



Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

Report 9

The Function of Different Binding Agents in Deep Stabilization

Mårten Janz
Sven-Erik Johansson

English
Translation
July 2002



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 chosen from among its members.

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Foreword – English Translation

Translation of this document was made possible through collaborative effort of Swedish Deep Stabilization Research Centre and the US National Deep Mixing (NDM) program. The mission of both organizations is to facilitate advancement and implementation of deep mixing technology through partnered research and dissemination of international experience.

The Swedish Deep Stabilization Research Center with its headquarter at the Swedish Geotechnical Institute (SGI) coordinates research primarily on dry mix methods. An international conference on “dry mix methods for deep soil stabilization” was held in Stockholm in 1999. The findings from research and state-of-the practice in Europe, particularly on stabilization of organic soil, were presented and published in the proceedings. SGI is also a partner of EuroSoilStab, the R&D project focusing on organic soils and infrastructure applications.

The National Deep Mixing program coordinates a program of deep mixing research in the US. The international workshop on “Deep mixing technology for infrastructure development” was held in Oakland, California in 2001. A forum of users and experts from industry, government and academia examined the current practice and research needs; and identified the challenges ahead for implementation of deep mixing technology.

We hope dissemination of international experience serves as a step toward our better understanding and promotion of this innovative technology in the construction industry.

July 2002

Göran Holm, Linköping, Sweden

Ali Porbaha, California, USA

Foreword

In autumn 1999 the Swedish Deep Stabilization Research Centre (SD) ran a course on the chemistry of soils and binders in the hope of contributing to a wider knowledge of the basic chemistry of deep stabilization. The present documents the course content as well as providing a general theoretical account of the function of different binding agents in deep stabilization. SD is conducting an extensive research programme on the properties of stabilized soils, focussing among other things on relevant parameters, the effectiveness of different binding agents in typical Swedish loose soils, and environmental impacts. The findings of this programme will be published by SD in later reports and the function of binding agents will be further discussed in that context.

The authors of this report are Mårten Janz of the Swedish Cement and Concrete Research Institute (formerly of the Department of Building Materials at the Lund Institute of Technology) and Sven-Erik Johansson of Cements AB.

Linköping, June 2001

Göran Holm
Project Manager, SD

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Summary

A knowledge of the chemical reactions that give binders their strength is important in order to understand why a given binder may provide good stabilization in some soils while performing poorly in others. The binders in common use today are cement and lime. Blast furnace slags and fly ashes have also been used to some extent. These binders have somewhat different reactions and require different conditions in order to perform, but their reaction products are closely similar. Since cementitious materials have been used for a very long time, the properties of their reaction products are well-known and studied.

In clay and silt a mix of cement and lime has been found often to give stabilization with high strength and very good interaction with the surrounding ground. The cement reacts with the water in the soil providing a rapid strength gain. The lime too reacts with water forming calcium hydroxide. The lime reaction does not result in any chemical strength gain but does have a temporary positive effect on stability due to the large amounts of water consumed. The permanent strength gains from lime as a stabilizer are due to the products of a slow, secondary reaction between the calcium hydroxide and pozzolanic minerals in the soil. In dispersed clays with low plasticity calcium hydroxide can also provide a stabilizing effect by ion exchange involving calcium ions and positive ions present on the surface of the clay particles.

If the soil has pozzolanic properties the use of latent hydraulic and pozzolanic additives is inappropriate, as these additives will consume Ca(OH)_2 which would otherwise have reacted with the pozzolanic minerals in the soil. The pozzolanic properties of the soil will thus not be fully utilized and the weight of reaction products that can form is smaller.

In soils with high organic content the best results are obtained with cement or a combination of cement with latent hydraulic or pozzolanic additives. The reason why lime is ineffective is that the humic acids frequently present in organic soils inhibit the pozzolanic reactions between calcium hydroxide and pozzolanic minerals. In any case, these soils usually contain only small amounts of pozzolanic minerals for the calcium hydroxide to react with. Humic acids also affect the cementitious reaction, slowing the reaction rate.

Provided the selected stabilizer has the desired function in the soil at hand, the outcome is determined by the ratio of the water content of the ground to the quantity of binder added, i.e. the water/total-cementitious ratio *w_{tr}*. Thus a soil with high water content requires more binder than does a dryer soil to achieve the same water/total-cementitious ratio and the same stabilization effectiveness. This is particularly true of cement-based binders. If lime is used as a binder, the strength increases directly as the quantity of lime as long as there are still pozzolanic minerals present in the soil. If all the pozzolana in the soil is consumed by reaction with Ca(OH)_2 , further quantities of lime will not provide any further gain in strength.

In general one may say that the reactivity of a binder is largely determined by its fineness, which is normally expressed as the specific surface. The higher the specific surface the more rapidly the material reacts. In the case of latent hydraulic or pozzolanic additives vitreosity is also of great importance for reactivity. If the material is vitreous (amorphous) it is highly reactive, while crystalline additives can be completely inert.

Temperature is of the greatest importance for the reaction rate and the final outcome. Pozzolanic reactions in particular are negatively impacted by low temperature. If a technical /förundersökning/ is carried out under laboratory conditions at 20 °C there is a risk that pozzolanic reactions will contribute far more to the strength gain in the test than they will in the field. Thus laboratory tests can give misleading results. Hence it is most important that technical /förundersökningar/ are carried out at the same temperature that is expected to exist in the soil to be stabilized.

Another factor that can give rise to misleading results in laboratory tests is the mixing method. Homogenization and mixing in laboratory conditions tends to be considerably more efficient than in the field. Attention should be paid to this fact when interpreting the results of /förundersökningar/.

Industrial residues, such as ash from heating plants and factories, can be reactive and hence usable for soil stabilization. It can be economically attractive to use such residues to replace a portion of other binders if the stabilization site is close to the source of the ash. Longer haulage distances generally make this option unprofitable. With regard to environmental impacts it is important to understand that all products used will have an impact on their surroundings depending on their composition. Residues can be of highly variable quality and therefore their chemical composition and leachability should always be tested. The use of a residue is justifiable if the impact of alternative uses or landfilling would be more severe.

1. Introduction

PURPOSE

The appropriate choice of binder for deep stabilization depends on an understanding of the chemical and physical reactions which give the stabilized soil its enhanced strength. The purpose of the present report is to offer an account of these reactions in order to enable an informed choice of binder to be made based on its stabilizing effect in the soil at hand.

BACKGROUND

Since the 1970s Swedish engineers have used deep soil mixing to stabilize loose clays and silts, primarily for road and railway construction but also for light building foundations, trenches for buried services, slope stabilization etc. Originally lime was the only binder used, but cement has been widely used since the mid 1980s. It has been found that considerably higher strength is achieved with cement, either alone or mixed with lime (Åhnberg et al. 1995). The introduction of cement has made it possible to stabilize “problem soils” with high organic contents and high water:soil ratios. Trials have also been carried out in which a portion of the binder is replaced with industrial residues. Axelsson et al. (2000), for example, showed that ground granulated blast furnace slag has a positive effect in the stabilization of peat.

Deep stabilization is often economically attractive as well as offering environmental benefits, as the alternative may be removal of the loose soil stratum, entailing a major haulage effort. The haulage effort required to bring the binder to the site depends on the distance to the nearest depot.

If the opportunity exists to use ash, slags, or another industrial residue, both environmental and economic gains may be achievable, as the alternative disposal method for such residues in many cases is to dump them at a landfill site. However, the use of residues will only bring an environmental gain if alternative disposal would have a more severe environmental impact than stabilization. It is essential to ensure that the binder does not contain heavy metals or other hazardous substances that can leach out. The use of a residue will normally only be economically justifiable if the stabilization site is close to the source of the residue. An essential condition in order for a residue to be considered at all is that it possesses the desired stabilizing function. Residues must always be tested in the soil to be stabilized.

2. Cementitious, calcareous and pozzolanic reactions

Portland cement, lime, and latent hydraulic or pozzolanic materials react with water under certain conditions forming similar reaction products with high strength. Cement yields high-strength reaction products immediately on reacting with water. Lime reacts with water to form calcium hydroxide, which has no bearing capacity itself but which forms high-strength products in a secondary reaction with certain pozzolanic soils or additives. Latent hydraulic materials have to be activated with e.g. calcium hydroxide in order to react, while pozzolanic materials require the availability of calcium hydroxide throughout the reaction process. The reactivity of cement, latent hydraulic and pozzolanic materials depends among other things on the ratio of lime to silica, $\text{CaO}:\text{SiO}_2$. The larger this ratio is, the more hydraulic is the material. Table 2.1 summarises the strength-enhancing reactions of cement, lime, granulated blast furnace slag, fly ash from power and heating plants fuelled with pulverized coal, and silica fume. It will be apparent that a mix of cement and lime gives a rapid initial strength gain from the cementitious reaction, followed by a slow pozzolanic reaction.

Table 2.1 Strength-enhancing reactions.

Binder	Reaction	Coreagents	Time scale
Cement	Hydraulic	Water	Days
Lime	Puzzolanic ¹⁾	Water + pozzolanic soil or pozzolanic additive	Months
Granulated blast furnace slag	Latent hydraulic	Water + $\text{Ca}(\text{OH})_2$ from e.g. cement or lime	Weeks
Fly ash ²⁾ and silica fume	Puzzolanic	Water + $\text{Ca}(\text{OH})_2$ from e.g. cement or lime	Months

¹⁾ An initial hydraulic reaction forms $\text{Ca}(\text{OH})_2$, which then participates in a pozzolanic reaction. The strength gain is due to the products of the secondary pozzolanic reaction.

²⁾ Fly ash from power and heating plants fuelled with pulverized coal.

A feature common to cement, lime, latent hydraulic and pozzolanic materials is that their reaction rate is determined to a large degree by the surface area of the material that is exposed to water. If the particle size is small, a correspondingly larger surface area is exposed. A measure of fineness is the specific surface [m^2/kg]. The higher the specific surface, the more rapid the reaction rate.

The products of cementitious, calcareous and pozzolanic reactions are similar, consisting mainly of calcium and siliceous compounds with smaller amounts of aluminium, iron and other elements. Since materials of the cement type have been used since ancient times, the properties of their reaction products are well-known and studied.

2.1 PORTLAND CEMENT

Portland cement is a hydraulic binding agent, i.e. it reacts with water forming a hard mass. It is manufactured by mixing Portland clinker with approximately 5 % of gypsum and grinding it to a particle size of 1 – 100 μm and a specific surface of $\sim 300 - 550 \text{ m}^2/\text{kg}$.

Various additives may be included in the mix during grinding to modify the properties of the cement. Swedish Standard SS 113 4201 divides cements into five classes known as cement types I–V. Cement type I is a pure Portland cement containing no additives, while cement type II/A-LL is a modified limestone filler (CaCO_3). The commonest type I cements in Sweden are SH-cement and Anläggningcement, while the type II cement sold today, containing $\sim 15\%$ limestone filler, is Byggcement. Byggcement has superseded the Std-cement (“standard cement”) that was formerly sold. Std-cement was a pure Portland cement, i.e. a type I cement. Byggcement and Std cement are similar in their strength development.

