during the period 1996 – 2004. Members of the Centre include authorities, lime and cement manufacturers, contractors, consultants, research institutes and universities.

The work of the Swedish Deep Stabilization Research Centre is financed by its members and by research grants.

The Swedish Deep Stabilization Research Centre is located at the Swedish Geotechnical Institute and has a Steering Committee with representatives choosen from among its members.

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Mirja Kosche

Division of Soil and Rock Mechanics
Royal Institute of Technology (KTH), Stockholm
MSc Thesis

Linköping 2004

Förord

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I föreliggande arbetsrapport redovisas laboratorieförsök med stabiliserad kaolinlera avseende gränszonen stabiliserad jord – ostabiliserad jord.

Linköping i november 2004

Göran Holm
Projektledare för SD

Arbetsrapport

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Foreword

Deep stabilisation of soft soils with the lime-cement column method is common in the Swedish construction industry since the method was developed over 30 years ago. Extensive research is going on for a deeper knowledge about the stabilisation mechanisms and to enlarge the field of application.

The Swedish Deep Stabilization Research Centre (SD) was established in 1996 by governmental authorities, research organisations and industry. SD comprehends theoretical and practical-applied research (SD, 2002). The research activities include issues related to planning, design, execution and control.

In 1997 a research project started at the division of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm. The main objective of the project is to increase the knowledge of the behaviour of laterally loaded lime-cement columns. Different functions and failure mechanisms in stabilised soil are investigated. Stefan Larsson, Tyréns AB, performs the project as an industrial PhD-project. Within the project a large number of model tests have been performed. The first series of tests are published in two conference papers (Larsson, 1999a; Larsson & Broms 2000).

In some of the model tests a thin layer of soft or even liquefied clay around the columns was observed. The intention of the thesis in hand was to investigate this soft boundary layer, its soil-mechanical characteristics and the content of selected cations. The thesis presents the results of the conducted model tests.

The work was carried out at the Division of Soil- and Rock Mechanics, Royal Institute of Technology, Stockholm, under the supervision of Stefan Larsson. Stefan Larsson and the author performed the preparation of the soil, column installation, geotechnical testing and sampling. Professor Gunnar Jacks at the Department of Land and Water Resources, Royal Institute of Technology, Stockholm, and the author carried out the chemical investigation.

Summary

Around lime-cement columns in laboratory prepared kaolin clay, a thin layer of soft or liquefied material has been observed. A hypothesis, based on the literature, was developed that explains the phenomenon by a front of cations, presumable sodium and potassium ions, which have been superseded by the calcium ions that migrate from the columns.

This thesis deals with the transition zone and the boundary layer around lime-cement columns in kaolin clay. A brief overview of the Swedish lime-cement column method is presented but the main part of the thesis describes the conducted series of laboratory tests. The thesis presents the results of the test series, demonstrates changed properties in the transition zone and in the boundary layer, and discusses the chemical process.

The main object of this thesis was to describe the model tests and to present results from geotechnical and chemical analysis. A second object was to investigate the boundary layer and to find out in how far deterioration in soil mechanical characteristics in this layer is provable and whether this is reflected in ion contents. The work is limited to the study of lime- and cement stabilised laboratory prepared kaolin. Furthermore, the thesis does not discuss the mechanical effects on real applications. No tests have been performed on natural soft soils.

Small-scale lime-cement columns (ϕ50 mm) have been installed in laboratory-prepared kaolin. Seven column types were manufactured that differed in producing method, binder mixture and amount of peptizer (lignosulphonate). The undrained shear strength in the transition zone and in the surrounding soft soil was tested at several column ages (after 7, 14, 30 and partly 90 days). Samples were taken for geotechnical tests: remoulded shear strength; water content; Atterberg limits. Chemical tests by AAS (Atomic Absorption Spectrophotometer) were performed in order to determine the content of some cations (sodium, partly potassium and calcium). A total of over 1000 tests were performed.

The results from the geotechnical tests presented in this thesis show the effect of migration of calcium ions and superseded sodium and potassium ions on the transition zone and the boundary layer. The addition of a peptizer, lignosulphonate, was found to have a negative effect on the boundary layer. In some cases the kaolin clay was liquefied.

A second important observation was that the combination of using wet mixing and only cement as binder had a negative effect on the boundary layer. Dry mixing and lime as binder had no negative effect on the undisturbed shear strength. However, the sensitivity increased in the boundary layer around all columns

This study is an initial step for the understanding of the mechanisms that influence the boundary layer between the transition zone and the surrounding soft soil. The phenomenon merits further investigations on lime-cement treated natural soft soils.

Table of contents

1 INTRODUCTION

1.1 Lime-cement columns

Due to the development of deep mixing methods it is possible to build infrastructure on areas with poor ground conditions. The soil is improved with respect to the strength and deformation properties in order to increase stability and to prevent large or unsymmetrical settlements.

The Swedish lime-cement column method is suitable to stabilise various soft soils. The method was developed 30 years ago and since then the method has been successfully used to improve the soil especially under road and railway embankments. As a result of these good experiences, the field of application has been extended. For example, lime-cement columns have been used to stabilise excavations, slopes and high embankments.

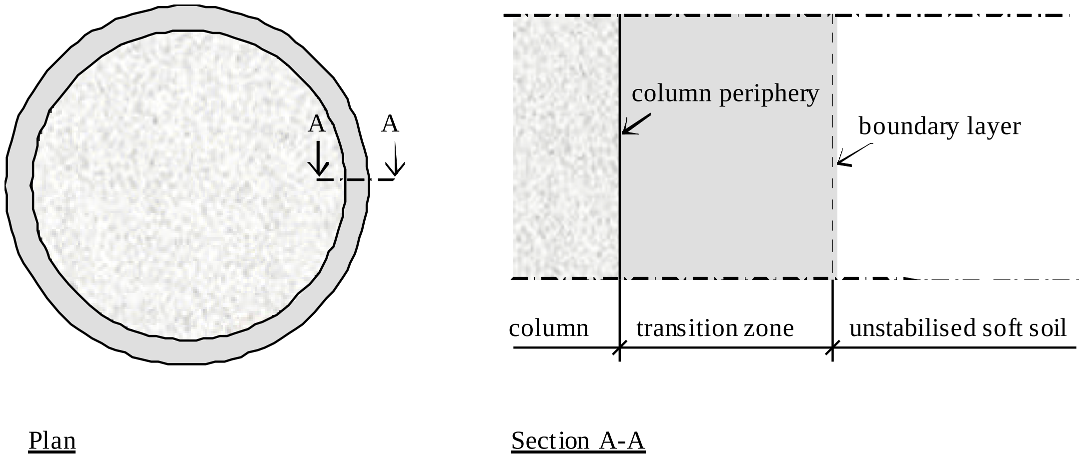
1.2 Background

During the period autumn 2000 to summer 2001, a number of model tests were performed and reported as a MSc thesis (Honkanen & Olofsson, 2001) at the Division of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm. In these model tests, columns were manufactured by casting with slurry consisting of lime, cement, clay, water and peptizer. The peptizer, lignosulphonate, was used to liquefy the slurry in order to facilitate the column manufacturing and to create columns with uniform properties. In a number of tests, when the columns were extracted after the model test, 7 days after the column installation, a soft boundary layer around the columns and around the column rows was observed. The soft boundary layer was located between a relatively hard zone, approximately 10 to 20 mm thick, and the surrounding unstabilised soft soil.

The migration of calcium ions due to cation exchange in soft soils has been the subject of many investigations, e.g. Rogers et al. (2000a and 2000b), Rogers & Glendinning (1997 and 1994), and Rajasekaran & Narasimha Rao (1997 and 2000). The observed distances of migration differ; Rogers et al. reported 30 to 50 mm, Rajasekaran & Narasimha Rao reported 200 mm. The migration of calcium ions in the surrounding soft soil results in changes in the mechanical characteristics, e.g. the undrained shear strength increases. These investigations have studied mainly lime as binders (filled in a hole in the soil), but also lime in combination with some other kinds of binder (cement, fuel ash, blast furnace slag; see: Rogers et al. 2000b) or lime in combination with inorganic additives (calcium sulphate, sodium sulphate, calcium chloride; see: Rajasekaran & Narasimha Rao 1997, 2000). The soils tested by Rogers et al. (2000) in the field were London clay, lower Lias clay and poorly compacted clay fills. The soils used in the investigations of Rajasekaran & Narasimha Rao (1997, 2000) were marine clays (formed under shallow coastal sea water conditions) prepared for laboratory tests. However, none of these investigations touch on a soft or liquefied boundary layer in front of the affected area around the stabilised soil.

A soft boundary layer has been observed in the field, but this phenomenon has not been well documented. Åhnberg et al. (1995) have studied the stabilisation of soil with lime and cement in the laboratory and observed a thin layer of soft clay around the stabilised soil. This was explained by a shrinking of the stabilised material. Some field trials were performed, and again a layer of soft clay in the surrounding of the trial column (lime/cement: 50%/50%) was observed. Several ion contents were measured at different distances from the column. A decreased salt concentration was assumed to be the cause of the soft boundary layer.

In this thesis the zone around the columns mechanically influenced by the mitigation of ions is determined as the transition zone, according to Figure 1.1. The thin layer between the transition zone and the surrounding soft soil is determined as the boundary layer. The boundary layer is visually approximately 1mm thick.



Plan

Section A-A

Figure 1.1 The transition zone and the boundary layer around columns.

In a previous series of model test at Royal Institute of Technology (so far unpublished tests by Larsson 2001), a liquefied boundary layer was observed. Laboratory prepared kaolin clay was stabilised by single columns. The columns were manufactured using a slurry consisted of water, cement, lime and lignosulphonate. Samples were taken from the liquefied boundary layer and from other parts of the surrounding soil for water content determination. It was clear that the water content was about the same in the liquefied boundary layer as in the surrounding unstabilised soft soil. The liquefied consistency of the soil in the boundary layer indicated that there is a chemical explanation to the phenomenon. After a consultation with professor Gunnar Jacks at the Department of Land and Water Resources, Royal Institute of Technology, Stockholm, it was assumed that the reason for the liquefied boundary layer to take place is a front of cations, presumable sodium ions. These have been superseded by the calcium ions that migrate from the columns.

1.3 Object and hypothesis

The adsorbed cations in the clay crystals are assumed to play a major role in the observed phenomenon. They can be replaced by other cations. Calcium has a valence of two, sodium and potassium have each a valence of only one, i.e. one calcium ion can take the place of two sodium or potassium ions. The calcium ions are supposed to exchange the existing (adsorbed) cations at the negative charge sites of the clay crystals (see Brady, 1984). In the area of the stabilised kaolin clay a lot of calcium is mixed in the soil because it is part of the binder (see Chapter 2.5). In this area, presumable sodium and potassium ions are superseded by calcium ions. The sodium and potassium ions migrate in a front outward due to (natural) diffusion processes driven by the migration of calcium ions. The intensity of the front of sodium and potassium ions is supposed to get lower in the longer term because a well-balanced distribution is the aim of diffusion processes.

The higher content of monovalent cations reduces the forces of attraction between the clay particles (see Brady, 1984). As a result, the soft clay can get liquefied. This is supposed to be the reason for the changed soil mechanical characteristics.

The object of this thesis was to investigate the boundary layer observed in the stabilised laboratory prepared kaolin clay and to find out if soil mechanical characteristics are reflected in the ion contents.

1.4 Structure of the thesis

The first chapter is an introduction to the subject and explains the background of this investigation.

The second chapter gives a brief overview of the Swedish lime-cement columns method.

In the third chapter, the methods and materials used in this laboratory investigation are described. First the general conditions for the experiments are given and second how the kaolin clay was prepared in the laboratory. The different methods for column installation and the column arrangement are described. The different mixing recipes and their background are listed and the methods used to determine the geotechnical and chemical properties are described.

The fourth chapter presents the results, first some selected examples to give a summary of the range of the results and after that the results in detail.

In chapter five the results and the influence of several factors are discussed.

The sixth chapter presents the conclusions.

2 THE SWEDISH LIME-CEMENT COLUMN METHOD

2.1 Field of application

The Swedish lime-cement column method is a deep mixing method. That means a method to improve soft soils by adding dry or wet binder for reducing settlements and/or improving the stability. They can also act as a vertical drain and accelerate the settlement process.

Lime-cement columns are suitable for various soft soils like clay, silt and gyttja. Their widest field of application is under embankments for roads or railways (over 80 %), but they can be used also for reduction of vibration along and/or under railway embankments or for slope stabilisation. Additional examples of application are for excavations as needed for pumping stations or as alternative to sheet pile walls for temporary excavations like e.g. piping trenches. (See: Holm, 1999 and SGF, 2000)

2.2 Installation

Lime-cement columns consist of a mixture of the natural soil and the binder. For the installation of the columns a special mixing tool and a machine with one mixing shaft with an inner tube for the binder are needed. The mixing tool usually has two or three pairs of inclined paddles with a diameter of 0.5-0.8 m and an injection outlet (Figure 2.1).

The mixing tool is drilled downwards to the required depth and by that disaggregates the soil. This stage in the mixing process cycle is called “Penetration” or “Downstroke”. It is followed by the “Retrieval” (or “Upstroke”), in which the binder is fed into the soil at a constant flow rate and the mixing tool is drilled upwards at a constant retrieval speed. Normally the direction of rotation changes between penetration and retrieval. While the binder is fed into the soil the mixing tool mixes and compacts the mixture (dispersion phase). The binder is fed into the soil by an air pressure (depending on the machine type 200 – 1000 kPa).

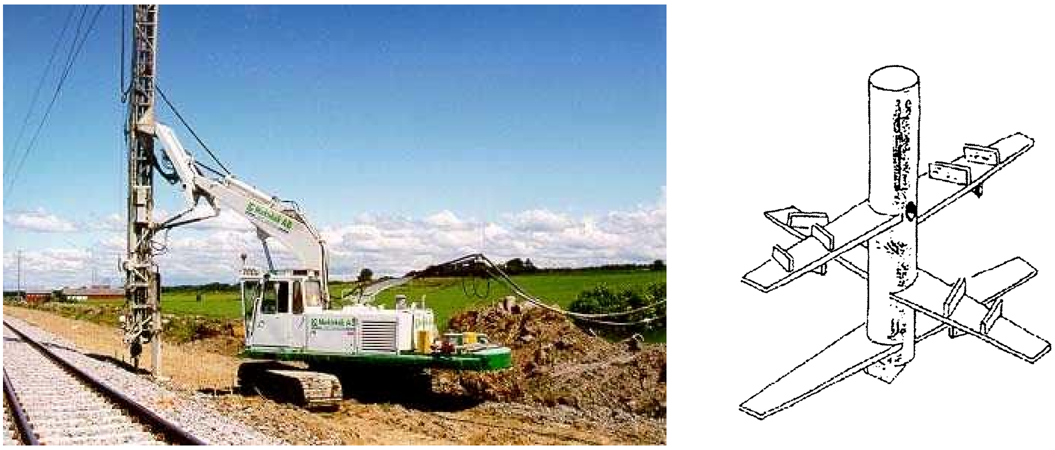


Figure 2.1 Machine for column installation and a mixing tool (SGF 2003, Larsson, R. 1999).

The Swedish deep mixing method can produce 25m long columns. They usually have a diameter of 0.6 or 0.8 m. The columns can even be produced inclined in relation to the vertical (up to about 70 degrees).

2.3 Placement

Lime-cement columns can be placed in many different ways, for example as single columns, in blocks or panels of columns or in a stabilised grid, as shown in Figure 2.2.

For the reduction of settlements under an embankment they normally are placed as single columns in a square pattern with a centre distance of 0.8 to 1.7 m. Columns placed in panels, grids or blocks are used for slopes, excavations or under embankments where the columns are subjected to lateral forces. Lime-cement columns are often combined with preloading and surcharging in order to reduce or eliminate the long-term creep settlement (SGF, 2000).

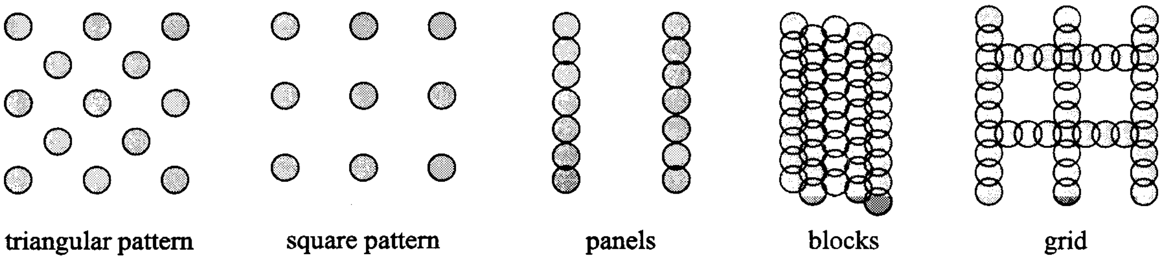


Figure 2.2 Column placement possibilities.

In the case of small bridges lime-cement columns combined with surcharging can be a cost-effective alternative compared to e.g. pile foundation since the columns can be used for both the bridge and the approach embankment. Thus very small differential settlement can be achieved because the whole construction is more flexible. (See: Holm, 1999)

2.4 Binders

Different types of binders are used depending on the type of soil and the requisite stabilising effect. Usually a mixture of lime and cement is used, but also other kinds of binder like mixtures with slag cement or additives in small amounts. When the method was developed thirty years ago, only lime was used as binder (e.g. Broms & Boman, 1979). Since 15-20 years, mostly mixes between lime and cement are used in Sweden. A mixture of lime and cement results in a rapid strength increase. For the stabilisation of organic soils binders like cement and granulated blast furnace slag are normally used.

Laboratory mixing trials are helpful for the choice of suitable binder and required quantity. Usually the content varies between 80 - 110 kg/m^3 for lime-cement columns (SGF, 2000).

2.5 Chemical reactions

There are many factors affecting the stabilisation process, like for example soil gradation, type and amount of clay minerals, organic content, nature of exchangeable ions, pH, water content, temperature, type and quantity of binder and the mixing process in-situ.

The basic reactions for soil stabilisation with lime and cement described in the literature (e.g. Janz & Johansson, 2001 or Boardman et al., 2001) are:

- dewatering The initial reaction of quicklime added to a soil-water system is highly exothermic; the water in a hydration reaction slakes the quicklime. Because a lot of water is removed from the soil system by this hydration reaction and because of the heat generation of the reaction, the workability of the soil can be improved.
- modification by cation exchange: The cations adsorbed at the negative charge sites of the clay crystals are replaced by the calcium ions. This process results in flocculation/agglomeration of the soil particles so that the clay is more easily crumbled.

- solidification due to hydraulic reactions (of cement): The calcium, silicon and aluminium ions from the cement react with the water and form a hard mass of calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH) and calcium hydroxide ($Ca(OH)_2$). The reaction products CSH and CAH are known from concrete as the hard grey mass between the gravel stones.
- solidification due to pozzolanic reactions: The calcium ions from a binder, lime or cement, react with silicon and aluminium ions that are dissolved from the clay minerals. The products of pozzolanic reactions are calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), the same products as from hydraulic reactions.

The first two reactions take place rapidly and cause changes in the engineering properties. But in the case of dewatering these changes disappear if the soil is moistened again.
The solidification as a result of hydraulic and pozzolanic reactions is a slower process and improves the soil characteristics in the longer term.

2.6 Design model

In the present Swedish calculating model for stability calculations, interaction between the columns and the unstabilised clay is assumed (SGF, 2000). The same compression and shear deformation are assumed to occur in both clay and column at all levels. The load is transferred partly by the columns, partly by the unstabilised soil. The load is transferred through the columns to an underlying firm ground or to a soil with better properties. The interaction between the columns and the intermediate unstabilised clay creates a block of improved strength and deformation parameters. The undrained shear strength of stabilised soil increases normally by the factor 10 to 20. In Sweden the maximum design value of the undrained shear strength of the columns is limited to 100 kPa, in favourable cases 150 kPa. The columns are mainly intended to be axially loaded since the tensile strength is limited or negligible. To increase the shear resistance of the columns in the direct shear zone, overlapping columns are installed in rows. Failure is assumed to occur along a slip surface through the columns and the surrounding soil as shown in Figure 2.3. However, a number of failures have occurred in stabilised excavations, slopes and high embankments. According to Broms (1999b) these failures could indicate that the stability is overestimated when the weighted average shear resistance is used in design. Occurred failures can, however, be caused by a combination of several factors. The calculation

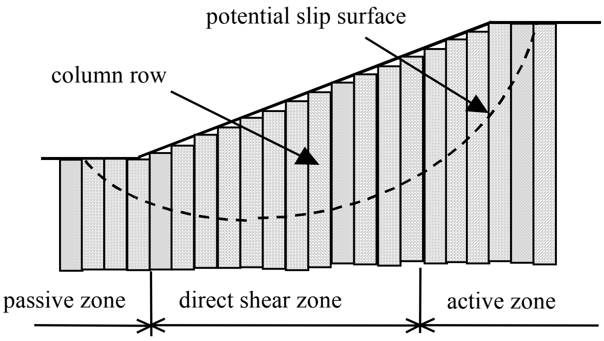


Figure 2.3 A potential slip surface passing a column row stabilised slope (Larsson, 1999b).

methods used in Sweden do not take into account the various failure mechanisms that may be observed. A loose boundary layer around stabilised soil has not been given as a reason for failures.

Kivelö (1998) has proposed models for single columns at the ultimate limit state. This study shows that there are a number of failure mechanisms that can occur, depending on the load and soil conditions. In the shear zone, where the columns are subjected to lateral forces, the columns are assumed to act as dowels. A number of failure mechanisms for rows of columns have been discussed by Broms (1999a).

The common assumption for the design models presented is that an interaction exists between the columns and the surrounding soft soil. Shear forces must be transmitted to the columns if they shall contribute to an increased stability. The magnitude of the transmitted shear force is consequently crucial for the stabilising effect.

2.7 Advantages and disadvantages

The advantages of ground improvement by lime-cement columns are good economy, flexibility and that they are non-polluting. The economy of lime-cement column projects often is good because they are quickly feasible and not so expensive equipment is needed. The method is very flexible since column spacing; column depth and column diameter can be adjusted to the respective problem. By the installation of lime-cement columns the existing soil on the site is used and only small vibrations and low noise are caused. The method has been used in a great number of projects for varying applications for 30 years.

It must be taken into consideration that the strength is reached at approximately 14 to 30 days after installation and that the construction time is even longer when preloading or surcharging is applied. Single columns are not suitable for the stabilisation in direct shear zone or the passive zone of slip surfaces. In these applications the columns are recommended to be placed in the form of panels, blocks or grids. Lime-cement columns installed overlapping in rows have been used for the stabilisation of landslides in Sweden (see: Holm, 1999).

Ground improvement by lime-cement columns has a high stabilising effect in clay and even in clay with silt strata and silty clay. If the clay contains sulphides or sedimentary organic soil, the strength increase can be relatively slow, full load should be applied earliest 2-3 months after the installation of the columns. For silt and silt containing sulphides a stabilisation with lime-cement columns is possible. In peat or sedimentary organic soil the stabilising effect is normally lower than in clay. In most cases column stabilisation in sedimentary organic soil can be possible; mixing trials give helpful information (see: SGF, 2000).

3 METHODS AND MATERIALS

3.1 General framework

The soil used for this test series was kaolin that was delivered as powder, mixed with water and consolidated in the test boxes. It is common to use kaolin for model tests. The main reason is that kaolin is an industrial product and thereby reproducible, easy to handle and the coefficient of consolidation is relatively high, which results in reasonable times for the consolidation of the soil. The use of undisturbed natural clay samples of this size is difficult and costly. The main disadvantage of using kaolin clay is that the results cannot be used without great care in order to draw conclusions concerning consequences for field applications. Natural soils are not as homogeneous and they are normally complex in their composition.

The test boxes, 500 mm in diameter, were separable in two equal parts. In each test box, the columns could thereby be tested at two column ages. In order to make tests possible at four column ages, two test boxes were used. Except for the time, other varied factors were binder mixture, producing method and peptizer. More details are explained in Chapter 3.4 "Test program". Lime and cement powder were used as binder. A common peptizer from concrete production was used; lignosulphonate that contains high sodium content. In the concrete industry the use of peptizers is common for a better flow ability.

3.2 Soil preparation

Dry kaolin powder was mixed with tap water to a slurry with a water content of approximately 100 %. This slurry was poured in the cylindrical test boxes, 500 mm in diameter. They had a draining sand layer, separated by filter paper, in the bottom. A steel plate and sealing plastic film was put on top. This facilitates the applying of an air pressure for the consolidation of the clay. The pressure was raised in steps during the first week until a maximum of 60 kPa, which was hold for 10 days. Drainage was possible in the bottom of the box, as shown in Figure 3.1. The preparation of the kaolin clay and the installation of the lime-cement columns in the test boxes correspond to the procedure described by Larsson (1999a).

After the consolidation, the kaolin had a natural water content of 46 %, a liquid limit of 47 %, a plastic limit of 31 %, shear strength of 6.0 kPa and a sensitivity of 3.7.

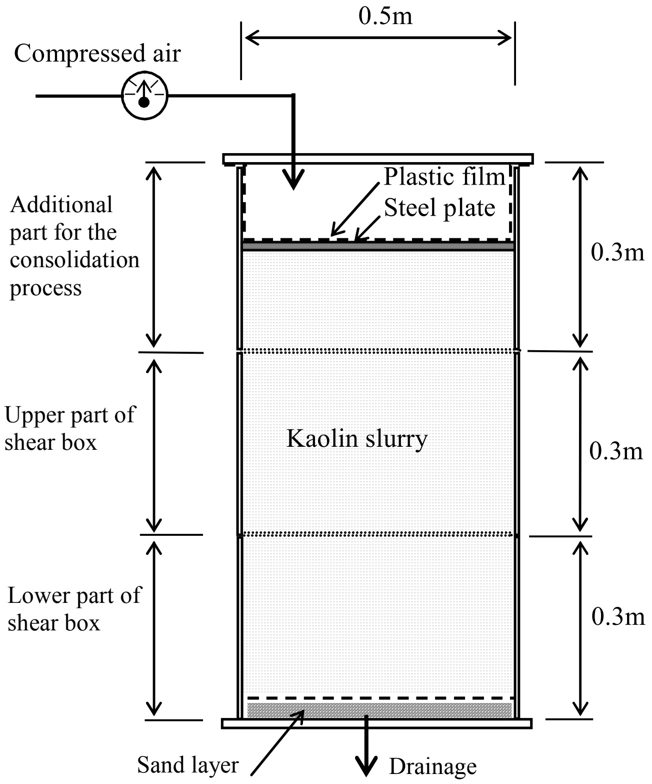


Figure 3.1 Schematic of consolidation process (Larsson 1999a).

3.3 Installation of columns

After 10 days consolidation of the clay, the air pressure and the steel plate were removed. The clay surface was smoothed and the position of the columns was marked (positions of columns see Figure 3.3). The columns were installed with three different methods: dry mixing; wet mixing and; the casting method (see the following three subsections).

After the column installation the boxes were closed again with a filter paper, a 5 cm sand layer and a steel plate. A low pressure, 15 kN/m^2, was applied in form of steel weights. The water level was kept constantly at the height of the upper edge of the box, in order to prevent drying the emergence of cracks (see Figure 3.2).