The usual raw materials for the manufacture of Portland clinker are clay and limestone. Other materials of similar chemical composition can be used. After grinding and mixing, the raw material is calcined in a rotary kiln at $\sim 1450^\circ\text{C}$. The heat drives off carbon dioxide and the material is sintered. After leaving the kiln the material is cooled rapidly. The pelletized product is known as Portland clinker.

A typical chemical composition of Portland cement appears in Table 2.2. While the chemical composition is expressed in terms of oxides, the substances are actually present in the form of compounds known as clinker minerals. In addition to the components shown in the table, smaller amounts of TiO_2 , MnO_2 , P_2O_5 and Cl^- may occur.

Table 2.2 Typical composition of Portland cement. (Johansson 1994A)

Oxide	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O
Content [%]	60–70	17–25	2–8	0–6	0–6	1–4	0,2–1,5	0,2–1,5

Mixing cement with water initiates a chemical process (hydration) which forms a hard cement paste. When a cement particle undergoes hydration an extremely fine-pored cement gel forms around the particle. Fig. 2.1 shows schematically the changes in the structure of the cement paste as five cement particles react with water. Fig. 2.2 is a photomicrograph of the gel structure of cement paste. The similarity with Fig. 2.1 is striking. The reaction products constituting the cement gel include CSH gel, ettringite, and monosulfate, described in detail below. Since the cement gel is porous and contains chemically combined water (water of crystallization), its volume will be greater than that of cement particle prior to reaction. Thus as the reaction between the cement and the water proceeds, the voids between the cement particles will gradually be filled with cement gel. At the same time the cement paste grows denser and stronger.

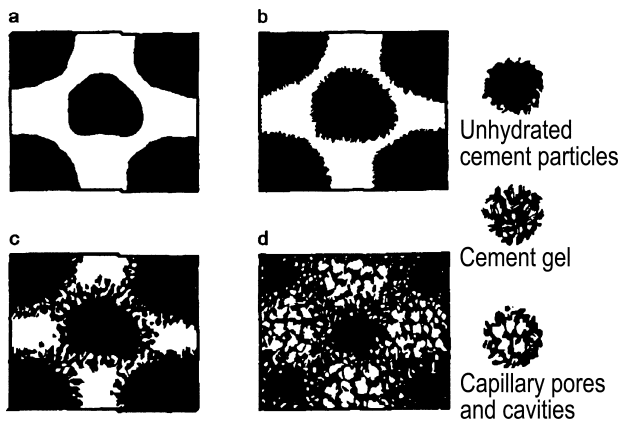


Fig. 2.1
Structure of cement paste:
 a) Immediately after mixing
 b) After a few minutes
 c) Upon setting
 d) After some months
 (Fagerlund 1994)

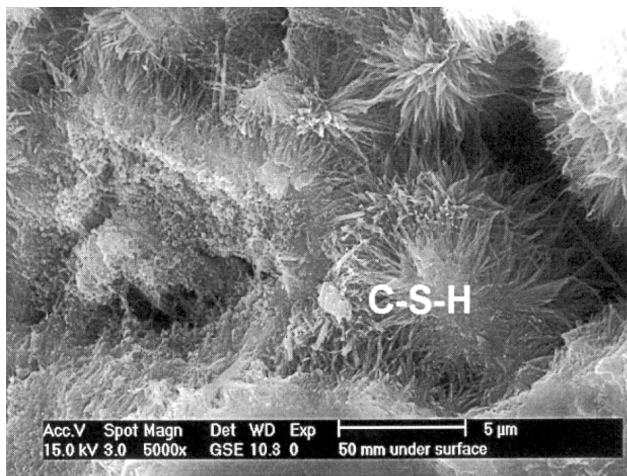


Fig. 2.2
ESEM photograph of cement gel
containing CSH crystals.
 Photo: Finger Institute, Weimar University.

The strength of the cement paste depends largely on its porosity. Wide separations between the particles result in higher porosity and lower strength. A measure of the cement content, and hence of the separation between the particles, is given by the water:cement ratio wcr .

$$wcr = \frac{W}{C} \quad (1)$$

where W is the weight of mixing water [kg] and C the weight of cement [kg]. A high wcr implies wide separations between the cement particles, which in turn means high porosity and low strength.

The water:cement ratio is one of the most important quality parameters of cement when used as a binding agent. An example of the relation between quality and *wcr* may be seen in Fig. 2.3, which shows how the strength of a concrete increases as *wcr* decreases.

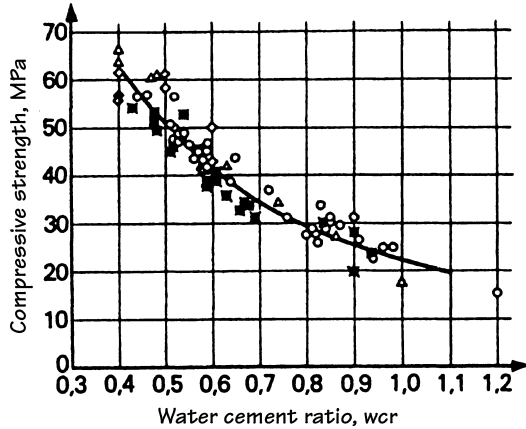


Fig. 2.3
Relation between *wcr* and compressive strength. The curve refers to concrete (cube samples), but similar relations apply in soil stabilization. (Ysberg 1979)

As we have seen, it is the chemical reactions that occur as the cement hydrates that reduce the porosity resulting in a gain in strength. In cement chemistry it is customary to use an abbreviated notation for the oxide constituents of cement: CaO = C; SiO₂ = S; Al₂O₃ = A; Fe₂O₃ = F; SO₃ = S'; MgO = M och H₂O = H. Table 2.3 shows the most important clinker minerals in Portland cement.

Table 2.3 The most important clinker minerals.

Name	Chemical formula ¹⁾	Abbreviation
Tricalcium silicate	3CaO·SiO ₂	C ₃ S
Dicalcium silicate	2CaO·SiO ₂	C ₂ S
Tricalcium aluminate	3CaO·Al ₂ O ₃	C ₃ A
Tetracalcium aluminate ferrite (Ferrit)	4CaO·Al ₂ O ₃ ·Fe ₂ O ₃	C ₄ AF ²⁾

¹⁾ Although e.g. tricalcium silicate is written as 3CaO·SiO₂, this does not imply that the oxides are present individually. The true chemical formula is Ca₃SiO₅.

²⁾ Tetracalcium aluminate ferrite ranges between C₆A₂F and C₆AF₂, the average composition being close to C₄AF.

The clinker minerals C₃S, C₂S och C₃A do not occur pure in Portland clinker: some impurities are always present. The impure form of C₃S is called alite, of C₂S belite, and of C₃A aluminate. The hydration of C₃S and C₂S, of C₃A and of C₄AF is described in sections 2.1.1 through 2.1.3 respectively.

In a Portland cement containing all the clinker minerals, the reactions described in sections 2.1.1 through 2.1.3 will occur concurrently. Fig. 2.4 illustrates the reactions of a Portland cement. The first peak (1) is due to the release of soluble substances from the cement, the first silicate reactions (Equations 2 and 3), and the formation of ettringite (Equation 4). These reactions take place in the first few minutes.

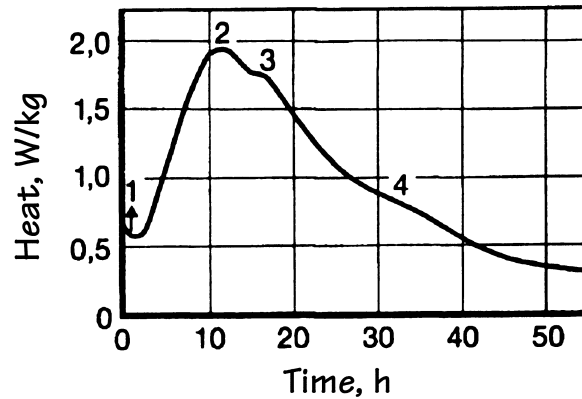


Fig. 2.4 Heat exchange for a typical Portland cement at 20 °C. (Taylor 1990)

When the cement begins to set a second evolution of heat occurs, reaching a maximum after ~10 – 20 hours (2). This is primarily due to the aluminate and silicate reactions described in sections 2.1.1 and 2.1.2. After this peak has passed, it becomes more difficult for the water to penetrate into the cement particles, and the reaction and heat evolution subside (the process becomes diffusion-controlled). At (3) further formation of ettringite occurs and at (4) ettringite is converted to monosulfate, see Equation 5. According to Taylor (1990) the total heat evolution of a normal Portland cement is approximately 450 kJ/kg.

About half of the cement has normally reacted after 3 days, 60 % after seven days and 90 % after three months. The reaction rate, and hence the strength gain, is mainly controlled by the ratio of C_3S to C_2S (C_3S gives a rapid-hardening cement while C_2S gives a cement that reacts slowly), the fineness of the grind, and the temperature.

2.1.1 Hydration of calcium silicates (C_3S , C_2S)

When C_3S is mixed with water, calcium ions are rapidly released into solution and hydroxide ions form, causing the pH to rise above 12 within a few minutes. When the concentration of calcium and hydroxide ions reaches a certain threshold calcium hydroxide crystallizes out of solution, while a layer of calcium silicate hydrate (CSH) forms on the surface of the C_3S particles. As CSH layer grows it forms a barrier which the water must penetrate in order to reach the unhydrated C_3S and through which ions must diffuse out. The hydration reaction thus becomes diffusion-controlled and approaches 100% asymptotically. Initially the hydration rate is temperature-dependent, but the temperature dependency is less pronounced after the reaction becomes diffusion-controlled.

C_2S undergoes hydration in a similar way but more slowly due to its lower reactivity, see Fig. 2.5. The figure also shows that it is the reaction products of C_3S and C_2S that result in the highest strength.

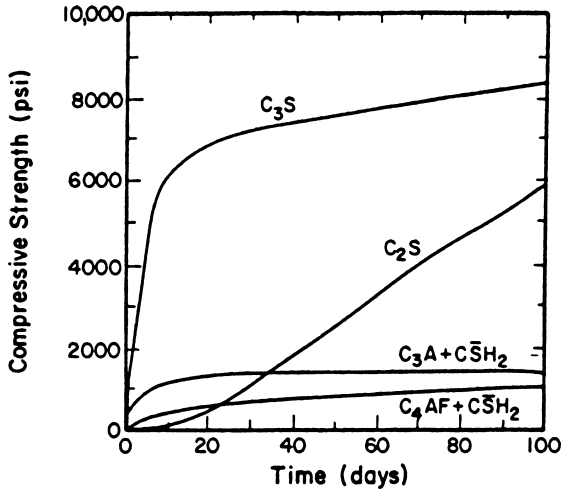


Fig. 2.5
Strength curves of the pure clinker minerals. (Young 1985)

The reactions of C_3S and C_2S may be written:



where $C_3S_2H_4$ is the CSH gel. CSH has the highest strength, while CH makes only a minor contribution.

According to Bogue (1955) the heat evolution on complete hydration is 500 kJ/kg for C_3S and 260 kJ/kg for C_2S .

2.1.2 Hydration of tricalcium aluminate (C_3A)

If cement contains no gypsum, and hence no sulfate, the reaction of C_3A with water gives calcium aluminate hydrate (CAH) immediately. The cement then sets at once. Gypsum is added to moderate the reaction in order to delay setting. In the presence of gypsum ($C\bar{S}'H_2$) the C_3A reacts with water and gypsum to form ettringite ($C_6A\bar{S}'_3H_{32}$).