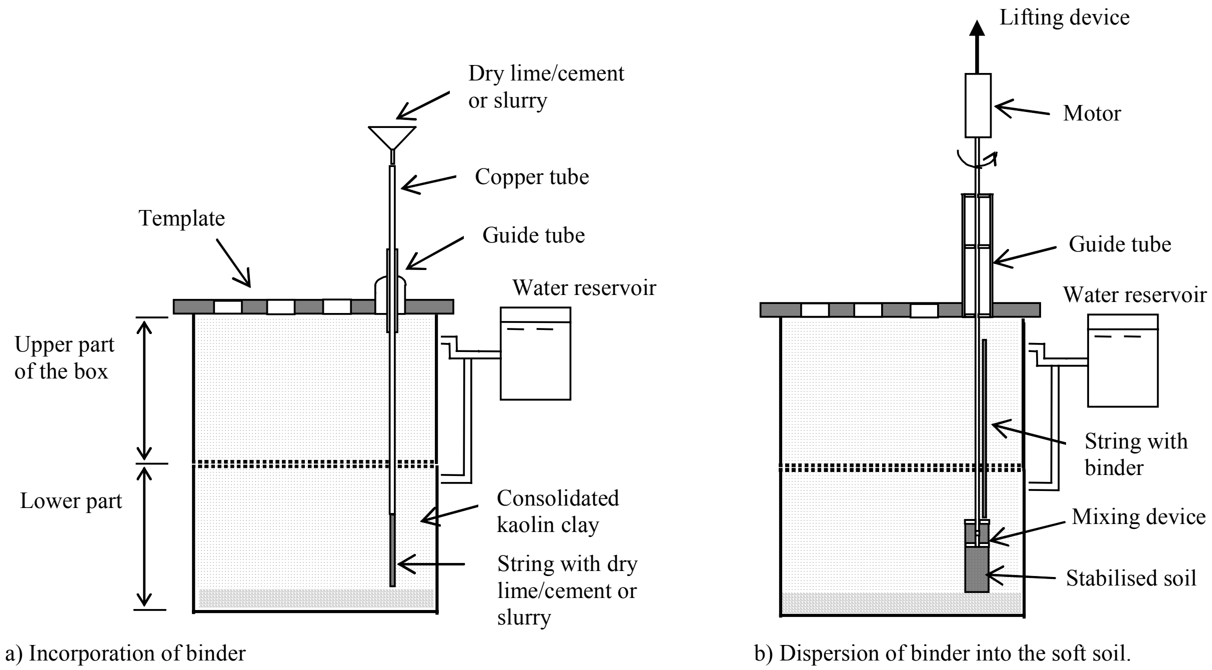


Figure 3.2 Schematic of the installation of columns (modified after Larsson, 1999a).

3.3.1 Dry mixing

For the column installation by dry mixing, a brass tube (outer diameter 1,4 cm), closed at the bottom from inside with a plug on a rod, was pushed down to the requisite column length. The tube was guided by a special guiding tube (see Figure 3.2), which was tightened on a plastic plate for an easier positioning. The plug was removed and the dry lime-cement mix was filled in steps into the brass tube by using a funnel tube. In a number of steps the binder mixture was pushed out in the hole with a rod while withdrawing the brass tube. The brass tube was pushed down afterwards another time in the clay and the hole was filled again with the lime-cement powder. The two holes were placed eccentric, so that a main part of the column cross-section was reached. The two like these produced strings of dry binder mixture in the kaolin clay were then mixed with the surrounding clay to form a column. The mixing process was facilitated by another guiding tube that was tightened on the plastic plate. Every column was mixed three times at a constant rotational speed of 300 rpm and a constant speed of 2 m/min upwards during retrieval. A mixing device with three pairs of inclined paddles was used.

3.3.2 Wet mixing

The wet mixing is similar to the dry one. The difference is that the binder is pre-mixed with water to form a slurry before it is put in and mixed with the kaolin clay. There is only one hole in the centre of the column and this is made by a brass tube with an outer diameter of 1.8 cm or 2.0 cm, depending on the volume of the lime-cement-water mixture.

3.3.3 Casting

A third method for column installation is the casting. For this a brass tube with the outer diameter of the completed column (5.0 cm) was slowly pressed down in the clay with an open bottom. The clay inside was taken out in small steps with a spiral bent sheet metal on a rod until the length of the column was reached. Dry kaolin, cement, lime and peptizer were mixed with tap water and then poured in the brass tube while this was slowly withdrawn. A small paddle-type mixing device was used in order to prevent air-bubbles in the mixture.

3.4 Test program

3.4.1 Arrangement of the columns

In order to avoid the influence of the migration from different columns on each other, the minimum required space in between the columns was estimated roughly (Davidson et al., 1965) to 40 – 160 mm. Seven columns were installed in each of the two boxes. 500 mm long columns were installed for the tests on 7 to 30 days old columns. In one of the two test boxes, four of the columns were only 250 mm. Figure 3.3 shows the arrangement of the columns in the two boxes. The columns were placed in a hexagon around one column in the middle.

On the left the arrangement of the columns in box 1 for testing after 7 and 90 days is presented and on the right the one in box 2 for testing after 14 and 30 days. The columns in the two test boxes have the same numbers because they were installed with the same recipes. They were apportioned in two boxes to get the possibility of tests at four column ages. The time schedule including column installation and testing for the two test boxes is shown in Figure 3.4.

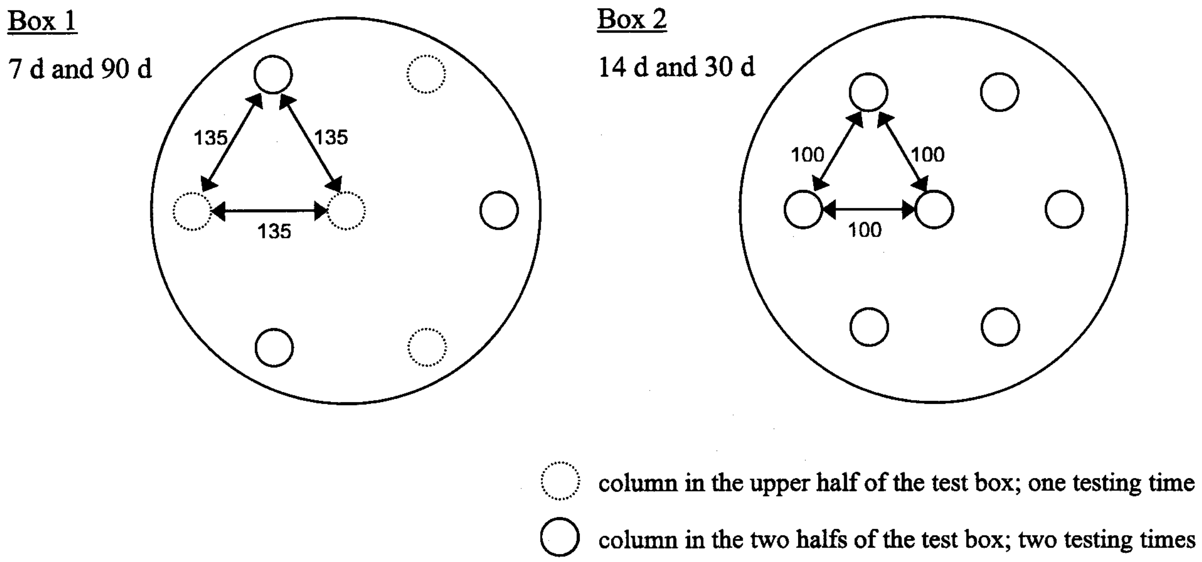


Figure 3.3: The arrangement of the columns in the two test boxes (all lengths in mm).

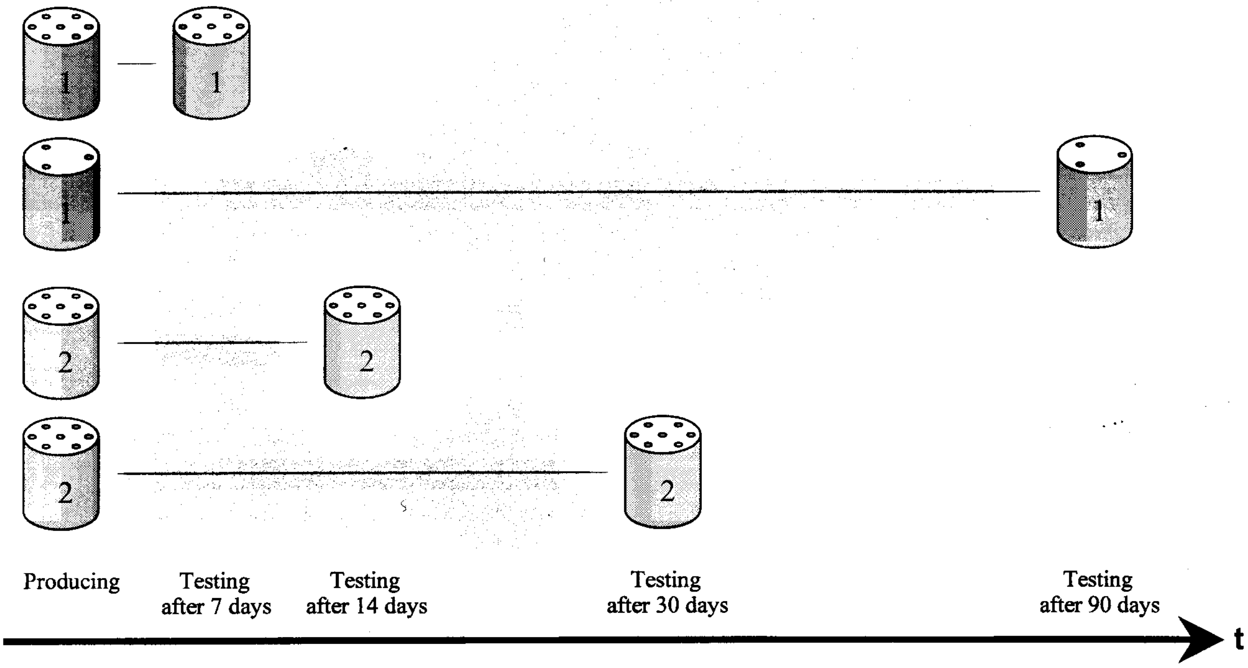


Figure 3.4: Time scheme with the test boxes.

The columns in box 1 were installed first and the ones in the upper part of this box tested after 7 days. The part of the columns in the lower half remained until the column age of 90 days was reached. In the meantime columns were installed in box 2 and tested after 14 days (upper half) and 30 days (lower half).

3.4.2 Mixing recipes

Seven different mixing recipes were used in order to study a number of influencing factors. The recipes differ in producing method, lime to cement ratio and if peptizer was added or not. Table 3.1 shows an overview.

Table 3.1: The mixing recipes of the different columns and their column ages.

Column	Column age [days]	Producing method	Lime/cement ratio [%]	Binder content [kg/m^3]	Peptizer content	
					[%]*	[kg/m^3]
A	7, 14, 30	Dry	70/30	150	0	
B	7, 14, 30, 90	Dry	30/70	150	0	
C	7, 14, 30	Dry	0/100	150	0	
D	7, 14, 30	Dry	0/100	150	5	7.5
E	7, 14, 30, 90	Wet	0/100	150	0	
F	7, 14, 30	Wet	0/100	150	2	3
G	7, 14, 30, 90	Wet	30/70	150	7	10

* weight-% of the dry binder weight

In the first column of the table the number of the different trial columns is listed. The composition of the columns has an intended order: from the one that is assumed to have the lowest liquefying effect on the boundary layer, to the one that is assumed to have the highest one.

The second column of the table shows the column age. Not all of the trial columns were tested after 90 days, only the columns B, E and G. This selection was made to have one column of each type of producing method. A selection was necessary because of the requisite minimum distance between the columns. At every column age, geotechnical tests were performed: natural water content, Atterberg limits, undisturbed and remoulded undrained shear strength, and chemical test.

In the third column of the table the producing method: dry mixing, wet mixing or casting, as described in Chapter 3.3.

The fourth column of the table shows the ratio of lime to cement in the binder mixture. Quicklime was used in column A,B, and G; column A 70 % and column B and G 30 %, The other columns had only cement as binder.

The fifth column of the table shows the amount of binder in kilogram per cubic metre stabilised soil. The binder content was 150 kg/m³, which is quite high compared to the amounts usually used in praxis (around 100 kg/m³, see Chapter 2.4). The binder content is the same as for the tests performed by Larsson 1999 and Larsson & Broms 2000.

In the sixth and last column of the table the peptizer content (lignosulphonate) is listed in weight percent of the amount of dry binder. Peptizer was used in column D, F and G: 5, 2 and 7 %, respectively. The relatively high peptizer contents was chosen based upon a series of tests performed in connection to a previous project where peptizer was used to facilitate mixing and to improve the mixing quality for stabilised laboratory prepared kaolin clay (Honkanen & Olofsson 2001). A very high content of lignosulphonate was required to achieve an effect on the mixture consistence. Recent tests performed by Hoffstedt & Johansson 2002, also show that it requires high contents of lignosulphonate to liquefy a clay-binder mixture. The peptizer content for column G, 7 wt-% of the binder content, was chosen in order to deliberately increase the sodium content.

The offset of the recipes describes in a way the history of lime and lime-cement columns. The first mixture is one of the oldest recipes with much lime and only little cement. The second one contains only a third lime and the rest cement. The third mixture has only cement as binder. All of these three are installed with the dry mixing method and without peptizer. The recipe of the fifth column with only cement as binder but installed with the wet mixing method is common in Japan today and elsewhere. The three other column mixtures contain peptizer in different percentages to study its effect combined with the installation method. There are considerations about using peptizer for lime-cement columns to improve the mixing quality. But it is questionable whether this could have a negative liquefying effect on the surrounding soil.