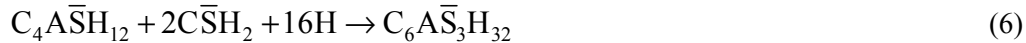


A small fraction of the C_3A reacts within a few minutes, covering the cement particle with ettringite which thus forms a diffusion barrier. The reaction now becomes diffusion-controlled and proceeds slowly. Ettringite is only stable in the presence of a large excess of sulfate, which is generally the case during the first 24 hours. When the concentration of sulfate falls the ettringite is converted into monosulfate. The diffusion barrier breaks down and the reaction speeds up again:



According to Bogue (1955), the heat evolution on complete hydration of C_3A is 870 kJ/kg.

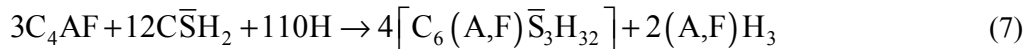
If the monosulfate is later exposed to a new source of sulfate ions, ettringite can re-form:



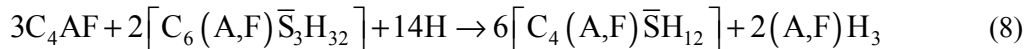
Since ettringite is considerably less dense than monosulfate, ettringite re-formation is accompanied by swelling. Thus if ettringite forms in concrete that has hardened there is a risk of cracking. For this reason, sulfate-resisting cement with low C_3A content (Anl ggningscement) is used for construction in environments with external sulfate sources. It is doubtful whether delayed ettringite formation causes problems in deep stabilization as the stabilized soil is probably sufficiently porous to allow ettringite to form without compromising stabilization performance.

2.1.3 Hydration of ferrite (C_4AF)

The hydration of ferrite is similar to that of C_3A but proceeds more slowly with less evolution of heat (420 kJ/kg according to Bogue 1955). In the presence of gypsum, sulfate-rich compounds of the ettringite type form first:



As the sulfate content falls, compounds poorer in sulfate form:



2.2 LIME

The lime used for deep stabilization is made from limestone, which mainly consists of calcium carbonate ($CaCO_3$). The limestone is crushed and calcined (heated) at somewhat over 1000 °C, which drives off carbon dioxide. The product is mainly calcium oxide (CaO), known as *burnt lime* or *quicklime*. The calcination reaction is described by Equation 9.



Burnt lime is characterized by its degree of calcination and by particle size. The degree of calcination indicates how much of the carbon dioxide (CO₂) has been driven out of the limestone. In production control it is usually measured as *residual* CO₂ (Pihl and Kuusipuro 1997). A distinction is made between hard-burnt and soft-burnt lime, but these terms are relative and have no established definitions. Hard-burnt lime has higher density and hence lower porosity and specific surface, and is therefore less reactive than soft-burnt lime. The reactivity of lime also depends on its particle size: more finely ground lime reacts more rapidly.

The reactivity of lime is measured by the heat evolved when 150 g of burnt lime is mixed with 600 mL of water (SS 13 40 03). The faster and higher the temperature rise, the more reactive is the lime. Fig. 2.6 shows examples of hydration curves for different limes.

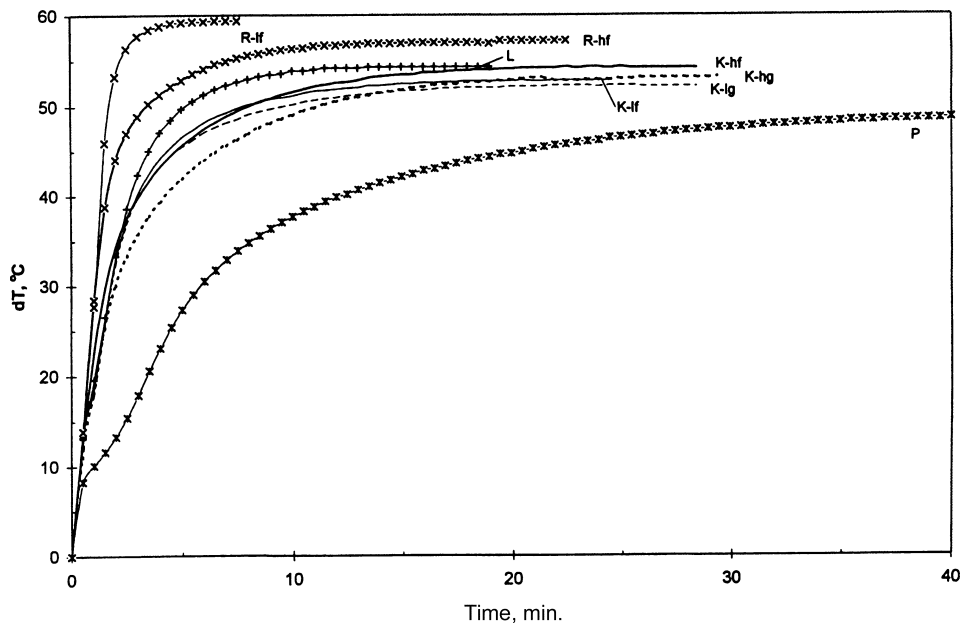


Fig. 2.6 Examples of hydration curves. (Åhnberg and Pihl 1997)

A typical lime composition appears in Table 2.4. Besides the components shown, there may also be small quantities of TiO₂, P, S, Cl⁻ and CO₂ and other species.

When burnt lime is mixed with water, *slaked lime* or *hydrated lime*, Ca(OH)₂, is formed.



The hydration of lime generates a great deal of heat. According to Boynton (1980) the total heat evolved is 1163 kJ/kg. The reaction also results in the pH increasing to ~12.5, which is a condition for the secondary pozzolanic reactions. During soil stabilization, hydration dewateres the soil giving a rapid gain in stability. This stability gain is lost if the soil rehydrates. However, rehydration usually takes place slowly enough for the soil to have been stabilized by other reactions in the meantime.

**Table 2.4 Example of composition of burnt lime.
(Product specification, Nordkalk QL 0.0.1 LA, August 1998)**

Component	Total CaO	CaO-aktiv	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O
Content [%]	94	90	1.5	0.8	0.4	1.7	0.1	0.05

The slaked lime does not set and hence gives no strength gain. The gain in strength from soil stabilization with lime is dependent on secondary pozzolanic reactions with additives or with the surrounding soil:



or on ion exchange, see section 3.2. CASH, or calcium aluminate silicate hydrate, is very similar to CSH but also contains aluminium.

However, if slaked lime (Ca(OH)_2) comes in contact with the air it reacts with carbon dioxide and calcium carbonate re-forms. This gives a strength gain independent of pozzolanic reactions and is the reaction responsible for the strength of e.g. mortars and renders.



Burnt lime is sensitive to atmospheric moisture and carbon dioxide. The probable reason why the hydration curve labelled P in Fig. 2.6 is lower than the others is that the lime was affected by contact with air. Atmospheric moisture causes some of the lime to hydrate to Ca(OH)_2 , see Equation 10. The slaked lime may then react with carbon dioxide to form calcium carbonate, see Equation 12. This means that special care must be taken during the transport and storage of lime. Åhnberg and Pihl (1997) showed that lime stored in contact with the air deteriorates appreciably, see Fig. 2.7. After one week there is already a substantial loss of reactivity.

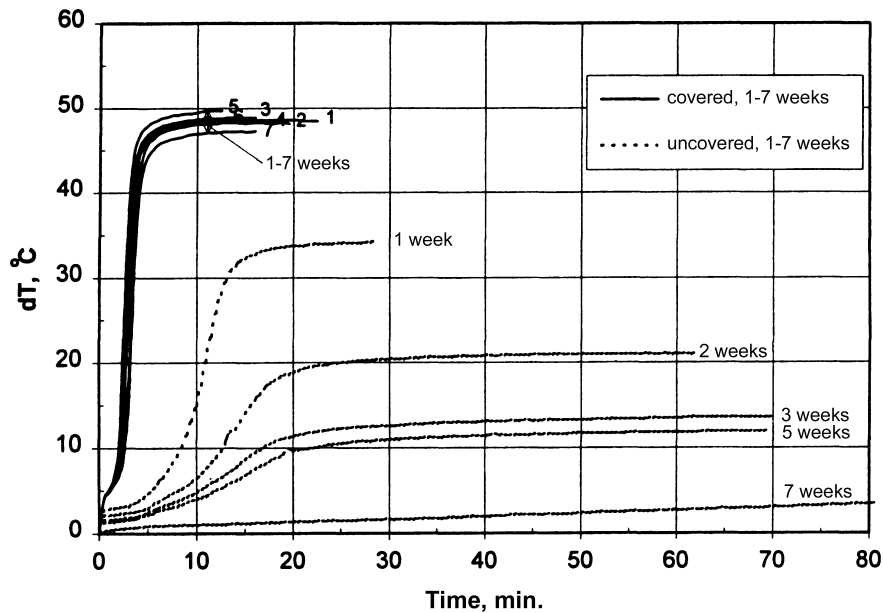


Fig. 2.7 Examples of hydration curves of limes stored in half-filled containers, covered and uncovered. (Åhnberg and Pihl 1997)

2.3 LATENT HYDRAULIC AND POZZOLANIC ADDITIVES

As we have mentioned, we distinguish between hydraulic, latent hydraulic and pozzolanic materials. Which group a material is assigned to depends on the ratio of lime to silica in its composition. The higher the $\text{CaO}:\text{SiO}_2$ ratio the more hydraulic the material is, see Table 2.5. Hydraulic materials, such as Portland cement, react spontaneously with water and were dealt with above.

Latent hydraulic materials contain lime but require activation before it can react with water. The commonest latent hydraulic binder is ground granulated blast furnace slag, which is a processed residual product from iron smelting.

Table 2.5 Properties of hydraulic, latent hydraulic and pozzolanic materials. (Fagerlund 1983)

Material	Grain size [μm]	Structure	$\frac{\text{CaO}}{\text{SiO}_2}$	SiO_2 content [%]	Specific surface [m^2/kg]
Portland cement (hydraulic)	1–100	Crystalline	~ 3	~ 20	300–500
Ground granulated blast furnace slag (latent hydraulic)	1–100	Vitreous (amorphous)	~ 1	~ 35	300–500
Fly ash (pozzolanskt)	1–100	Vitreous (amorphous)	~ 0	50–60	300–500
Silica fume (pozzolanic)	0.01–1	Vitreous (amorphous)	~ 0	85–95	20 000

Pozzolan materials or *pozzolanas* contain practically no lime but have high silica content. They therefore require lime from an external source before they can react. Two commonly used pozzolanas are fly ash, a residue from pulverized coal fuelled power plants and heating plants, and silica fume, a residue from the manufacture of metallic silicon or ferrosilicon. The word pozzolana comes from the town of Pozzuoli on the Bay of Naples, where the Romans found a siliceous volcanic ash which they mixed with lime to make a hydraulic binder (Rutle 1958).

The reactivity of latent hydraulic and pozzolan materials depends on their *fineness* and their *vitreosity*. Fineness is normally expressed as specific surface [m^2/kg]. The essential difference between silica fume and fly ash is their fineness: silica fume is extremely finely divided with a specific surface of $\sim 20,000 \text{ m}^2/\text{kg}$, while fly ash has a specific surface of $\sim 300 - 500 \text{ m}^2/\text{kg}$. Due to its extreme fineness, silica fume contributes far more to strength gain than does fly ash. Fig. 2.8 illustrates the effect of fineness on strength gain. The figure shows strength curves for a slag concrete in which a large portion of the Portland cement has been replaced with blast furnace cement, but similar relations between fineness and strength exist for all binders.

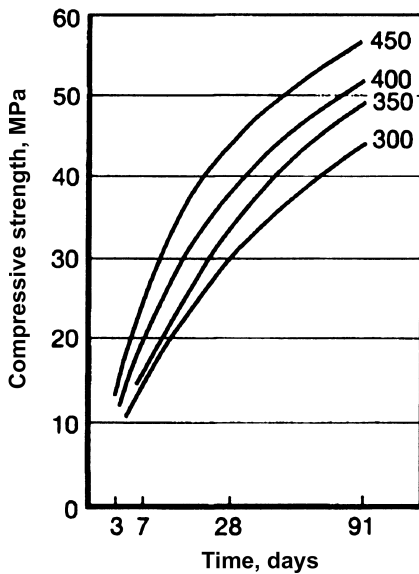


Fig. 2.8
The fineness of a stabilizer affects its strength gain (illustrated here by slag cement). The slag addition was 75 %. The specific surface [m^2/kg] of the slag is indicated alongside each curves. (Schröder 1968)

For latent hydraulic and pozzolan additives vitreosity is also an important parameter. A vitreous (amorphous) material has higher reactivity than a crystalline material, which can be completely inert. High vitreosity is achieved by rapid cooling from the molten state.

As in the case of pure cement paste (see above), the strength of the paste formed by additives depends largely on its porosity, which in turn depends on the separation between the suspended particles. A measure of the additive content, and hence of the particle separation, is given by the water/total-cementitious ratio *wtr* (compare with the water/cement ratio in Equation 1):

$$wtr = \frac{W}{C + D} \quad (13)$$

where W is the weight of mixing water, C the weight of cement and D the weight of additive [kg]. The lower the w/cr the denser the paste and the higher its strength.

2.3.1 Granulated blast furnace slag

Granulated blast furnace slag is a residue from pig iron manufacture in blast furnaces. The reactivity of the slag depends on how rapidly it is cooled after leaving the furnace. Rapid cooling gives a vitreous, highly reactive slag, while slow cooling gives a crystalline, inert slag which is unsuitable as an additive for deep stabilization. Before a slag is used as an additive its reactivity should therefore be measured or verified with the manufacturer. According to BS 6699 the vitreosity of a reactive slag must be greater than 85 %.

The reactivity of a slag is also influenced by its fineness. Slag is normally ground to approximately the same fineness as cement. Quality requirement for fineness may be found in BS 6699, which calls for a specific surface exceeding 275 m²/kg, and in ASTM C 989, which permits a maximum of 20 % oversize on the 45 mm screen.

Besides CaO and SiO₂ granulated blast furnace slag contains appreciable quantities of Al₂O₃ and MgO and smaller amounts of other minerals. Table 2.6 shows an example of the mineral content of blast furnace slag.

Table 2.6 Example of composition of granulated blast furnace slag. (Product sheet for Merit 5000, SSAB Merox AB)

Mineral	CaO	SiO ₂	Al ₂ O ₃	MgO	S	FeO	Na ₂ O	K ₂ O
Content [%]	36	36	10	13	1	0,4	0,4	0,6

Before granulated blast furnace slag will react it must be activated, e.g. with Ca(OH)₂. The reaction products of lime and Portland cement contain Ca(OH)₂, making these products excellent activators for slag. Activation by Ca(OH)₂ from lime or cement gives a latent hydraulic reaction. After the slag is activated the reaction takes place largely spontaneously with its own lime content. It is also possible to activate slag by means of alkalis and sulfates, but these have different reactions and yield reaction products with different properties and are therefore discussed separately in section 7.2.

The main strength-enhancing reaction product is a CSH gel of the same type as that formed by Portland cement, but its CaO/SiO₂ ratio is lower and the gel contains more aluminium oxide and magnesium oxide. The aluminium oxides react with lime and gypsum or with calcium hydroxide, forming crystals resembling ettringite and monosulfate (Johansson 1994B).

The reaction is exothermic like the cementitious reaction, but is slower and therefore gives a slower strength gain and lower heat evolution than with cement. However, the long-term strength from slag admixture can be higher.

The reaction rate is very temperature-dependent. If the temperature increases the reaction rate rises, giving accelerated strength gain. Conversely the strength gain is slower at low temperatures. A method of raising the temperature and thereby hastening the strength gain is to mix cement and possibly burnt lime with the slag.

2.3.2 Fly ash from pulverized coal fuelled power and heating plants

Fly ash from pulverized coal fuelled power and heating plants is a filter dust that is separated from flue gases. The properties of fly ash vary widely with the combustion process and the coal type. Black coal gives a fly ash with lower CaO content than brown coal, but different black coals and brown coals also vary widely. Thus a change in the coal burnt by a power station can result in a fly ash with entirely different properties. At some power/heating plants the combustion and filtration processes are such that the ash totally lacks pozzolanic properties and is hence unsuited for use as a stabilizing agent. High combustion temperatures (1500 – 1700 °C) and rapid cooling give a fly ash with a more rounded particle shape and high vitreous content which is suitable as a stabilizer, see Fig. 2.9. A quality assessment must therefore be made prior to using a batch of fly ash for deep stabilization.

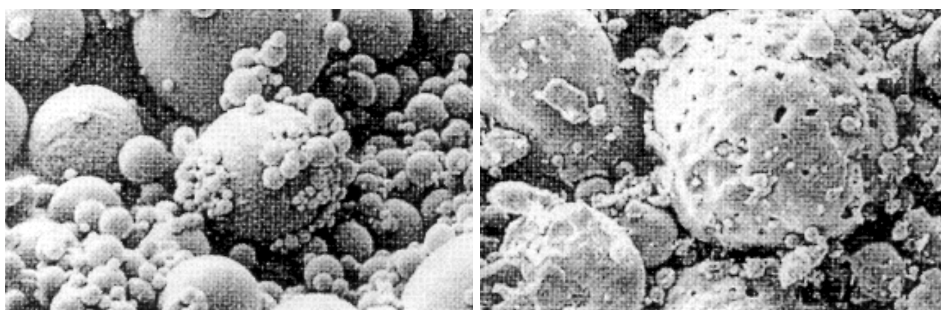


Fig. 2.9 Examples of fly ashes from different combustion processes. The ash on the left is a high-quality ash with rounded, intact particles. The ash on the right has large, angular, porous particles which absorb water. (Johansson 1994B)

The essential properties of a fly ash are its fineness, vitreous content and loss on ignition (a measure of the amount of uncombusted carbon). The vitreous content is normally between 60 % and 90 % but should be as high as possible. Crystalline ashes are completely inert. BBK 94 states a number of requirements for fly ash for use in concrete manufacture. The requirements for deep stabilization need not be so exacting as those prescribed by BBK 94 for concrete structures.

As mentioned above, the composition of fly ash can vary widely. Table 2.7 shows an example of chemical composition. In addition to the components shown, some fifty metals are present in trace concentrations up to 0.05 %. Some fly ashes may also contain radioactive substances.

In order for a pozzolana such as fly ash to react with water at all an external source of lime is necessary, e.g. in the form of Portland cement or burnt lime. When cement or burnt lime react with water they form calcium hydroxide, Ca(OH)_2 , which in turn may form either a strength-enhancing CSH

Table 2.7 Example of chemical composition of a fly ash (Johansson 1994B).

Mineral	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O
Content [%]	40-55	20-30	5-10	3-7	1-4	0.4-2	2	1

gel of the same type as Portland cement but with a lower CaO/SiO₂ ratio, or calcium aluminate silicate hydrate (CASH), which is closely similar to CSH but contains aluminium. In this reaction 100 g of pozzolan can form a maximum of 150 g of CSH gel or CASH gel. The pH of the pore water falls because hydroxide ions (OH⁻) are consumed.

The reaction with cement can be briefly described as follows:



and the reaction with burnt lime (CaO) as:



The pozzolanic reaction is slow and is slowed further by the formation of a shell of CSH gel around the particles of fly ash. The reaction rate and strength gain are proportional to the consumption of Ca(OH)₂, as illustrated by Fig. 2.10. The strength gain is thus very slow, but the effect of pozzolanic reactions on long-term strength can be considerable.

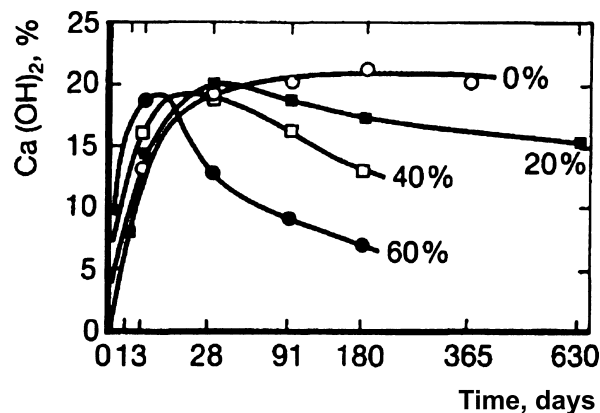


Fig. 2.10 The strength gain from the pozzolanic reaction is proportional to the Ca(OH)₂ consumption. This is illustrated in the figure by the calcium hydroxide content measured at successive intervals in cement pastes containing different amounts of fly ash. The percentages show the content of fly ash. The fall in the Ca(OH)₂ content is due to the pozzolanic reaction.

As with granulated blast furnace slag, the reaction rate is temperature-dependent, with an elevated temperature giving a more rapid strength gain.

2.3.3 Silica fume

The manufacture of metallic silicon or the alloy component ferrosilicon produces flue gases containing extremely fine particles of silicon dioxide, SiO_2 . The flue gases are cleaned by filtration and the filter dust, silica fume, can be used as an additive. In recent decades silica fume has achieved widespread use in concrete manufacture. Silica fume is normally added at a rate of 1 – 5 % of the cement weight.

Silica fume is considerably more consistent in quality than fly ash. Like fly ash, it contains uncombusted carbon and free CaO. Quality requirements for silica fume can be found in BBK 94, which also specifies requirements for reactivity.

The chemical composition of silica fume varies depending on whether it derives from the manufacture of metallic silicon or ferrosilicon, see Table 2.8. The dominating mineral component in either case is silicon dioxide (SiO_2).

Silica fume undergoes the same pozzolanic reaction as fly ash, see above. The strength gain is more rapid than that of fly ash but slower than that of cement. The pozzolanic reaction is highly temperature-dependent, so that the short-term strength is lower at low temperatures. However, long-term strength is increased by replacing part of the cement with silica fume.