3.5 Sampling and testing

Both geotechnical and chemical properties were tested at the different column ages. Fall-cone tests were performed on the undisturbed kaolin clay in the test boxes. Then the samples were taken. These were 5 to 10 mm thick, beginning at the edge of the column. The sample of the boundary layer was taken as thin as possible. On this disturbed samples, the shear strength with the fall cone test, the water content, the Atterberg limits and the sensitivity were determined. Afterwards the cation contents were investigated with the help of an AAS. The test methods are described in detail in the following subsection.

At the time for the tests (after 7, 14, 30 and 90 days) the steel weights and steel plate were taken down and the sand layer and filter paper were removed. The upper layer of the clay including the upper third of the columns was cut carefully with a steel wire and removed by hand. Around all of the columns the transition zone and a boundary layer was visible. An exposed surface after 14 days is shown in Figure 3.5.

Figure 3.5 Testing surface after 14 days.

3.5.1 Soil mechanical tests

On the smooth surface cut with the wire the fall cone tests were carried out to determine the undisturbed shear strength. The fall-cone apparatus was fastened on an extension arm in order to facilitate testing over the whole surface. The cone was dropped at the surface in arbitrary distances from each column periphery. The sinking depth of the cone was noted down and the undisturbed shear strength determined according to Swedish Standard SS 02 71 25. Different cones were used to reach a proper sinking depth depending on the stiffness of the clay.

Samples were taken in the column and circular around it. Figure 3.6 shows an example of the positioning of the samples (the thickness of the samples is given in mm). First, one sample from the column and the boundary layer were taken. Between the column and the boundary layer two (after 7 and 14 days) and three (after 27 and 90 days) samples respectively, were taken. The number of samples differed because the distance between the column and the boundary layer increases over time. Three samples were taken outside the boundary layer, 5, 5, and 10 mm thick respectively. The samples were stored in tightly shutting plastic boxes in a constant cool, humid climate and tested the following day.

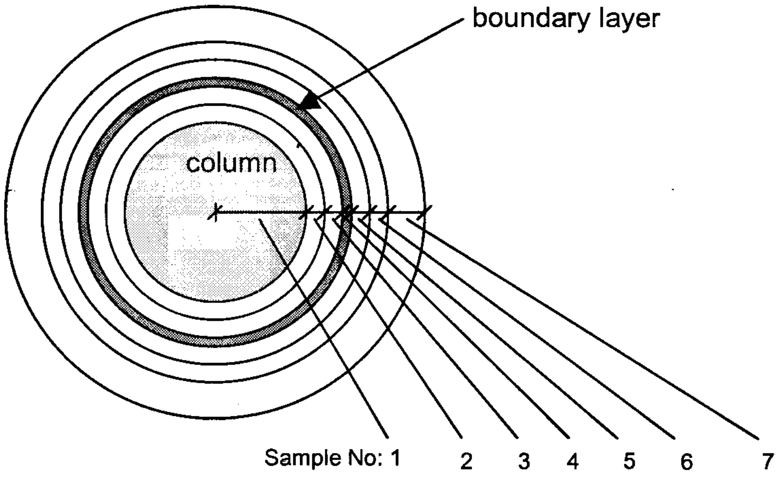


Figure 3.6: example for samples location around a column.

The natural water content was determined according to Swedish Standard SS 02 71 16. An amount of approximately 20 g was taken from every remoulded sample, put into a small tin and weighed before and after drying at 105 degrees Celsius.

The remoulded shear strength was determined by the fall-cone method (SS 02 71 25). The samples were remoulded properly and smoothed out before a cone from the testing apparatus was dropped at the sample's surface, its sinking depth read and noted down together with its weight. This procedure was repeated at least three times (until approximately the same value was reached). The fall-cone apparatus is shown in Figure 3.7.

Figure 3.7 Fall-cone test apparatus.

The liquid limit was determined according to Swedish Standard (SS 02 71 18 and SS 02 71 20). When testing remoulded clay and the sinking depth of the 60 g cone is in a certain range of values, the liquid limit can be determined. If it is not, the sample has to be dried or distilled water has to be added. This was done, if necessary, from a part of the sample directly after the fall-cone tests for the shear strength.

The plastic limit was determined according to Swedish Standard (SS 02 71 18 and SS 02 71 21). A part of the remoulded sample was taken for testing the plastic limit by forming rolls with a diameter of 3 mm by hand and meanwhile drying them on a gypsum plate until they broke in small pieces. The water content, the plastic limit, was ascertained as described above.

The sensitivity was calculated as the quotient between the undisturbed shear strength and the remoulded shear strength.

3.5.2 Chemical tests

In order to determine the content of exchangeable cations in the samples, a testing liquid of each sample was produced. The testing liquid contains the cations of the sample in the same percentages and can be tested with a special apparatus, AAS (Atomic Absorption Spectrophotometer). The sodium ion content was determined of all samples. Sodium was assumed to cause the impaired soil-mechanical characteristics. To get supplementary information, the potassium and calcium ion contents were measured for some chosen samples.

For the testing liquid the amount of moist sample material corresponding to 5 g dry material was calculated with the natural water content and weighed out. To each sample 20 ml barium chloride was added and the mixture shaken over night. Then it was filtered and the liquid filled up with distilled water to 100 ml. Some of these liquids showed, a for the measurement device, a to high concentration of sodium ions so all the samples were diluted with distilled water (5 ml of the sample filled up with distilled water to 50 ml). This liquid was tested with the AAS, the used one was of the Varian SpectrAA model.

An AAS works as follows: The sample is sucked into a flame formed by acetylene and air (for sodium and potassium) or acetylene and nitrous oxide (for calcium). The elements are atomised and for sodium (Na) and potassium (K) their emission is measured and calibrated with standard solutions. For calcium (Ca) cathode lamps with the elements in question are used. When the light from the lamp passes through the flame, a part of the specific radiation from the lamp is absorbed, proportional to the concentration of the sample. The absorption-concentration relationship is calibrated with standard solutions. Ionisation of the elements may disturb the measurement. In order to minimise that excess caesium (for sodium and potassium) respectively lanthanum (for calcium) is added.

3.5 Reliability

Two columns of each recipe were installed in the two boxes. Each of them was tested at two different column ages. The upper half of the one column was tested after 7 days and the lower half of the same column after 90 days. The upper half of the other column was tested after 14 days and the lower half after 30 days. The fact, that two columns of the same type were installed and tested after different column ages can result in different column diameters.

Two persons performed all tests.. This had on the one hand the advantage that the same tests were done of the same persons on all the samples. The test procedure was always the same. But on the other hand it had the disadvantage that not all the tests could be done on one day. Therefore the tests were done on the planned testing day and the day after.

To get an impress about how exact the ion content testing procedure with the AAS was, it was done on one sample three times. From this followed that the results were within a range of ± 2.6 % from the mean value.

Two or three samples that are not from a boundary layer show a really not explainable high sodium ion content. To exclude that the water content of these samples was changed during the tests, the water content was tested again after several weeks. The water content was changed a little, but this influenced the sodium ion content in such a little way that it was hardly visible in the figures. So the reason for the high sodium ion content of these samples is not a change of the water content.

There is an uncertainty related to the positioning of the fall cone tests and the sampling location. All tests and samples are related to an assessment of the centre of the column. The error in the location of the tests and samples taken related to the centre of the column is estimated to ± 2mm.

The results from the cone test performed at the boundary layer are probably somewhat too high since the cone is larger than the thickness of the boundary layer. Where the boundary layer was very loose or liquefied, column D to G, there is a risk that the cone was hanged between the transition zone and the surrounding soft soil.

The assessment of the sensitivity ratio in the boundary layer is uncertain, especially in the case were the undisturbed shear strength was low. Since the sensitivity ratio is defined by the undisturbed shear strength divided by the remoulded shear strength, the ratio becomes uncertain when two small numbers are divided. This is probably the reason why the sensitivity ratio varies considerably.

4 RESULTS

4.1 General

The results are presented in detail in section 4.3 to 4.9. Some guidance about how to read the figures is given in the following paragraphs.

The distance on the x-axis of the figures is related to the centre of the columns. The column periphery is located at distances between 25 and 29 mm. This range is because of imprecision in the mixing procedure, e.g. the mixing device may vibrate during mixing. The first row of graphs shows the results after 7 days, the second row those after 14 days and the third one those after 30 days. The fourth row, for column B, E and g, shows the results after 90 days for.

The graphs showing the Atterberg limits and the ion contents are presented in steps to make clear that the measured values are valid for the respective range. These tests were performed on the disturbed sample for which a minimum volume is needed (see Chapter 3.4.4: Sampling and testing).

No results from fall-cone tests in the columns are presented. When testing the shear strength in the area of the columns, the cone (even the heaviest one of 400 g) often sank less than 5 mm, which is the minimum for calculating the shear strength after the Swedish Standard.

The cation contents are presented in $cmol_c/g$, which means in centimol (referred to the charge) per gram dry mass of the sample.

4.2 The raw material

The sodium ion content and the potassium ion content of the dry kaolin-, lime-, cement- and peptizer powder were tested. The testing liquid was produced of the dry powder of the raw materials in the same way as of the soil samples that is described in Chapter 3.4.4. For kaolin and peptizer also the calcium ion content was determined, the one of lime and cement is usually quite high and was therefore not tested. The results are listed in Table 4.1.

Table 4.1: The results of the raw material.

	Sodium [cmol$_c$/g]	Potassium [cmol$_c$/g]	Calcium [cmol$_c$/g]
Kaolin	0.65	0.22	0.61
Lime	0.55	0.59	not tested
Cement	3.41	11.95	not tested
Peptizer	16.43	0.02	2.44

It is obvious that the sodium ion content of the peptizer is much higher than the one of the other raw materials, but the cement also contains a relatively high amount. Cement contains a high amount of potassium related to the other materials The calcium ion content in the peptizer is four times as high as the one of the kaolin.

4.3 Unstabilised kaolin clay

Table 4.2 shows some properties in the unstabilised kaolin clay, based on the results from the analysis on the outer samples taken. The samples are thus taken 7 to 90 days after installation of the columns.

Table 4.2: Properties in the unstabilised kaolin clay.

Property	Average	Coefficient of variation
Undrained shear strength	6.0 kPa	0.10
Sensitivity	3.7	0.14
Water content	46%	0.02
Liquid limit	47%	0.03
Plastic limit	31%	0.05
Sodium ion content	0.48 cmol$_c$/g	0.15
Potassium ion content	0.47 cmol$_c$/g	0.18 (few tests)
Calcium ion content	0.74 cmol$_c$/g	0.26 (few tests)

4.4 Column A

The diameter of the column that was tested after 7 days was 55 mm. The column that was tested after 14 days had a diameter of 50 mm. In the lower part of the same testing box, the column was tested after 30 days and had a diameter of 55 mm (see Chapter 3: Test Program).

The diameter of the boundary layer that was visible as a "ring" around the column at the testing surface was 85 mm after 7 days, 95 mm after 14 days and 105 mm after 30 days. The results are presented in Figure 4.2.

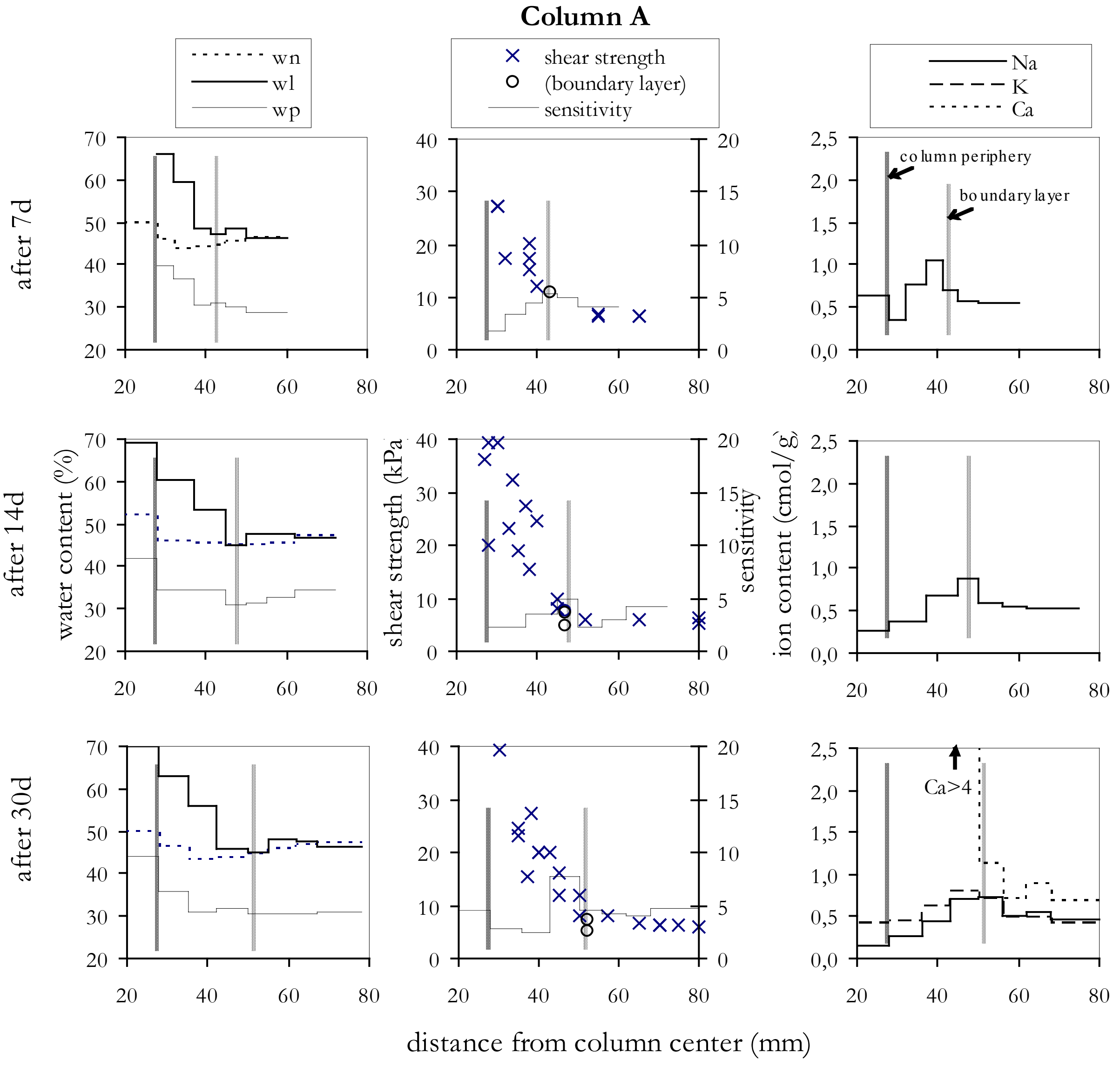


Figure 4.2 Test results, column A.