Table 2.8 Chemical composition of silicon fumes from the manufacture of metallic silicon and ferrosilicon. (Hjort 1982)

Mineral component	Content[%]	
	From metallic silicon manufacture	From ferrosilicon manufacture
SiO_2	94 – 98	86 – 90
C	0.2 – 1.3	0.8 – 2.3
Fe_2O_3	0.02 – 0.15	0.3 – 1.0
Al_2O_3	0.1 – 0.4	0.2 – 0.6
CaO	0.08 – 0.3	0.2 – 0.6
MgO	0.3 – 0.9	1.0 – 3.5
Na_2O	0.1 – 0.4	0.8 – 1.8
K_2O	0.2 – 0.7	1.5 – 3.5
S	0.1 – 0.3	0.2 – 0.4
Loss on ignition	0.8 – 1.5	2.0 – 4.0

3. The function of binders in soil

The reactions that provide effective soil stabilization are (i) the reaction of cement with the water in the soil, (ii) pozzolanic reactions between $\text{Ca}(\text{OH})_2$ from burnt lime or cement and pozzolanic minerals in the soil, and (iii) ion exchange between calcium ions from lime or cement and ions in the clay. The Cementitious reaction have been described in section 2.1 above, pozzolanic reactions between the soil and $\text{Ca}(\text{OH})_2$ are described in section 3.1, and stabilization by ion exchange is described in section 3.2. A temporary stabilizing effect can also be achieved by the dewatering that takes place when binders consume water. However, this effect is reversed as the soil rehydrates.

Assuming that the binder used has the desired function in the soil at hand and that mixing has been carried out correctly, the outcome depends on the quantity of binder added, i.e. on the water/total-cementitious ratio *w_{tc}*, cf. Fig. 2.3. In the case of burnt lime, however, the soil must contain enough pozzolana to react with the $\text{Ca}(\text{OH})_2$. If all the pozzolana in the soil has been consumed, adding more lime will give no strength increment.

At a minimum, the quantity of binder added must be sufficient to build up a load-bearing skeleton. If less than this quantity is used, no stabilization will occur, see Fig. 3.1. Thus more binder of a given type needs to be added to a porous, watery soil such as peat or mud than to a more densely compacted soil.

Fig. 3.2 shows shear strengths of a number of stabilized soils. It will be seen that the lowest strengths are achieved in peat and mud, which are the most “porous” soils (those containing the least solids). In Fig. 3.3 the water/total-cementitious ratios of the soils in Fig. 3.2 have been calculated. Although the shear strengths in Fig. 3.3 refer to quite different soil types, it is clearly seen that a higher water/total-cementitious ratio gives lower strength. The inverse relation between water/total-cementitious ratio and shear strength is still more obvious for any one given soil, see Fig 3.4.

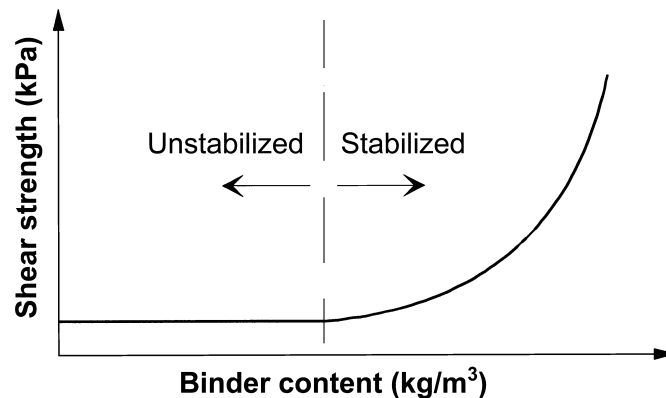


Fig. 3.1 General relation between binder quantity and shear strength.

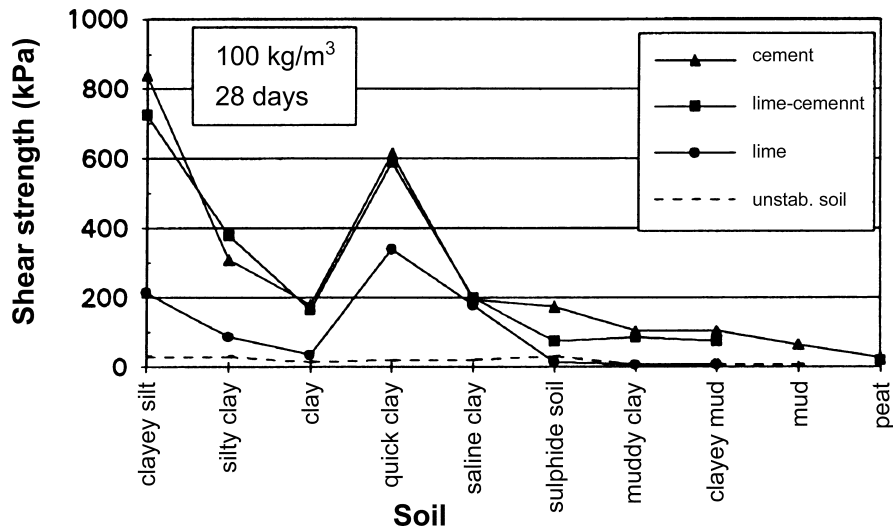


Fig. 3.2 Measured shear strengths of stabilized soils 28 days after mixing, and the shear strengths of the same soils in unstabilized, "undisturbed" condition. Stabilization and strength determination performed in laboratory. (Åhnberg et al. 1995)

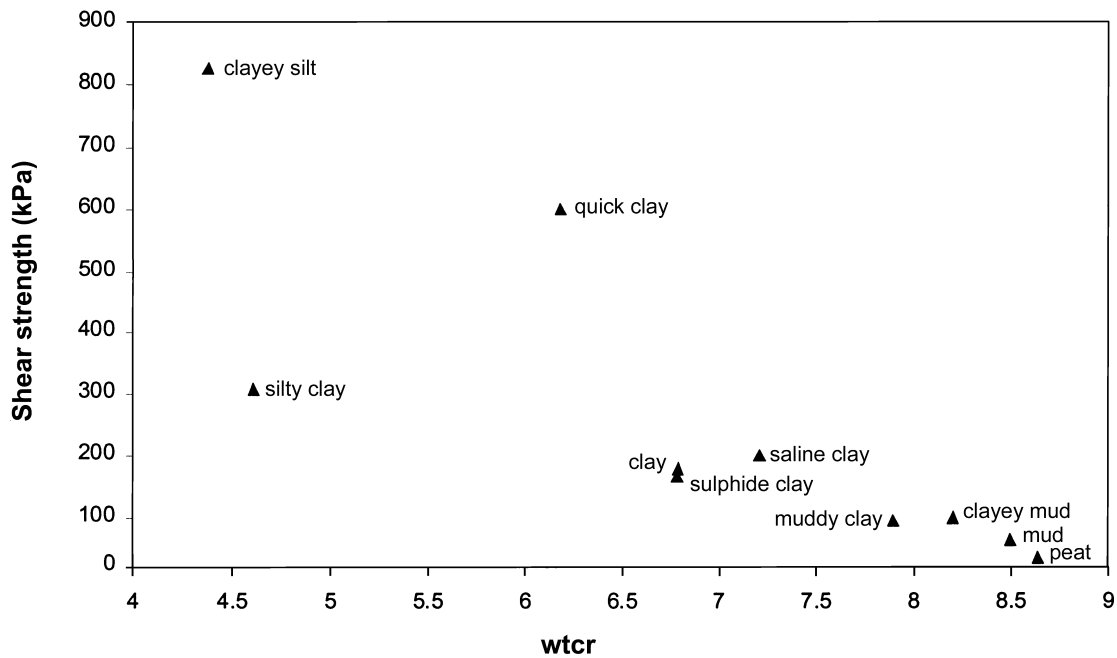


Fig. 3.3 Measured shear strengths of cement stabilized soils as a function of water/total-cementitious ratio wtcr 28 days after mixing. Stabilization and strength determination performed in laboratory. Values after Åhnberg et al. (1995).

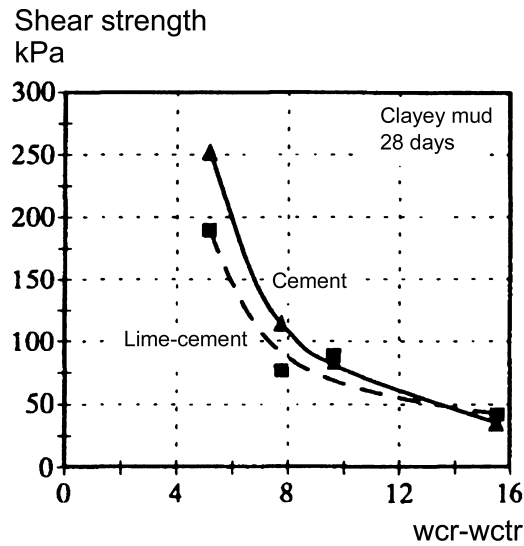


Fig. 3.4 Relation between water/total-cementitious ratio wcr and strength for a clayey mud stabilized with cement and with lime, respectively, 28 days after mixing. Stabilization and strength determination performed in laboratory. (Åhnberg et al. 1995)

3.1 POZZOLANIC REACTION OF SOIL WITH CALCIUM HYDROXIDE

Soils, particularly clays and silts, usually contain aluminous and siliceous minerals. Some of these possess pozzolanic properties, i.e. under certain conditions they can react with $\text{Ca}(\text{OH})_2$ to form strength-enhancing reaction products. The pozzolanic reaction is similar to that which occurs between fly ash or silica fume and $\text{Ca}(\text{OH})_2$, see Equations 14 and 15. The soil can also contain larger quantities of aluminous minerals which take part in the reaction. The reaction product will then be not a CSH gel but calcium aluminate silicate hydrate (CASH), a closely similar mineral containing aluminium. Clays and silts low in aluminium form CSH gel as per Equations 14 and 15. The reaction can be written schematically as



The composition of the CASH gel can vary depending on the pozzolanic minerals present in the soil. Varieties of CASH include the minerals C_2ASH_8 (stratlingite or straeltingite), C_4AH_x and the series from C_3AH_6 to C_3ASH_2 (hydrogarnet).

The calcium hydroxide may originate either from the reaction of cement with water or from that of lime with water, see sections 2.1 and 2.2 respectively. The cementitious and calcareous reactions also result in a high soil pH, which is a condition for the subsequent pozzolanic reaction. The pozzolanic reaction is strongly temperature-dependent. A low temperature results in a slow strength gain. The hydration of cement and particularly that of lime generates heat, which plays an important role in initiating the pozzolanic reactions.

100 g of cement reacts with 25 g of water yielding 100 g of CSH and 25 g of Ca(OH)_2 . The calcareous reaction forms a considerably larger amount of Ca(OH)_2 : 100 g of CaO reacts with 32 g of water yielding 132 g of Ca(OH)_2 , since this is the sole reaction product. If stratlingite is formed in the pozzolanic reaction between soil and Ca(OH)_2 , 100 g of Ca(OH)_2 yields 282 g of stratlingite. Thus, since soil is consumed in the pozzolanic reaction, the weight of strength-enhancing reaction products formed exceeds the weight of binder added. This is illustrated in Table 3.1.

Table 3.1 Quantity of stabilizing products from complete reaction of 100 g binder.

	Strength-enhancing reaction products [g]		
	reaction with water	pozzolanic reaction	total
100 g cement yields	100	71	171
100 g CaO yields	0	373	373

The above discussion assumes that the soil contains sufficient pozzolanic minerals for all of the Ca(OH)_2 to react to form stratlingite. If the soil is saturated with Ca(OH)_2 the CaO will yield less strength-enhancing reaction products than shown in Table 3.1. Burnt lime can yield a greater total weight of reaction products than cement, and in certain soils with high contents of pozzolanic minerals it can therefore give a higher final strength. However, since pozzolanic reactions are slow, it takes an extremely long time for all the Ca(OH)_2 to react to form CASH. The rate at which the pozzolanic reaction proceeds depends partly on the temperature, partly on the contact surface between the soil and the Ca(OH)_2 , i.e. on the specific surface of the soil and on the mixing method. To accelerate the reaction, as much as possible of the pozzolanic soil must be exposed to Ca(OH)_2 . Fig. 3.5 shows laboratory measurements of the strength gain of soils containing pozzolanic minerals after stabilization with lime, lime+cement, and cement. The storage temperature was 8 °C for the specimens stabilized with cement and lime+cement and 20 °C for the specimens stabilized with lime.

With cement as stabilizer, high strength is quickly attained as CSH begins to form within a few hours of water being added. Fig. 3.6 shows schematically the growth in the weight of pozzolanic reaction products of lime and cement in the presence of an excess of pozzolanic minerals.

However, the weight of reaction products is only an indication of the strength of the stabilized soil. The strength actually imparted to a soil by a given weight of reaction products depends on how well the soil particles are bound together by the products and how effectively they fill voids and “densify” the soil.

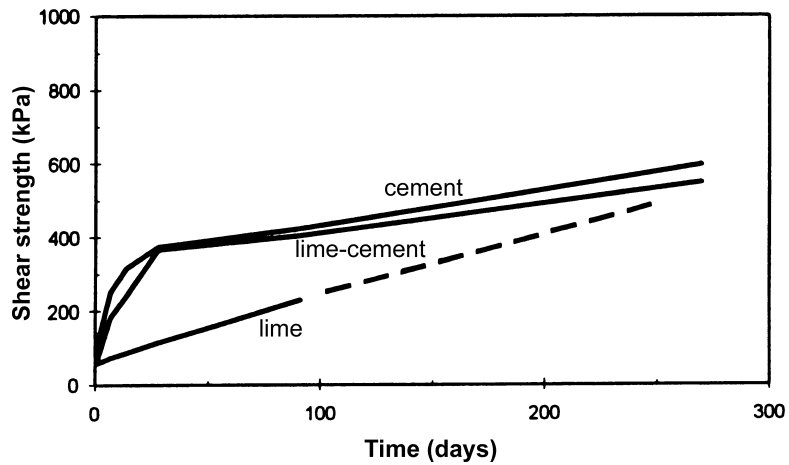


Fig. 3.5 Mean measured strength gain of soil stabilized with lime, lime+cement, and cement. Specimens stabilized with cement and lime+cement were stored at 8 °C, specimens stabilized with lime at 20 °C. (Åhnberg et al. 1995)

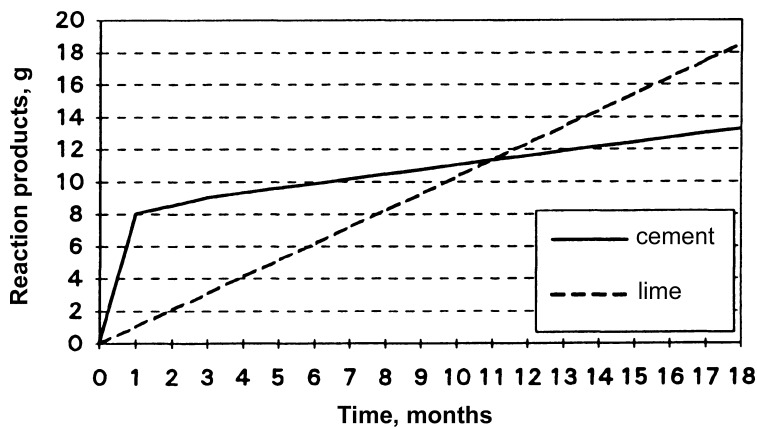


Fig. 3.6 Schematic graph of weight of pozzolanic reaction products formed by 10 g stabilizer per 100 g dry solids in the presence of an excess of pozzolanic minerals. (Åhnberg et al. 1995)

3.2 STABILIZATION OF CLAY BY ION EXCHANGE

Clays can undergo a structural change by ion exchange which stabilizes the soil. The ion exchange can convert a dispersed clay with low plasticity into a flocculated form with high plasticity, see Fig. 3.7. A dispersed clay consists of flat particles separated by thin films of water. On the surfaces of the particles there is a concentration of positive ions (cations), usually potassium or sodium. Mixing a binder with the soil introduces new ions – mainly calcium – which differ in charge and size from the cations in the clay. An ion exchange can then take place. The calcium ions disrupt the structure of the clay, causing it to flocculate and giving an apparent change in the particle size distribution. According to Assarsson (1977) the requirement of calcium ions is equivalent to ~ 0.1 g Ca(OH)_2 per kg clay.

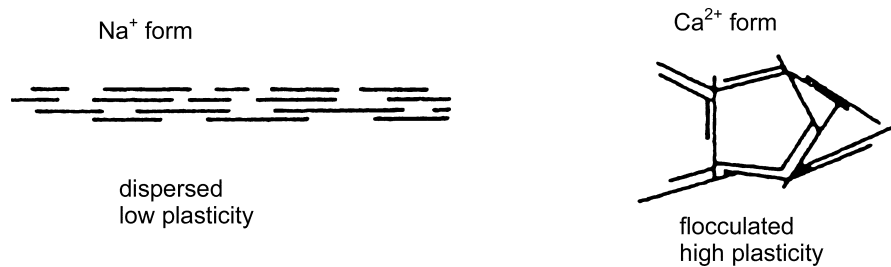


Fig. 3.7 Effect of ion exchange. Illite and kaolinite. (Müller-Vonmoos 1983)

The size of the ion exchange effect depends on the ion exchange capacity of the clay, which in turn depends on the total surface area of the particles and on the geological origin of the clay (Åhnberg et al. 1995). Moreover, cement has a lower ion exchange capacity than lime, as large quantities of potassium and sodium ions are released from the cement when it reacts with water. Ion exchange with the potassium and sodium ions in the clay is then reduced or inhibited by the potassium and sodium ions already present in the aqueous phase.

3.3 CLAY AND SILT

3.3.1 Stabilization with cement

When cement comes in contact with the water in the soil hydration begins immediately, giving a rapid gain in strength. About half of the cement has reacted after 3 days, ~ 60 % after 7 days, and ~ 90 % after three months. The reaction products are CSH gel, the product responsible for the strength gain, and calcium hydroxide, Ca(OH)_2 . The hydration of cement is described in section 2.1.

In pozzolanic clays and silts a secondary reaction can take place between the soil and the Ca(OH)_2 product which provides a further strength gain, see section 3.1. However, this reaction is much slower than the hydration of cement.

Cement reacts more slowly at low temperatures. In Sweden the temperature in the ground is normally around 8 °C, which means that the cementitious reaction is relatively slow. The cementitious reaction is exothermic, i.e. generates heat. According to Åhnberg et al. (1995) this reaction can raise the ground temperature by some 5 – 10 °C. The temperature rise is only temporary: when the cementitious reaction stops the ground temperature falls again. However, the secondary pozzolanic reactions are strongly temperature-dependent and thus the temporarily elevated temperature gives the pozzolanic reactions a better opportunity to start up.

Organic substances have a negative effect on stabilization effectiveness. Humic acids and other acid groups react with $\text{Ca}(\text{OH})_2$ forming insoluble products. They also depress the pH, making the strength gain slower. However, the organic content of clays and silts is generally too low to affect the effectiveness of stabilization by cement.

The stabilization effect of cement in the soil is largely based on the strength of the CSH gel. The gel grows outwards from the cement particles, see Fig. 2.1. To ensure that the strength of the stabilized soil is consistent, the cement must therefore be mixed into the soil in such a way that the cement particles are distributed as evenly as possible.

In the stabilization of clays by deep soil mixing with cement, a thin layer of relatively loose clay sometimes forms in a boundary zone between the stabilized clay column and the surrounding unstabilized clay. The presence of this boundary zone prevents the column and the surrounding soil from interacting as intended. The reason for the formation of this boundary zone is not understood. One suggested explanation is shrinkage of the column as the cement hydrates, leaving a narrow, water-filled gap between the column and the surrounding clay. Another explanation is that clays become more friable when they are desalinized. Åhnberg et al. (1995) measured a depressed Cl^- content in the neighbourhood of cement-stabilized columns, which could result in a boundary zone of looser clay. The boundary zone problem tends to be less pronounced when the cement is mixed with burnt lime.

3.3.2 Stabilization with lime

Burnt lime reacts very rapidly on coming in contact with the water in the soil, forming $\text{Ca}(\text{OH})_2$ with the generation of a great deal of heat, see section 2.2. The reaction gives no strength gain but merely results in dewatering and a sharp rise in temperature. The strength gain comes about by secondary pozzolanic reactions between aluminous and siliceous compounds in the soil and the $\text{Ca}(\text{OH})_2$ formed by hydration of the lime (see section 3.1), and in clay soils also by ion exchange (see section 3.2).

The dewatering can provide a temporary stabilizing effect, but this is not lasting as the water content of the soil will rise again when the reaction ceases. The violent evolution of heat can temporarily raise the temperature by 40 – 50 °C, approaching 100 °C locally (Åhnberg et al. 1995). This temperature rise plays an important role in initiating the secondary pozzolanic reaction, see section 3.1. The pozzolanic reaction is strongly temperature-dependent and the strength gain flattens out as the temperature returns to its normal value, i.e. around 8 °C in Sweden. However, because of the very

large amount of heat that is released on slaking it can take a considerable time for the ground temperature to return to normal.

Lime stabilization is more sensitive than cement stabilization to organic material in the soil. Humic acids react with Ca(OH)_2 forming insoluble products which precipitate out on the particles, inhibiting strength gain via pozzolanic reactions.

3.3.3 Stabilization with a cement–lime mix

It is often beneficial to combine cement and lime. The hydration of the cement gives a rapid strength gain, while the lime generates heat which accelerates the cementitious and pozzolanic reactions. The hydration of the lime also produces large amounts of Ca(OH)_2 , required for the slower pozzolanic reactions and for ion exchange in clays, see sections 3.1 and 3.2.

The amount of lime added should not exceed that required for reaction of the available pozzolanic minerals with the Ca(OH)_2 formed. Once all the pozzolana is consumed, the lime makes no further contribution to strength. According to Åhnberg et al. (1995), the optimal mix for high strength gain within a short time after deep soil mixing is in the range 60 – 90 % cement and 40 – 10 % lime.

3.3.4 Stabilization with latent hydraulic and pozzolanic additives

Blast furnace slag, being a latent hydraulic additive, requires activation by e.g. Ca(OH)_2 , after which the reaction can proceed spontaneously. Pozzolanic additives such as fly ash and silica fume require an external source of Ca(OH)_2 , see section 2.3. The Ca(OH)_2 may be supplied by hydration of cement or lime. Hence latent hydraulic and pozzolanic additives can never be used alone but only as additives to cement and lime.