The boundary layer is not apparent in the results with the exception of the sodium ion content, where a weak maximum occurs at the same distance as the visual boundary layer. The distance of the boundary layer from the column centre is increasing over time but the values of the liquid limit and the shear strength are relatively unchanged. After one month even the potassium ion content and the calcium ion content were tested, their curves show the boundary layer as expected. The natural water content and the plastic limit are quite constant at all column ages and no trend is visible, the highest values are after two weeks. Inside the column the values are higher than further away; the natural water content is increasing a little bit at higher distances.

The boundary layer moves approximately 10 to 15 mm between 7 and 30 days. However, there is no distinct drop in the undisturbed undrained shear strength.

4.5 Column B

The column that was tested after 7 days (in the upper part of test box 1) had a diameter of approximately 55 mm. The diameter of the column that was tested after 14 days (in the upper part of test box 2) was 50 mm and the one of the column tested after 30 days (in the lower part of test box 2) was 50 to 55 mm. The column that was tested after 90 days (in the lower part of test box 1) had a diameter of 55 mm.

The boundary layer – visible as a "ring" around the column at the testing surface – had a diameter of 90 to 95 mm after 7 days, 95 mm after 14 days, 105 mm after 30 days and 125 to 130 mm after 90 days.

The results are presented in Figure 4.3.

The results of column B show the boundary layer as a maximum of the sensitivity and the sodium ion content and as an indication of a minimum of the liquid limit. The phenomenon becomes more distinct after 14 and 30 days, i.e. the maximum of the sensitivity and the sodium ion content increases and the liquid limit has a minimum in the boundary layer. However, there is no distinct minimum in the shear strength with regard to the scatter in the results. After three months the sodium ion content is lower again, but still as high as after one week. The sodium ion content and the liquid limit are higher after two weeks than after one or three months. The peak is changing to a wider top range.

The natural water content is at all column ages fairly constant in the boundary layer and the surrounding samples. Inside the column the water content decreases over time. The plastic limit outside the column is quite constant at all column ages, after one and three months it is a little bit lower in the boundary layer. The boundary layer is recognizable in all figures and moves approximately 15 to 18 mm between 7 and 90 days.

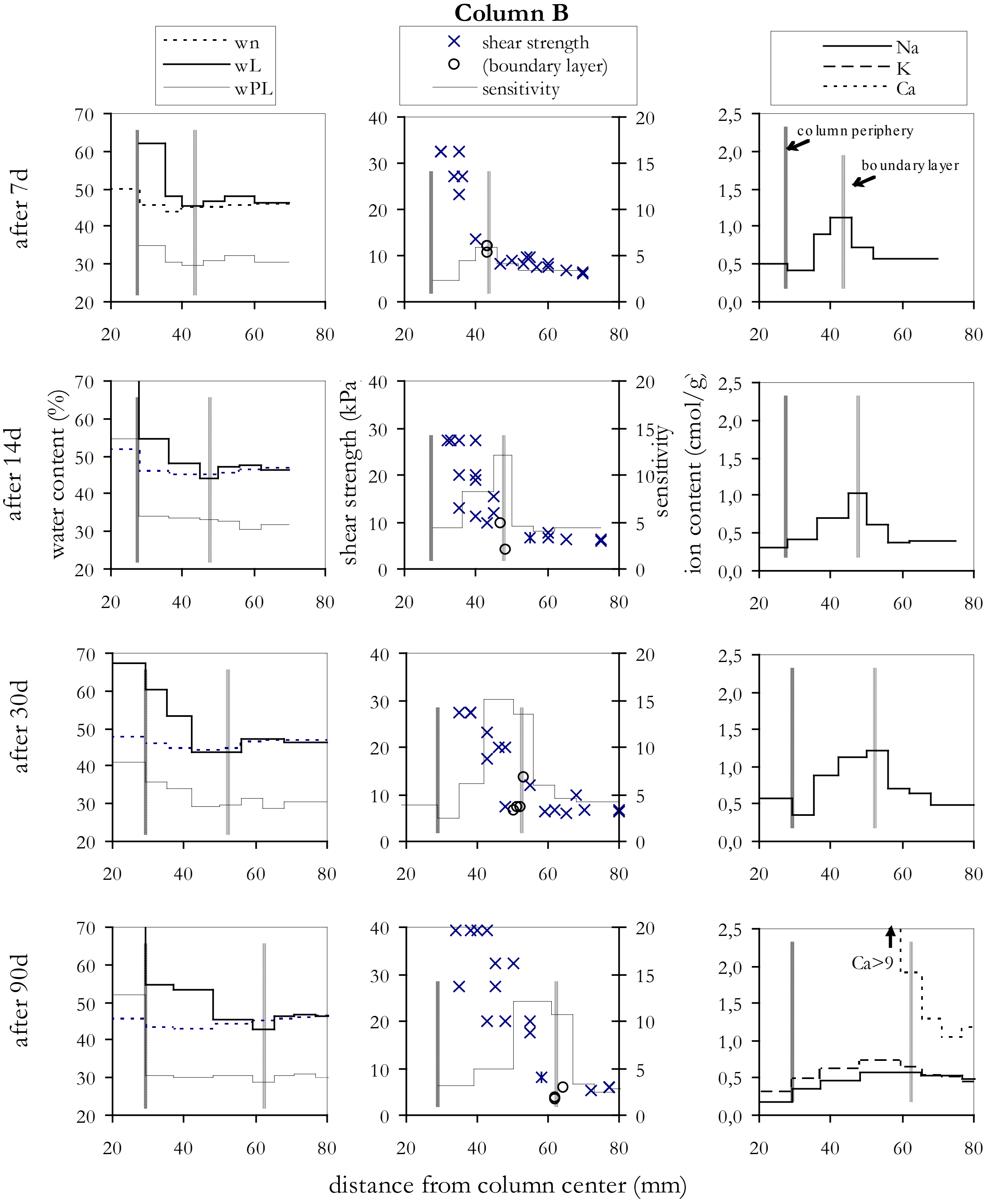


Figure 4.3: Test results, column B.

4.6 Column C

The column in the upper half of test box 1 was tested after 7 days and had a diameter of 53 mm. The column that was tested after 14 days was in the upper half of test box 2 and had a diameter of 51 mm. The diameter of the column in the lower half of test box 2 that was tested after 30 days was 55 mm (for column and sample positions see Chapter 3: Test Program)

The boundary layer was at all column ages visible as a "ring" around the column at the testing surface and had after 7 days a diameter of 80 to 83 mm, after 14 days 90 mm and after 30 days 92 mm.

The results are presented in Figure 4.4.

The boundary layer is well apparent in the results of column C at all column ages. Especially the values of the liquid limit, the sodium ion content and the potassium ion content after one week are distinct, i.e. they differ much from the surrounding values. These differences decrease to some extent over time. The shear strength in the boundary layer decreases over time and the sensitivity increases. The calcium ion content in the boundary layer is higher after one month than after one week (after two weeks it was not tested). The natural water content increases somewhat from the second sample outside the column outwards. Close to the column the water content is constant and higher than outwards next to it. Inside the column the natural water content decreases over time. The plastic limit decreases somewhat over distance and does not show a trend over time. The boundary layer moves approximately 6 mm between 7 and 30 days.

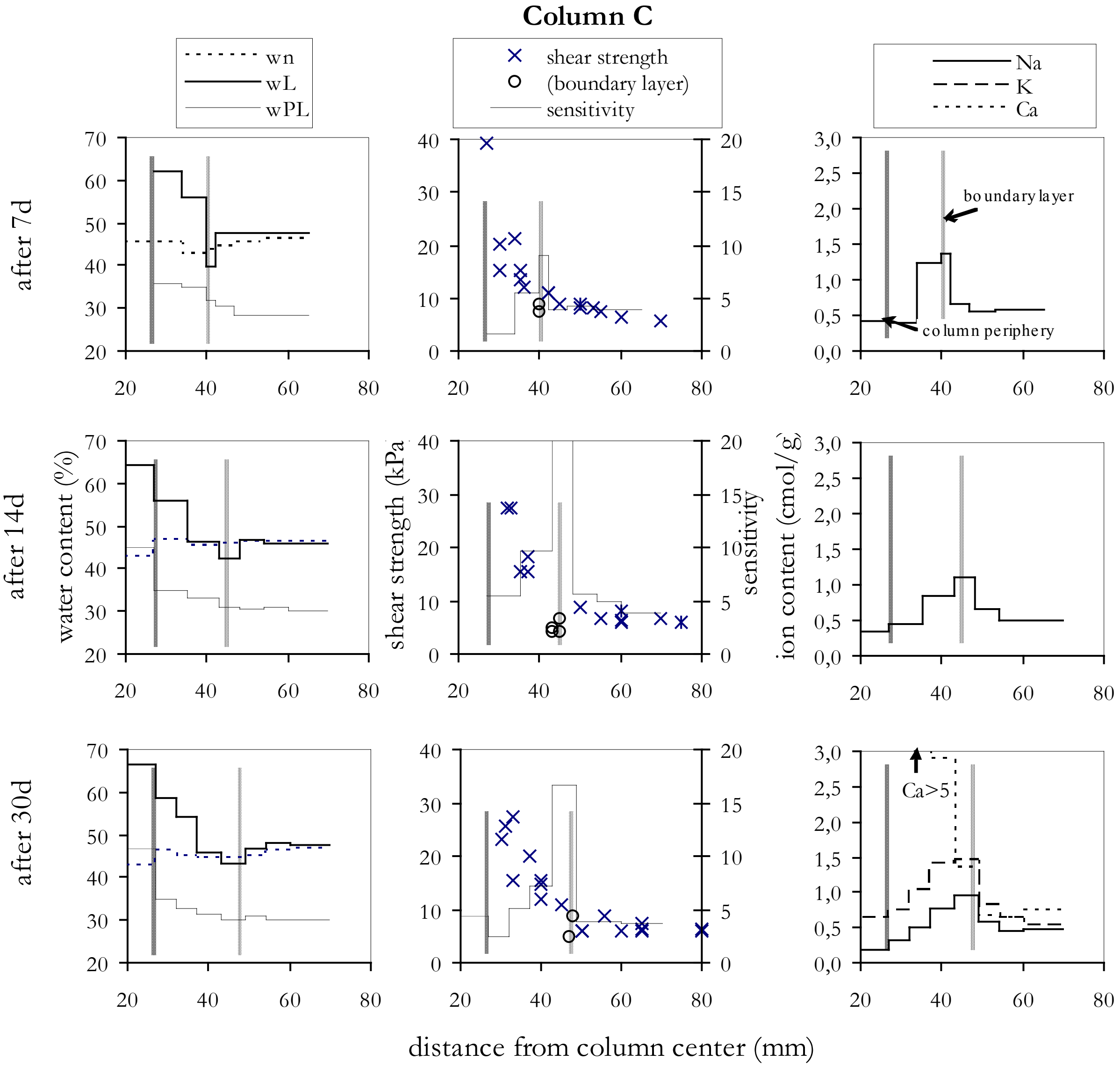


Figure 4.4 Test results, column C.

4.7 Column D

The column that was tested after 7 days (in the upper half of test box 1) had a diameter of 50 mm, the one that was tested after 14 days (in the upper half of test box 2) had a diameter of 48 mm and the diameter of the column that was tested after 30 days (in the lower half of test box 2) was 54 mm (see Chapter 3: Test Program).

At the testing surface a “ring” around the columns was visible at all column ages: the boundary layer. It had after 7 days a diameter of 80 mm, after 14 days a diameter of 80 to 85 mm and after 30 days a diameter of 90 to 95 mm.

The results are presented in Figure 4.5.