Since the pozzolanic reaction that takes place with the additives consumes Ca(OH)_2 , it reduces the ability of the clay or silt to form CASH, see section 3.1. Thus if latent hydraulic and pozzolanic additives are used, the soil cannot be fully utilized in the pozzolanic reaction and hence a smaller weight of reaction products is formed. It is therefore in principle unnecessary to add latent hydraulic and pozzolanic additives to pozzolanic clays and silts.

3.4 MUD AND PEAT

Mud and peat require larger stabilizer quantities than clay and silt. This is because they contain few solids to stabilize, and therefore more stabilizer is needed to bind the particles together. Mud and peat also have much higher porosity and water:soil ratio. The high water:content gives a low water/total-cementitious ratio, resulting in low strength. To increase the water/total-cementitious ratio and hence the strength, more stabilizer must be added.

According to Axelsson et al. (2000) there are indications that in soils with high organic content the quantity of binder must exceed a certain threshold before any stabilization is obtained. A possible reason for this threshold effect may be that sufficient binder must be added to neutralize the humic acids. Pousette (2001) also found that humic acids play a critical role in the ability of binders to stabilize soil. She measured up to a sixfold difference in shear strength between stabilized speci-

mens of low-humified Sphagnum peat and highly humified Carex peat. According to Pousette, stabilization of Carex peat requires a considerably larger quantity of stabilizer.

3.4.1 Stabilization with cement

Contact with the water in the mud or peat causes the cement to hydrate forming CSH gel and Ca(OH)_2 , see section 2.1. Compared with clay and silt, mud and peat have a considerably lower content of clay particles that can enter into pozzolanic reactions. The secondary pozzolanic reaction between Ca(OH)_2 and the soil is therefore slight and makes no significant contribution to strength.

Mud and peat have high contents of organic material, which may include humus and humic acids. Humic acids react with Ca(OH)_2 forming insoluble products which precipitate out on the clay particles. This further inhibits pozzolanic reactions. The acids also lower the pH, giving a slower strength gain. However, cement is less sensitive to humic acids than lime, since CSH gel can still form even if the acids react with the Ca(OH)_2 .

3.4.2 Stabilization with lime

Lime normally has very little stabilization effect in mud and peat. This is because the strength gain in lime-stabilized soils is mainly due to pozzolanic reactions with minerals in the soil. Organic soils such as peat and mud usually contain few clay particles with pozzolanic properties that the lime can react with. The pozzolanic reaction is also inhibited by humic acids, see above.

3.4.3 Stabilization with cement–lime mix

Since the strength gain from stabilization with lime is mainly due to pozzolanic reactions between Ca(OH)_2 and the soil, reactions which are weak in organic soils, the lime in a cement–lime mix can make very little contribution to strength. This was demonstrated experimentally by Axelsson et al. (2000), who showed that 50:50 mixes of rapid-hardening cement (SH) and lime give low shear strength compared with rapid-hardening cement alone.

3.4.4 Stabilization with latent hydraulic and pozzolanic additives

Pozzolanic reactions in organic soils can be promoted by the use of additives, which can therefore have a positive effect on stabilization. (The reactions and strength gain of additives are described in section 2.3.) Organic soils often do not contain enough pozzolanic particles in themselves to consume all the Ca(OH)_2 that is formed when the cement is hydrated.

Axelsson et al. (2000) showed that mixes with additives gave lower shear strength than cement alone at 14 and 26 days in two different muds. However, it is possible that the difference would decrease over time, as the pozzolanic reactions between additives and Ca(OH)_2 are slow and would not have proceeded to completion at 26 days.

3.4.5 Fillers

Fillers such as fine sand or limestone filler (inert calcium carbonate, CaCO_3) can be used to increase the number of particles in the soil. The filler has no chemical reaction but increases strength

by increasing the number of particles available for the binder to unite and use to build a load-bearing structure. Moreover, the filler may be presumed to fill any voids arising during stabilization.

Since no filler is absolutely inert, it is possible that fillers may enter into pozzolanic reactions. Siliceous sand, for example, may react with Ca(OH)_2 and contribute to the strength gain. However, since the sand grains are comparatively large and therefore have low specific surface, only a relatively small surface area is exposed to the calcium hydroxide and available for the pozzolanic reaction. The effect of pozzolanic reactions with the filler is therefore negligible.

By replacing a certain portion of the binder with filler, the cost of stabilization may at least theoretically be reduced.

4. Interpretation of laboratory results

Deep stabilization must always be preceded by laboratory tests to verify the technical performance of the binder in the soil at hand. In order to interpret the results of these tests it is necessary to allow for the effects of the work method and of possible temperature differences. The binder that gives the best stabilization effect in laboratory tests may not necessarily be the most effective in the field owing to e.g. the very different mixing methods involved.

4.1 EFFECT OF LABORATORY METHOD ON OUTCOME

There are several methods of homogenizing the soil and mixing the stabilizer into it. Homogenization is usually carried out by means of some form of kitchen mixer or concrete mixer and normally takes between 2 and 6 minutes. It normally takes place the day before the stabilizer is added. The same equipment is used for mixing the soil with the stabilizer. The mixing time is normally between 4 and 10 minutes (Edstam 2000).

The specimens are then formed and compacted into tubes. This operation too is done by a number of different methods. Both static and dynamic compaction are used.

In the case of peat, special methods have been developed for mixing and specimen preparation, see Andersson et al. (2001).

Differences in work methods between laboratories can result in variations in measured shear strength. Edstam (2000) reports a deviation of 22 % from the mean within laboratories and deviations of up to 53 % between laboratories.

Different binders stabilize the soil by different mechanisms. In the case of cement, the reaction products that bind the soil particles together grow on the surface of the cement particles. It is therefore important for the cement to be uniformly distributed through the soil. Lime reacts initially forming calcium hydroxide, and it is the secondary reaction of Ca(OH)_2 with minerals in the soil that gives the stabilized soil its strength. Since calcium hydroxide is soluble, uniform distribution of the lime is of less importance. Thus uneven distribution has a greater negative effect on cement than on lime.

Laboratory specimens are usually prepared with thoroughly fragmented soil and the samples are considerably better mixed than in the field. This means that laboratory tests result in higher strength than one can expect to achieve in the field. Hence no certain conclusions can be drawn from laboratory tests regarding the method by which the stabilized columns should be produced.

4.2 EFFECT OF TEMPERATURE ON OUTCOME

Temperature is of the greatest importance for the reaction rate and the final outcome. Pozzolanic reactions are particularly temperature-dependent. Thus if laboratory testing takes place at 20 °C the pozzolanic reactions will proceed considerably more rapidly than in the ground, which in Sweden normally has a temperature of ~8 °C. Lime and mixes containing pozzolanic additives can therefore exhibit considerably faster strength gains in laboratory tests performed at 20 °C than can be expected in the field. Cement too exhibits more rapid strength gain at elevated temperatures, but cement hydration is considerably less affected by temperature than are pozzolanic reactions.

The size and form of the specimens also has a major effect on reaction rate and on outcome. Small, uninsulated specimens stored in cold conditions (e.g. at 8 °C) will cool down rapidly, slowing the reaction rate. In the field, large volumes of soil are heated up by the cementitious reaction and still more so by the hydration of lime. The ground therefore takes considerably longer to cool than do small laboratory samples stored at 8 °C. The positive effect on the strength gain from the heat evolution of the binder may thus be less pronounced in a /förundersökning/ in the laboratory than it would be in the field.

For a correct comparison of the relative effectiveness of different binders it would be desirable to perform laboratory testing in such a way as to reproduce the environment in the ground as closely as possible.

5. Production of columns in the field

In deep soil mixing one aims to distribute the binder so that the chemical reactions can take place under the best possible conditions to produce uniform columns. Ideally the properties of columns should be uniform both between columns and along and across the individual column. However, soils have very complex rheological properties which make mixing difficult. The movement imparted to the soil by the mixing tool is quickly damped.

Deep soil mixing is carried out in Sweden by a method in which the dry binder is mixed into the soil by means of compressed air. According to Larsson (2000) this method can be divided into three phases: (i) insertion of the mixing tool, (ii) dispersion of binder in the earth, and (iii) molecular diffusion.

During the *insertion* phase the rotating tool is driven to the desired depth. In this phase the soil structure may be broken up, making the clay mineral more accessible for chemical reactions. The mixing tool in use today is normally inserted at a rate of 100 mm per revolution and has angled paddles to facilitate insertion, see Fig. 5.1. This means that relatively little energy is imparted to the process of pulverizing the soil and it is doubtful whether its structure is significantly modified. According to Larsson (2000), ways of generating the shear forces necessary to break up the soil structure include increasing the paddle angle, increasing the rotation speed, or increasing the number of shear zones. The number of shear zones can be increased by e.g. drilling holes in the paddles, using more paddles, angling the blades opposite ways, or using serrated blades. Another way to promote and facilitate the comminution of the soil would be to add a peptizing agent to the soil during insertion of the mixing tool.

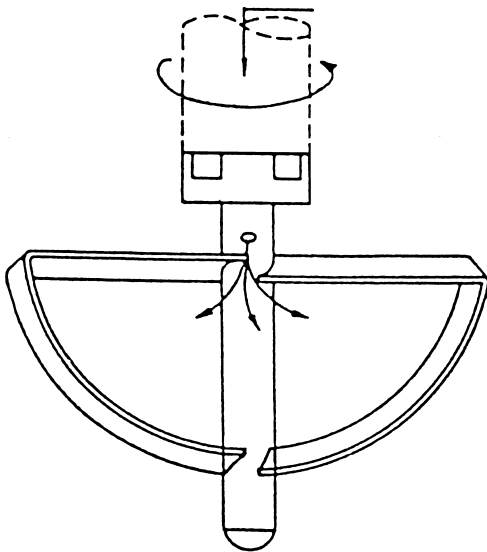


Fig. 5.1
The standard tool generally used for deep soil mixing in Sweden. (Carlsten & Ekström 1995)

During the *dispersion process* the binder is mixed and distributed, the solid particles are moistened, and agglomerates are broken up and distributed throughout the mix. The binder is expelled by compressed air through a hole above the mixing tool, see Fig. 5.1. Mixing and distribution of the binder through the soil are accomplished partly by the energy of the compressed air and partly by the rotation of the tool. The tool must be suitably designed to avoid variations in concentration of the binder across the width of the column. Moistening of the binder follows. Since the binder particles are too light to sink into the clay suspension under their own weight, moistening is difficult to accomplish without energy being supplied from the mixing tool. Moistening is therefore promoted by the high compressive and shear forces generated by the mixing tool. Finally, agglomerates must be broken up to avoid variations in concentration. Agglomerates prevent efficient utilization of the binder as not all the binder particles will contribute to a uniform strength gain within the stabilized volume of soil. Agglomerates are broken up by the strong compressive and shear forces generated as the soil is set in motion and “kneaded”. According to Larsson (2000) a kneading effect can be produced by the use of paddles at a large angle to the horizontal ($\sim 45^\circ$). Finally, after agglomerates have been broken up, the binder must be distributed through the mix in case it was not adequately distributed during the initial mixing. Distribution is most efficient if the soil has been thoroughly broken up during the insertion of the tool.