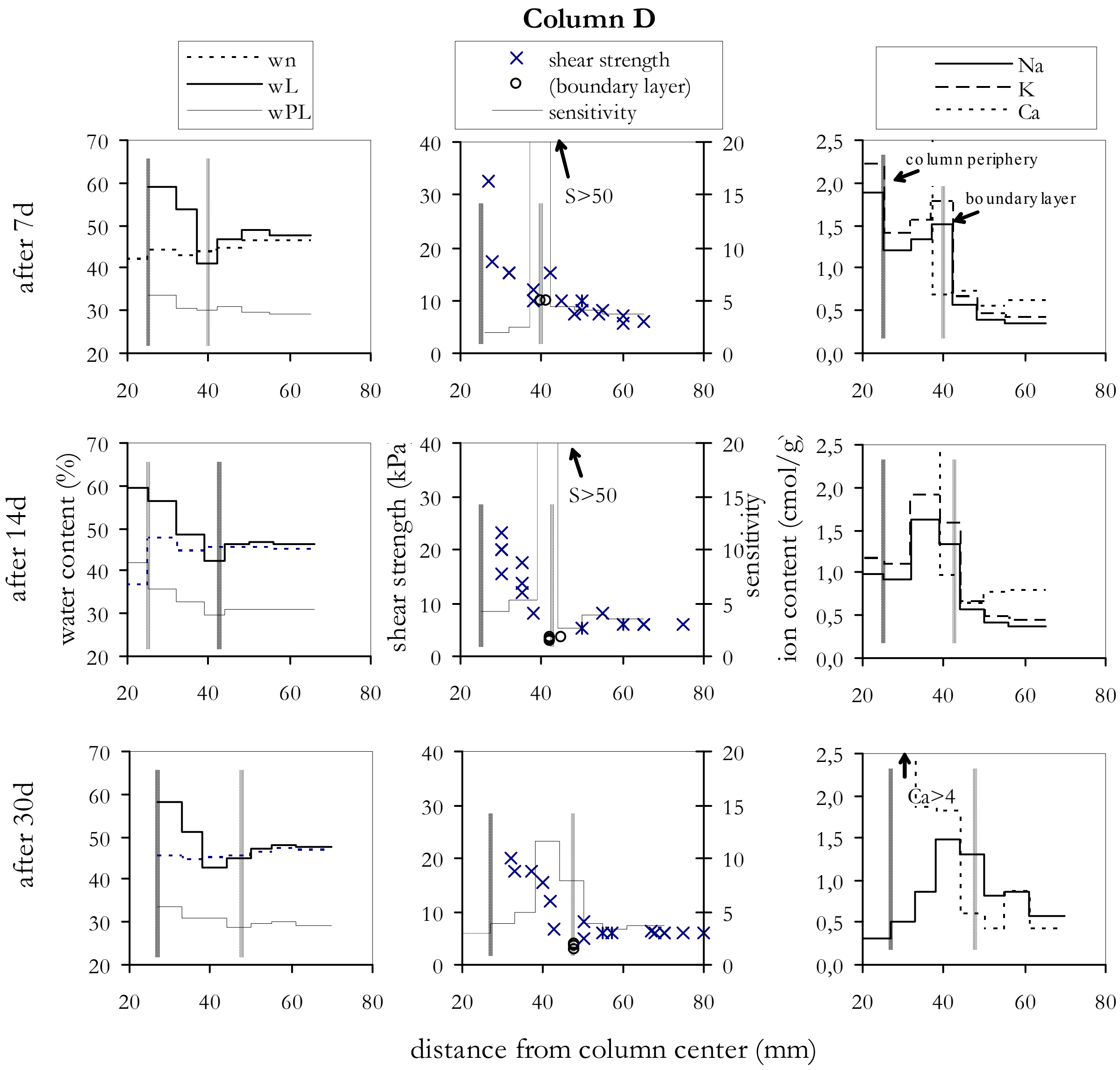


Figure 4.5 Test results, column D.

Almost all the results of column D show the boundary layer, especially the sodium ion content, the sensitivity and the shear strength. The sodium ion content shows much higher values in the boundary layer than in the surrounding samples. This difference and the magnitude decrease over time. The curve of the potassium ion content is similar to the one of the sodium ion content, close to the column almost the same but further outside lower in value. The values of these ion contents inside the column are decreasing over time. The calcium ion content in the boundary layer is lower than the sodium ion content. Close to the column the calcium ion content is much higher but decreases over time. The sensitivity has a notably peak after one and two weeks. After one month the sensitivity still has a quite high maximum. The liquid limit has a minimum at the boundary layer, a very low one after one week and not so clear ones later. Even the plastic limit has a minimum in the boundary layer. The trend of the shear strength is opposite; it has a significant minimum after two weeks and one month but not after one week. The natural water content is lowest inside the column and slowly increasing over distance; no trend in the time-dependent development is obvious. The boundary layer moves approximately 6 mm between 7 and 30 days.

4.8 Column E

The column that was tested after 7 days was in the upper half of test box 1 and had a diameter of 53 mm. The column in the upper half of test box 2 was tested after 14 days and had a diameter of 51 mm. The diameter of the same column in the lower half of test box 2 that was tested after 30 days was 55 mm. The one of the column that was tested after 90 days (in the lower half of test box 1) was 50 mm (Column placement and samples location see Chapter 3: Test Program)

At the testing surface the boundary layer was at all column ages visible as a "ring" around the column. This ring had after 7 days a diameter of 80 to 83 mm, after 14 days one of 90 mm, after 30 days a diameter of 95 mm and after 90 days one of 110 mm.

The results are presented in Figure 4.6.

The results of column E show the boundary layer clearly at all column ages. They illustrate undoubtedly that the boundary layer is moving outwards over time. The values of the liquid limit in the boundary layer are quite low at all column ages but no trend in the time-dependent development is discernible. The plastic limit has the lowest values in the boundary layer and the surrounding samples, further outside and closer to the column it is a little higher. Inside the column it is much higher and increases over time. The natural water content is quite constant and no trend in the time-dependent development is visible. The shear strength and the liquid limit are low at the boundary layer and the magnitudes are relatively constant over time. The sensitivity increases to 10-20 and no time-dependent development is visible. The sodium ion content in the boundary layer increases from 7 to 14 days. After 14 days the sodium ion content decreases somewhat. After 90 days, no significant peak can be seen. The potassium ion content shows after one and three months similar curves as the sodium ion content, but lower in value.

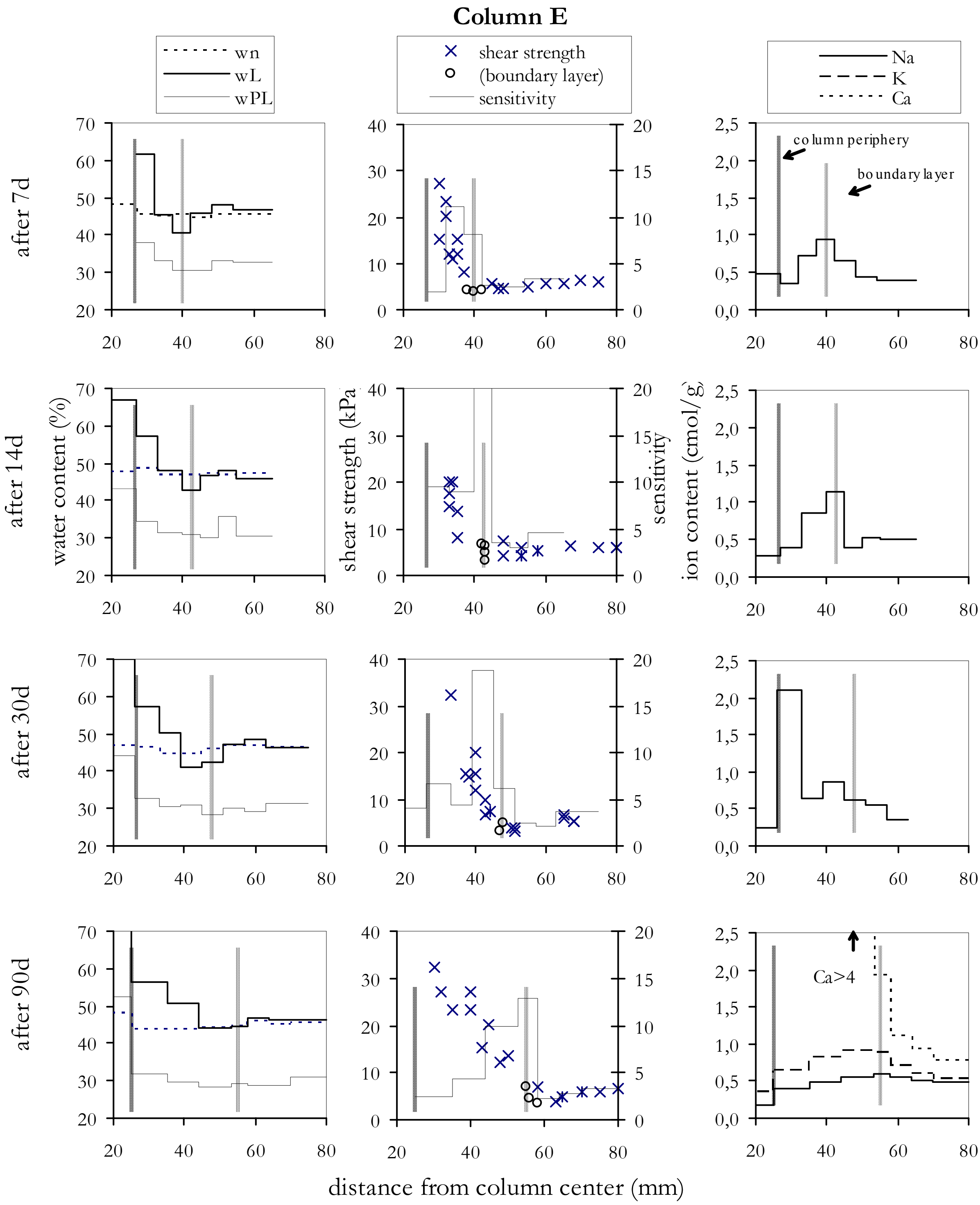


Figure 4.6 Test results, column E

The sodium ion content shows an unexplainable value after one month: the one of the sample close to the column is much higher than all the other ones. This value was measured twice; the potassium ion content, the natural water content and the Atterberg limits of this sample act like expected. So the only explanation for this value is a failure during the producing of the testing liquid.

The boundary layer moves approximately 16 to 18 mm between 7 and 90 days.

4.9 Column F

The column that was tested after 7 days (in the upper half of test box 1) had a diameter of 55 mm and the one that was tested after 14 days (in the upper half of test box 2) had a diameter of 55 mm. The diameter of the column that was tested after 30 days (in the lower half of test box 2) was 50 mm. (for column position and samples location see Chapter 3: Test Program Set-up)

The boundary layer was at all column ages visible as a “ring” around the column at the testing surface. The diameter of the boundary layer was 80 mm after 7 days, 90 mm after 14 days and 95 mm after 30 days.

The results are presented in Figure 4.7.

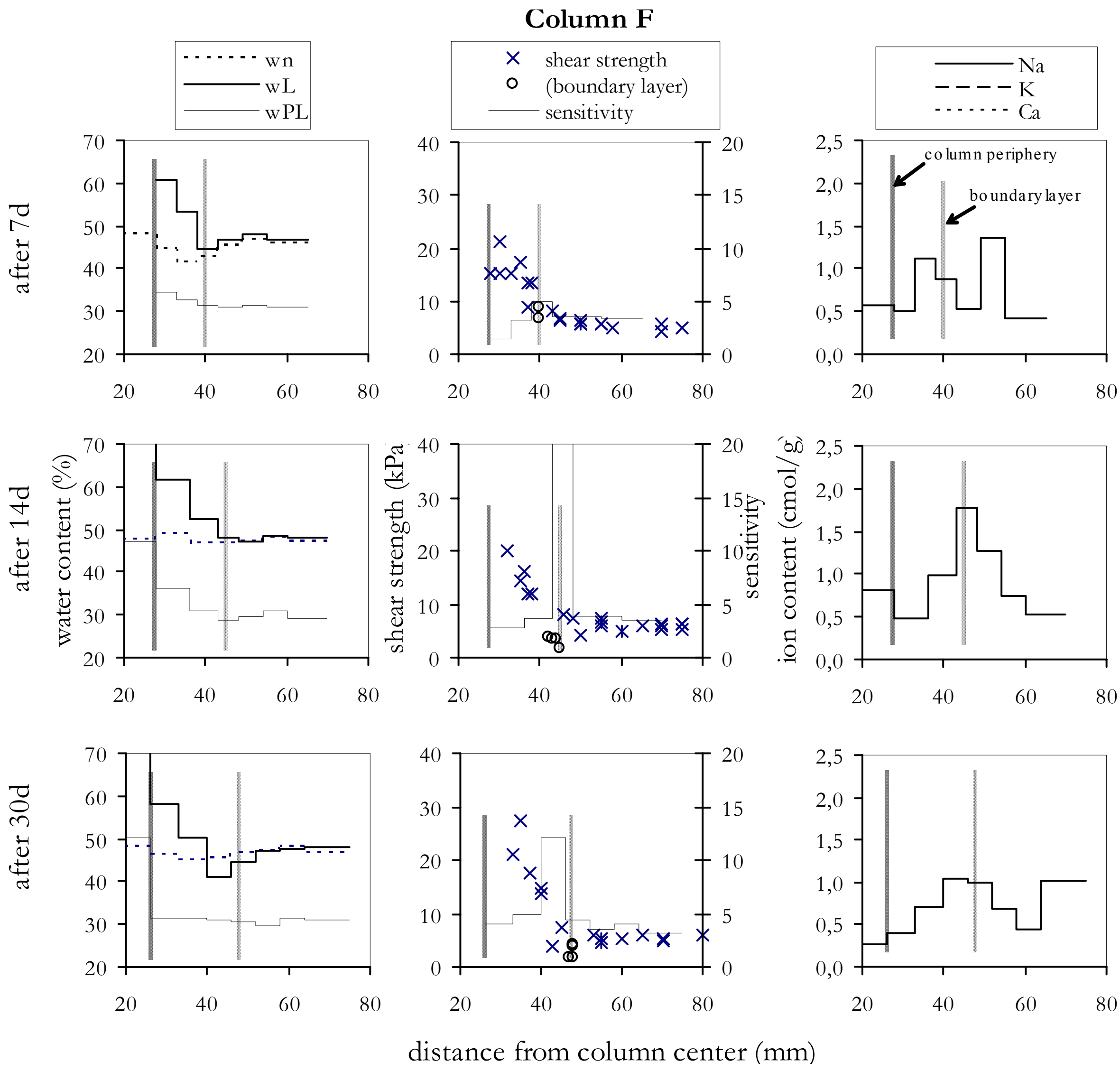


Figure 4.7 Test results, column F.

The boundary layer is clearly apparent in the results of column F. The liquid limit and the shear strength are low at the boundary layer; the sensitivity and the sodium ion content are high. The natural water content has the lowest values at the second sample outside the column and is increasing slowly over distance. After one week the difference between the values is higher than after two weeks or one month. The plastic limit is after one week and one month fairly constant. After one week no change in the values of the shear strength is visible at the distance of the boundary layer. The shear strength shows after two weeks and after one month a significant minimum at the distance of the boundary layer. After one month it is not as low as after two weeks but it is still the minimum and quite low. The sensitivity has after one week a little peak at the distance of the boundary layer, after two weeks it has an enormous peak. The maximum after one month is much lower again but still four times as high as the one after one week. The sodium ion content is after one week a little strange: the value of the sample one inside the boundary layer is higher (0.2 $\mathrm{cmol_c/g}$) than the one of the boundary layer. But the highest value is the one of the second sample outside the boundary layer (at a distance of 49 to 55 mm). After two weeks the sodium ion content has a significant maximum at the distance of the boundary layer. The boundary layer moves approximately 9 to 12 mm between 7 and 30 days.

4.10 Column G

The column G in the upper half of test box 1 was tested after 7 days and had a diameter of 45 mm. The upper half of the column G in test box 2 was tested after 14 days and had a diameter of 50 mm. The lower half of the same column (in test box 2) was tested after 30 days and had a diameter of 50 mm. The diameter of the column in the lower part of test box 1 that was tested after 90 days was 50 mm (for column and samples positions see Chapter 3: Test Program).

A “ring” around the column was at all column ages visible at the testing surface: the boundary layer. The diameter of this ring was 75 mm after 7 days and 85 to 90 mm after 14 days. After 30 days the boundary layer had a diameter of 95 mm and after 90 days one of 115 mm.

The results are presented in Figure 4.8.

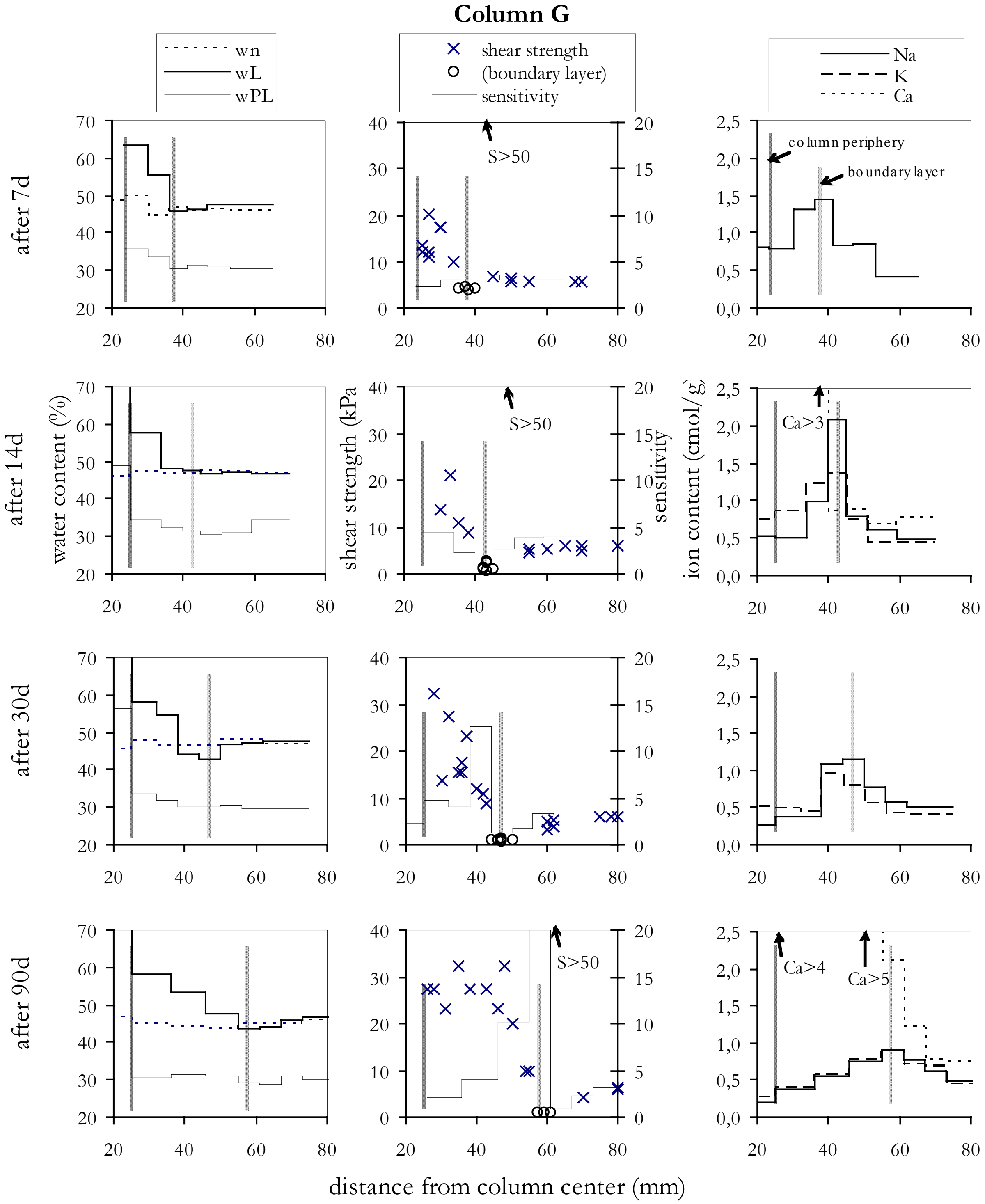


Figure 4.8 Test results, column G.

The boundary layer shows notable values in the results of column G at all the column ages. Especially the undisturbed shear strength and the sodium ion content are very distinct. The liquid limit has a minimum at the distance of the boundary layer except of the results after two weeks. After one and three months the liquid limit in the boundary layer is similar and lower than after one week. The plastic limit decreases somewhat further out from the column. The natural water content is almost constant and does not show a trend over time. The undisturbed shear strength is very low in the boundary layer at all column ages. The sensitivity shows a peak at the distance of the boundary layer but no trend in the values of the maximum is discernible. The highest value is after two weeks, the second highest is after three months. The maximum of the sensitivity is after one month only a little lower than after one week. The sodium ion content is much higher in the boundary layer than in the other samples. The peak has the highest value after two weeks. The maximum content decreases over time and the trend is similar as for column E. The curves of the potassium ion content are similar to the one of the sodium ion content but lower in value. Only the one after one month is a little bit different, the maximum is at the sample next to the boundary layer towards the column. The calcium ion content in the boundary layer is after three months higher than after two weeks.

The boundary layer moves approximately 18 to 22 mm between 7 and 90 days.

5 DISCUSSION

5.1 *General*

The discussion considers the results of the investigation on stabilised laboratory prepared kaolin clay. The main object of this thesis was to describe the laboratory tests and to present results. A second object was to investigate the boundary layer observed between the transition zone and the surrounding kaolin clay and to find out if geotechnical characteristics are reflected in the cation contents. Therefore the discussion is focused on the boundary layer. However, since a large number of tests are performed in the transition zone the results are briefly discussed in the following section.

5.2 *The transition zone*

The migration of calcium from the columns is small in terms of distance but it has a great effect on the kaolin clay characteristics. Figure 5.1 shows the shear strength in the transition zone and the boundary layer, in terms of the stabilisation effect S_{eff}. The stabilisation effect is defined as the shear strength in the stabilised soil s divided by the shear strength in the unstabilised soft soil s_0 (EuroSoilStab 2002). After 90 days, the transition zone is approximately 30 mm for all the columns. A distance of this size has also been observed in the field by Larsson 2000 and Rogers et al. 2000a. The stabilisation effect is approximately 3-10 adjacent to the column periphery and decreases relatively linearly towards the boundary layer. The stabilisation effect seams to be slightly higher for columns manufactured by dry mixing and without peptizer. The rate of migration of calcium ions seems to be unaffected by the different producing methods, binder mixtures and peptizer contents.

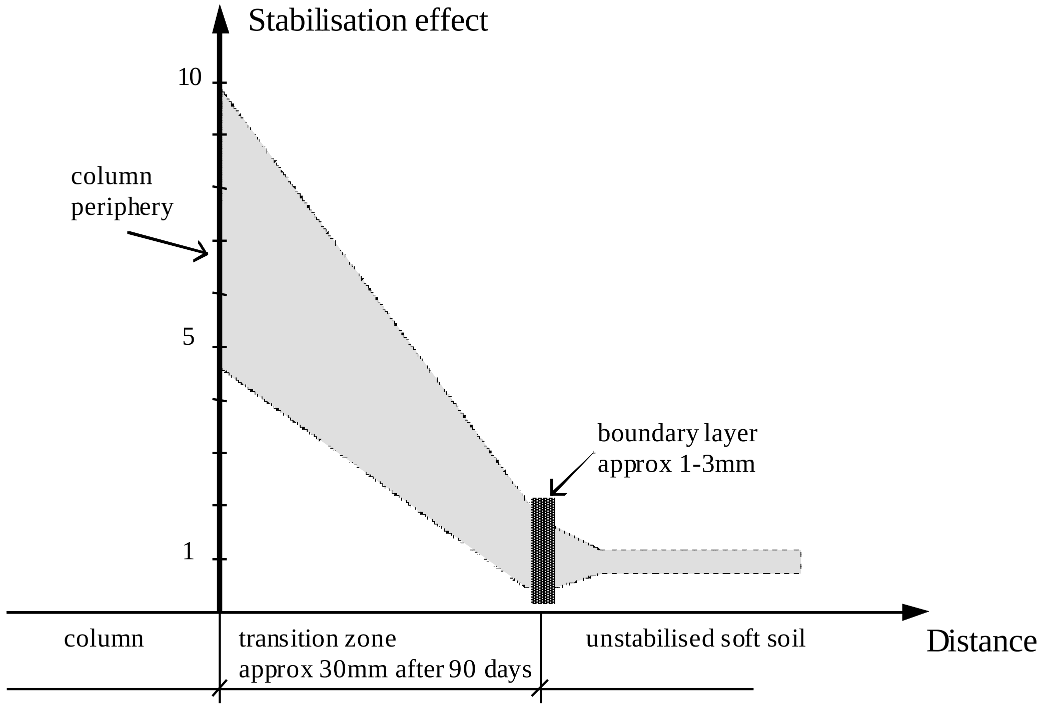


Figure 5.1 Schematics of the stabilisation effect in the transition zone around the columns.

5.3 The boundary layer

The column recipes differed in producing method, binder mixture and peptizer content. The characteristics of the boundary layer varied with the column recipes. The results derived from these observations are discussed below.

Figure 5.2 shows the quotient between the evaluated undrained shear strength s in the boundary layer divided by the undrained shear strength s_0 in the surrounding soft soil and the corresponding sensitivity S in the boundary layer divided by the sensitivity S_0 in the surrounding soft soil. Figure 5.3 shows the corresponding quotient between the evaluated sodium ion content in the boundary layer divided by the sodium ion content in the surrounding soft soil.

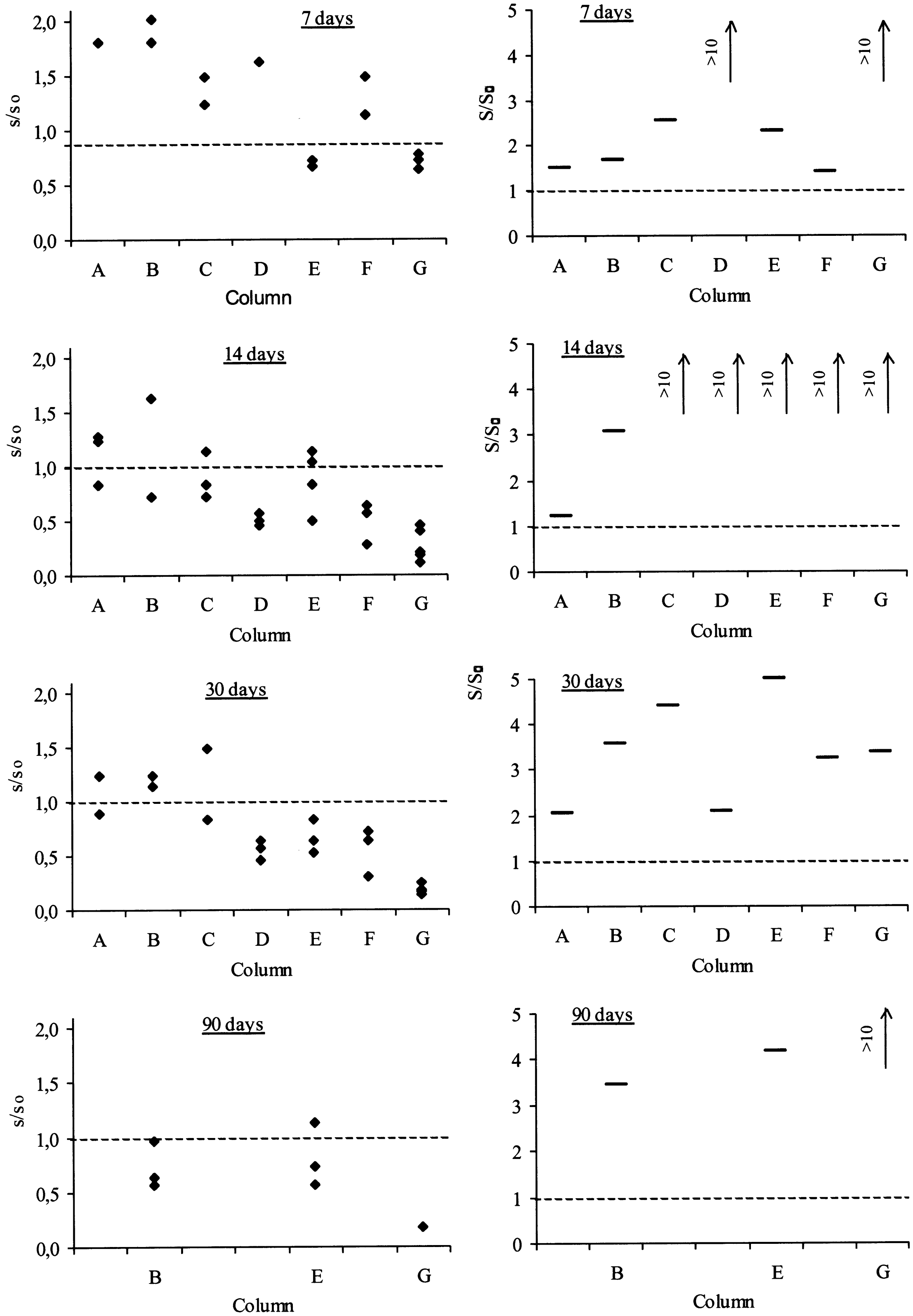


Figure 5.2 The quotient between the evaluated undrained shear strength in the boundary layer s divided by the undrained shear strength in the surrounding soft soil s_0 and the evaluated sensitivity in the boundary layer S divided by the sensitivity in the surrounding soft soil S_0.