The efficiency of the dispersion process with a given mixing tool depends mainly on the air pressure used for jetting and on the penetration per revolution and the rotation rate of the tool. One might also speculate that the dispersion process could be helped by mixing a peptizing agent with the soil to promote the formation of a finely divided system.

When the column is installed in the ground, the mixing process continues by *molecular diffusion*. This process is most prominent when lime is used, as dissolved Ca(OH)_2 can diffuse into earth with a lower Ca(OH)_2 concentration and react with the pozzolanic minerals in it. The reaction products of cement, on the other hand, mainly form on the surface of the cement particles. Correct implementation of the dispersion process is thus more critical when cement is used as the binder.

6. Long-term properties (durability)

The cementitious, calcareous and pozzolanic reactions have similar reaction products (CSH and CASH gel). Materials based on these reaction products have been in use for a very long time – they are known to have been used by the Etruscans in Italy 2500 years ago – and the properties of the reaction products are well-known and studied. CSH and CASH gels are normally very durable. Many buildings survive from the Roman period, when the ancient use of concrete reached its height, and some are actually still in use. One of the best known is the Pantheon in Rome, which has a free-bearing concrete dome spanning 43 metres. It was built c. 120 A.D. and is used today as a church.

In certain environments, however, the reaction products can break down rather quickly. To attain the required lifespan, stabilization must be capable of resisting the environment in which it serves. Deep stabilization can be subject to both physical and chemical attacks. Some of the mechanisms of attack are briefly described below.

In the upper soil layers stabilization may be susceptible to *frost damage*. When the water in a stabilized soil freezes to ice, it expands by 9 %. If the ice does not have room to grow without causing stresses there is a risk of cracking. However, there is no risk of frost damage if there is a sufficient volume of air for the ice to grow. Thus the water content must exceed a critical level for cracks to form.

The water in the soil can impact negatively on stabilization. If the water is soft and/or acid, *lime leaching* can occur. The water first dissolves the calcium hydroxide and then liberates calcium from the CSH gel. This process can only proceed and cause damage if there is a continuous inflow of soft or acid water and if the lime-saturated water can drain away. In other words, the soil must be permeable with a flow of water through it. The permeability of deep-stabilized soils is normally too low for there to be any risk of leaching. However, it is conceivable that a column could penetrate a permeable layer of sand or other stratum with flowing water.

If the soil contains sulfates the stabilization may be subject to *sulfate attack*, so-called *delayed ettringite formation*. As described in section 2.1.2, monosulfate can be converted to ettringite, accompanied by swelling, if sulfate ions are supplied from an external source. It is doubtful whether delayed ettringite formation causes problems in deep stabilization as the porosity of the stabilized earth is presumably high enough to allow ettringite to form without compromising the performance of the stabilization.

Certain salts, such as ammonium and magnesium salts, react with hydroxide ions, thus lowering the pH value. Since hydroxide ions are consumed, this mode of attack may be regarded as an acid attack.

With binders or binder combinations having different reaction products from those produced by cementitious, calcareous and pozzolanic reactions, other durability problems may be encountered than those mentioned above. Some such binders and binder combinations are discussed in Chapter 7.

7. Other possible binders and binder combinations

The use of other binders may be attractive in certain situations. An example might be an ash from a local heating plant or factory. The advantage of using such a locally produced ash may be economic, due to low price and transport cost, or it may be environmental if it enables utilization of a residue that would otherwise be disposed of in landfill. It is important to realise that almost all industrial residues products will have an environmental impact due to their composition. A proposed additive must be verified not to contain unsafe levels of heavy metals or other environmentally hazardous substances. It is only environmentally justifiable to use a residue if alternative uses or landfilling are worse options from an environmental viewpoint.

Unless the material is merely to serve as a filler, it is a fundamental condition of use that the material is reactive and that the reaction products add to the strength of the soil. It is also important that the products are stable.

7.1 HIGH-ALUMINA CEMENT

High-alumina cement is made from limestone and bauxite and thus consists mainly of calcium aluminate. Due to its production process high-alumina cement is several times more expensive than Portland cement and its limited use means that transport costs are high. Hydration is very rapid, taking place within a day, in which time it attains close to its full strength. High-alumina cement contains considerably more chemically combined water than Portland cement.

One of the most important reaction products of high-alumina cement is dicalcium aluminate hydrate, C_2AH_8 , an unstable compound which tends to change into tricalcium aluminate hydrate, C_3AH_6 . The transition from C_2AH_8 to C_3AH_6 leaves the material porous, resulting in a loss of strength. In concrete construction the use of high-alumina cement is therefore not permitted in load-bearing structures. The rate of change from C_2AH_8 to C_3AH_6 is hastened by moisture and temperature, the deleterious effect of temperature on strength being most pronounced if hydration took place at high temperatures. The durability of high-alumina cement in deep stabilization should be further investigated before it is used in the field.

Adding gypsum to high-alumina cement produces a very rapid strength gain. The sulfate in the gypsum activates the cement and ettringite is formed. The formation of ettringite is accompanied by expansion, with the result that it has lower strength than the products formed when high-alumina cement reacts with water without added gypsum. Ettringite is only stable at pH above 10, so mixes of high-alumina cement with gypsum should not be used in soils where lower pH values can be expected.

7.2 OTHER SLAGS

There are a variety of slags derived from the metallurgical industry. The steel industry produces a slag from the decarburization process in LD and Bessemer converters. There are also non-ferrous slags from other metal industries, e.g. copper, zinc, phosphorus and nickel slags.

Unlike blast furnace slag, these slags are generally crystalline and therefore inert. Hence the only purpose they can serve in deep stabilization is as fillers, see section 3.4.5. Caution must be exercised when using slags as fillers as some slags may contain heavy metals and other hazardous substances that can leach into the surrounding soil.

Alkali-activated and sulfate-activated slags are latent hydraulic slags that are activated by alkali and/or sulfates. Alkali and sulfates are effective means of activating slags such as granulated blast furnace slag. The strength gain can be very rapid. The properties of the reaction products vary according to the quantity and type of activator used. Knowledge of alkali-activated and sulfate-activated slags is deficient and they should therefore be used with great caution.

7.3 BIOMASS ASH AND REFUSE ASH

Biomass ash comes from the burning of wood, peat, straw etc. Like fly ash from pulverized coal fuelled power plants, biomass ash can have pozzolanic properties. The quality of the ash depends partly on the fuel burnt and partly on the combustion process. Before a biomass ash may be used its reactivity and chemical composition must be tested. If the fuel or the combustion process is changed the test must be repeated.

Refuse ash is a by-product of the cleaning of flue gases in refuse incineration plants. It can have pozzolanic properties. Since the content of the refuse can vary widely, the properties of the ash itself can vary. There is also a risk of it containing environmentally hazardous substances. Refuse ash should therefore be used with great caution. Both its technical and environmental characteristics must be continually monitored.

7.4 GYPSUM

When a gypsum–lime mix comes in contact with clay and water, ettringite is formed. Ettringite has a high density and fills out the voids between the clay particles. Holm et al. (1987) compared lime–gypsum mixes with lime alone in laboratory and field tests. The laboratory tests showed a more rapid strength gain in the presence of gypsum, while the field tests indicated no difference in the initial months after mixing.

The sulfates in gypsum can also be used to activate aluminous products such as fly ash, slags and high-alumina cement. Adding gypsum to high-alumina cement gives a very rapid strength gain due to ettringite formation.

The durability of lime–gypsum mixes and other gypsum combinations is poorly studied. However, given that ettringite is only stable at pH values over 10, gypsum addition is inappropriate in soils where the pH may be expected to be lower. Moreover, stabilization with gypsum in the immediate vicinity of concrete structures may result in sulfate attack on the concrete. The study by Holm et al. (1987) shows that gypsum may come under consideration for temporary soil reinforcement where a rapid gain in strength is desired and long-term stability is not an issue.

7.5 SLAKED LIME

The permanent strength gain obtained when lime (CaO) is used as a stabilizer is due to pozzolanic reactions between aluminous and siliceous compounds in the soil and the slaked lime (Ca(OH)₂) formed when the lime comes in contact with the water in the soil (see section 3.1). In clay there is also a possible strength gain from ion exchange (see section 3.2). This implies that slaked lime itself can be used as a stabilizer. However, this sacrifices the major heat evolution that takes place on the hydration of lime. The strongly temperature-dependent pozzolanic reactions will therefore proceed at a still slower rate. Slaked lime also does not afford the temporary stabilization effect due to de-watering that the hydration of burnt lime provides, see section 2.2.

8. Choice of stabilizing agent

The choice of stabilizing agent should always be based on the reactions that provide the gain in strength. The desired reactions must be possible in the soil in question. In mud and peat, for example, addition of lime will have little or no effect because the pozzolanic reactions are inhibited by humic acids and because of the scarcity of pozzolanic minerals in these soils. On the other hand, lime can be effective in clays and silts free from organic content but containing pozzolanic minerals.

Experience has shown that in clays and silts a mix of cement and lime often results in stabilization with high strength and good interaction with the surrounding soil. The higher the organic content and the fewer the pozzolanic particles in the soil, the more cement should be used. To achieve high strength in clay and silt within a short time after stabilization, Åhnberg et al. (1995) suggest that the optimal mix is in the range 60 – 90 % cement and 40 – 10 % lime.

The reactions that produce strength in latent hydraulic and especially in pozzolanic additives consume Ca(OH)_2 . This means that less reaction products can be formed between Ca(OH)_2 and the soil, and hence less reaction products will be formed overall. These additives may therefore be unsuitable in pozzolanic soils such as clay and silt.

Åhnberg et al. (1995) carried out trials in which a number of different soils were stabilized with 100 % lime, a mix of 25 % lime with 75 % cement, and 100 % cement. The effectiveness of stabilization was then assessed, see Table 8.1.

Axelsson et al. (2000) carried out a study in which the stabilization effect of different stabilizers was tested in mud and peat. These are problematic soils, high in organic content and poor in pozzolanic minerals and therefore difficult to stabilize. The stabilizers tested were various cements, lime, ground granulated blast furnace slag, fly ashes from two different coal-fuelled power stations, and by-pass ash from cement manufacturing. On the basis of the results of the tests and of the authors' own experience Axelsson et al. (2000) recommend the use of cement or a mix of cement and granulated blast furnace slag. The quantities of binder suggested are 100–200 kg/m^3 for mud, 150 – 250 kg/m^3 for peat, and 70 – 200 kg/m^3 for hydraulic fill.

Before the final choice of stabilizer is made, a technical preliminary investigation must always be done to test the properties of the stabilizer in the soil in question. If an additive is used, it must be remembered that its properties may vary widely from batch to batch due to variations in raw materials and in the industrial processes. These materials must therefore always be assessed from both technical and environmental points of view prior to use.

Table 8.1 Assessment of strength-enhancing effects of different stabilizers in soils tested by Åhnberg et al. (1995).

Stabilizers	Soils									
	clayey silt	silty clay	clay	clay (quick)	clay (saline)	clay (sulphide)	muddy clay	clayey mud	mud	peat
Lime	•	+	•	+	+	–	•	•	–	–
Lime-cement	+	+	+	+	+	+	+	•	•	•
Cement	++	++	+	++	+	+	+	+	+	+

– no effect or poor effect • fairly good effect + good effect ++ very good effect

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