5.3.1 Dry versus wet mixing

The producing method, dry and wet respectively, can be studied by comparing column C and E. These two columns are manufactured without peptizer and with only cement as binder. At 7 and 30 days after installation the undrained shear strength in the boundary layer is significant lower for column E, Figure 5.2. However, at 14 days after installation there is no significant difference. Furthermore there is no significant difference in the evaluated sensitivity between column C and E.

The producing method, dry and wet respectively, can also be studied by comparing column D and F. These two columns were manufactured including peptizer, 2% and 5% respectively. The results show no significant difference with respect to the undrained shear strength, the sensitivity, or the sodium ion content in the boundary layer between these two columns.

Consequently, there is no clear difference in the ion content or the geotechnical properties between the columns produced with the dry mixing versus the wet mixing method provided that cement was used as binder. However, since a difference in undrained shear strength was observed at two column ages between column C and column E, the influence of adding water should be further investigated.

The results obtained from column A and column E should also be discussed since these columns best represent the dry and wet method respectively. Column A is manufactured with the dry method and with a high content of lime as binder. Column E is manufactured with the wet method and with only cement as binder. The results show a significant difference in the strength properties in the boundary layer between the two columns. The undrained shear strength is significantly lower, and the corresponding sensitivity is significantly higher for column E. The results indicate that the combination of using wet mixing and only cement has a negative influence on the strength properties in the boundary layer.

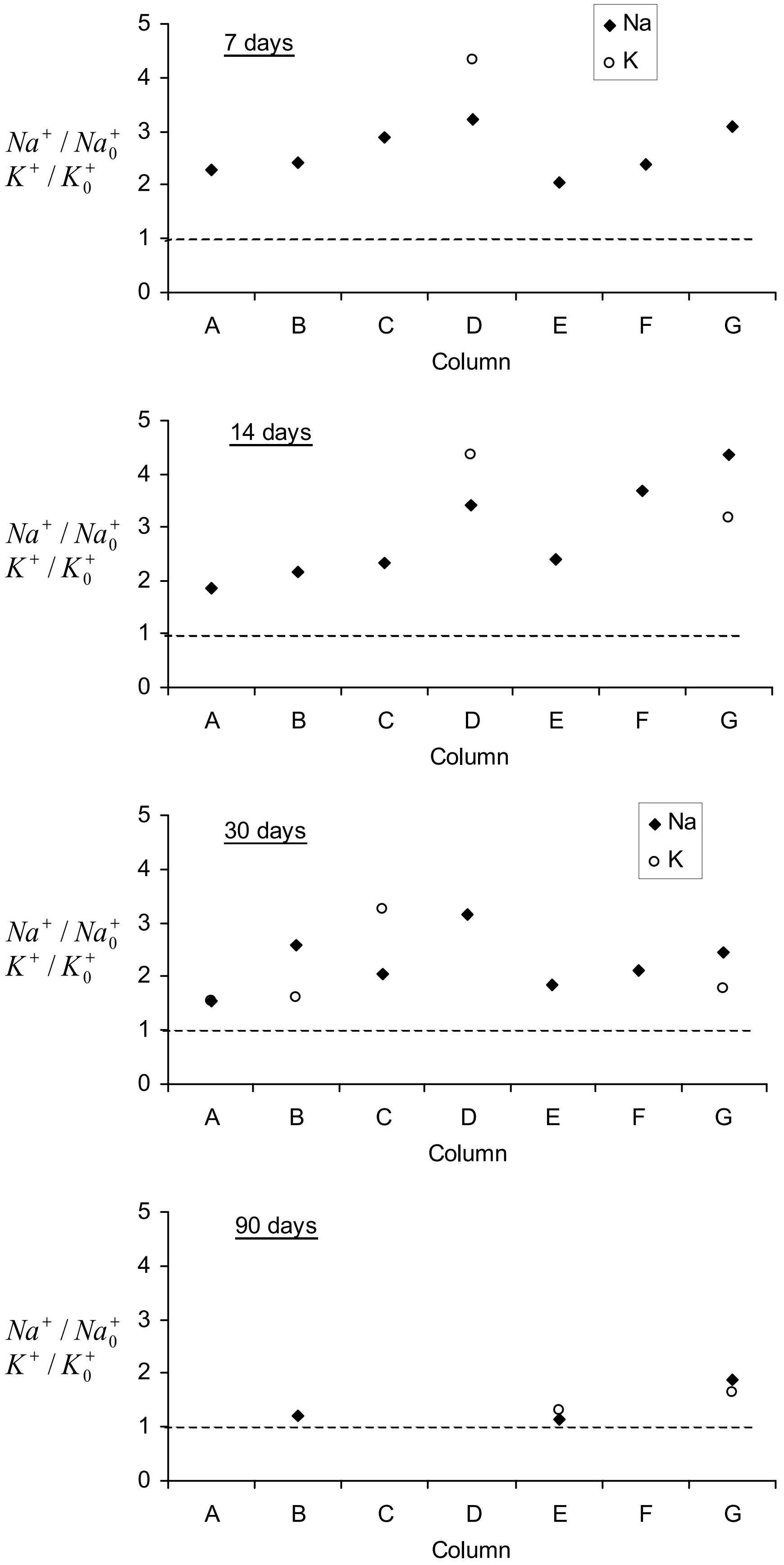


Figure 5.3 The quotient between the evaluated sodium and potassium ion content in the boundary layer divided by the sodium and potassium ion content in the surrounding soft soil.

5.3.2 Lime to cement ratio

The influence of the lime-cement ratio on the boundary layer can be studied by comparing column A, B and C. The binder mixture has an influence on the boundary layer: the more cement it contains the higher is the sodium ion content of the boundary layer. There are no significant differences in the measured undrained shear strengths. However, the sensitivity increases significantly as shown in Figure 4.2 – 4.4, indicating an influence on the strength characteristics.

5.3.3 Peptizer content

The influence of the peptizer content on the boundary layer can be studied by comparing column C and D that are manufactured by dry mixing method. Furthermore, column E and F can be compared that are manufactured by wet mixing method. Column G is manufactured by casting and contains a high amount of peptizer. The influence on the boundary layer is shown in Figure 5.3; increased peptizer content results in increased sodium ion content. Furthermore, the peptizer content has a significant and unfavourable influence on the undrained shear strength. However, the sensitivity ratio S/S_0 differs at different column ages. Figure 5.4 shows the boundary layer of column G (casting, 7% lignosulphonate) after 14 days. The strength loss is total and the clay is liquefied.

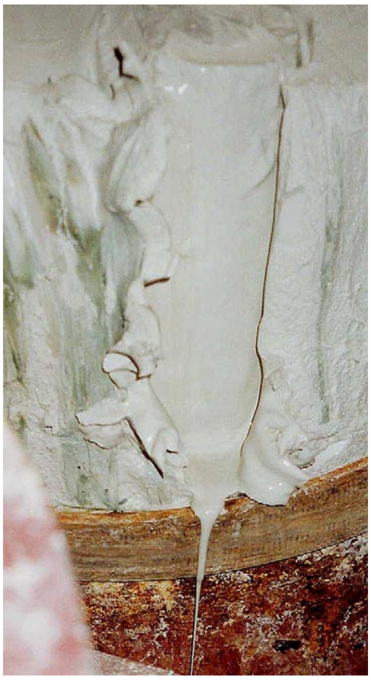


Figure 5.4 Example of a liquefied
boundary layer. Column G, containing 7% lignosulphonate.

5.4 The migration of cations

The calcium ion content has its first lower value in the boundary layer, closer to the column it is much higher and further away it decreases. The sodium and potassium ion contents show the highest values in the boundary layer. This validates the hypothesis that the calcium ions supersede the sodium and potassium ions. As described above (Chapter 1.3), the valence of calcium is two; the one of each sodium and potassium is only one. As a result, two sodium or potassium ions can be replaced by one calcium ion. That explains why the content of sodium and potassium ions increases in the boundary layer while the calcium ion content is very high in the column and outwards until the boundary layer. Lime and cement contain a high amount of calcium (in the form of CaO). The existing (adsorbed) cations at the negative charge sites of the clay crystals can be replaced by the calcium ions (see Brady 1984). In the columns sodium and potassium ions are superseded by calcium ions.

The assumption that the calcium ions drive the sodium and potassium ions little by little outwards is shown by the results. This is very clear illustrated by the figures in Chapter 4. Also the supposition that the intensity of the front of sodium and potassium ions is getting lower in the longer term (as a result of the diffusion processes) is well recognizable in the figures of the longer-term tested columns (see Figure 4.3, 4.6 and 4.8).

Liquefying as the result of the higher content of monovalent cations is supposed to be the reason for the impaired geotechnical characteristics. If additional sodium or potassium ions are mixed into the soil, the liquefying effect is expected to be even more intense. The peptizer used had a much higher sodium ion content than the other raw materials (see Table 4.1). These additional sodium ions are assumed to migrate outwards together with the superseded ions. So this is the proposed explanation for the higher sodium ion content in the boundary layer with higher peptizer content (Figure 5.3).

The cement used contained much more potassium than the kaolin and the lime. The strength of adsorption of potassium ions is higher than the one of sodium ions (see Brady 1984). Potassium ions also supersede sodium ions. This is assumed to be the explanation for the higher sodium ion content in the boundary layer with a higher cement content in the binder (Figure 5.3).

This study presents the results from the sodium ion content analysis for all seven columns. It is reasonable that the migration of potassium ions also affects the boundary layer (Hoffstedt & Johansson 2002). The analysis from the complementary potassium ion content analysis will be presented and discussed elsewhere.

5.5 Synthesis

With respect to the geotechnical properties, the boundary layer is a layer with an increased sensitivity and under certain conditions decreased undrained shears strength compared to the unstabilised kaolin clay. For columns manufactured with peptizer, decreased shear strength was observed after 14 to 90 days. With high peptizer content 5 to 7%, the strength loss was total and the kaolin clay was liquefied. With respect to the chemical composition, the boundary layer has an increased sodium and potassium ion content. This confirms the assumption that the reduced strength, which is measured by the geotechnical tests, is explained by the high sodium and potassium ion content.

The boundary layer should be investigated more comprehensive and more detailed, to determine how it influences the strength of stabilised natural soils. Natural soils are not as homogeneous as the soil used in the laboratory, they have another composition, and may behave differently. Soils with high natural sodium ion content, like marine sediments, should especially be investigated.

The peptizer, lignosulphonate, is shown to have a negative effect on the boundary layer between the transition zone and the surrounding soft soil. Before using peptizer in practice in order to facilitate the mixing process for lime-cement columns, the effects of migrated sodium and potassium ions on the boundary layer must be further investigated.

6 CONCLUSIONS

The transition zone and the boundary layer around lime-cement columns in laboratory prepared kaolin clay have been investigated. The columns had different recipes to consider several factors of influence: the installation method; the lime/cement ratio and; the peptizer content. A large number of geotechnical and chemical analyses was performed at different column ages in order to investigate the migration of calcium ions and the superseded sodium and potassium ions.

The following conclusions can be drawn from the laboratory tests:

- The migration of calcium ions increases the undrained shear strength in a transition zone around the columns. The transition zone is approximately 30 mm after 90 days independent of the manufacturing method, binder composition and the addition of peptizer.
- The natural water content is principally unchanged in the boundary layer.
- The liquid limit decreased in the boundary layer. In most cases the liquid limit had a distinct minimum at the boundary layer.
- The plastic limit was relatively unchanged in the boundary layer.
- The undisturbed shear strength had a minimum in the boundary layer when peptizer was used.
- The sensitivity increased at the boundary layer in all cases; in some cases the increase was very high. However, with the dry method and the binder mixture 70% lime and 30 % cement the sensitivity was relatively unchanged.
- The sodium and potassium ion content had a maximum close to or at the boundary layer.
- The calcium ion content was very high in the column and in the transition zone. In the boundary layer the calcium ion content was much lower and even less than the sodium ion content.
- The time-dependent development of the characteristics of the boundary layer is not the same at the different columns. In some cases the characteristics are getting more

distinct over time, in other cases they become less obvious over time.

- The producing method, dry versus wet mixing, had no significant influence on the boundary layer according to this experimental programme.
- The combination of using wet mixing and only cement as binder has a negative effect on the boundary layer with respect to the undrained shear strength. The combination dry mixing and lime as binder had no negative effect on the undrained shear strength. However, the sensitivity increased in the boundary layer around all columns.
- The type of binder has an influence on the boundary layer: the more cement the column contains the higher is the sodium ion content in the boundary layer.
- The use of lignosulphonate as peptizer has an influence on the boundary layer: the higher content, the higher is the sodium ion content in the boundary layer. With a high peptizer content, 5 to 7%, the strength loss was total and the kaolin clay was liquefied.

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