Svensk Djupstabilisering
Swedish Deep Stabilization Research Centre

Report 12

Mixing Processes for Ground Improvement by Deep Mixing

Stefan Larsson

Svensk Djupstabilisering

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

Ytterligare upplysningar om verksamheten lämnas av SD:s projektledare Göran Holm, tel: 013–20 18 61, 070–521 09 39, fax: 013–20 19 14, e-post: goran.holm@swedgeo.se,
internet: www.swedgeo.se.

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.

Further information on the Swedish Deep Stabilization Research Centre can be obtained from the Project Manager, Mr G Holm, tel: +46 13 20 18 61, +46 70 521 09

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EN DOKTORSAVHANDLING

Han som sitter därborta hade en doktorsavhandling
som vinden tog hand om
ja, bokstavligen blåste den bort
(någonstans i Tyrolen, tror jag).
Tålmodigt hade han arbetat på den
och säkert kändes det svårt
några år framöver, men numera tar han det stillsamt och filosofiskt.
- Vi behöver nog lite till mans en doktorsavhandling
som blåser bort, säjer han.

Och det krävs inte mer än ett öppet fönster.

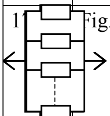
Ferlin 1951

Errata

Mixing Processes for Ground Improvement by Deep Mixing

Stefan Larsson

Page	*Line*	*Printed*	*Should be*
5	8 f.t.	Štìrbáèek & Tausk 1965	Štěrbáček & Tausk 1965
20	fig. cap.	- “ -	- “ -
21	fig. cap.	- “ -	- “ -
23	fig. cap.	- “ -	- “ -
27	fig. cap.	- “ -	- “ -
28	fig. cap.	- “ -	- “ -
30	fig. cap.	- “ -	- “ -
214	ref.	- “ -	- “ -
8	17 f.b.	Šterbácek & Tausk 1965	Štěrbáček & Tausk 1965
8	4 f.b.	- “ -	- “ -
19	5 f.t.	- “ -	- “ -
19	17 f.b.	- “ -	- “ -
19	10 f.b.	- “ -	- “ -
19	6 f.b.	- “ -	- “ -
21	7 f.t.	- “ -	- “ -
21	14 f.t.	- “ -	- “ -
23	3 f.t.	- “ -	- “ -
25	13 f.t.	- “ -	- “ -
26	11 f.t.	- “ -	- “ -
29	7 f.t.	- “ -	- “ -
12	11 f.t.	…deformations g Hold (1982)…	…deformations γ Hold (1982)…
24	4 f.b.	reference to Fig. 3.7 is missing	add: Fig. 3.7 shows the principle of an in-line static mixer.
34	13 f.t.	Both mixtures are divided into 36 parts or sub-volumes each containing 16 white and 16 black particles.	Both mixtures are divided into 36 parts or sub-volumes.
34	18 f.t.		add: There are however eight white particles in average in each sample.
34	fig. cap.	Rielly 1994	Rielly et al. 1994
46	Fig. 5.1	Unit on the x-axis	% of dry volume
49	8 f.t.	Fig. 5.4.	Fig. 5.5.
49	7 f.b.	(Fig. 5.4)	should be deleted
49	fig. cap. Fig. 5.5b	particle concentration f	particle concentration ϕ
49	Fig. 5.5b	γ	$\dot{\gamma}$
50	7 f.t.	Torrance (1986)	Torrance (1987)
53	fig. cap.	Fig. 5.9	Fig. 5.8
57	10 f.t.	Portland Cement Association (1990)	Portland Cement Association (1995)
60	21 f.t.	Fig 6.24a	Fig 6.27a
61	8 f.t.	Porbaha (1998a)	Porbaha (1998)
61	12 f.t.	Porbaha et al. (1998, …	Porbaha et al. (1998a, …
61	15 f.t.	EoroSoilStab 2002	EuroSoilStab 2002
71	Table 6.1	Walter (1999)	Walter (1998)
73-74	fig. cap. Fig. 6.7-9	degree of mixedness a compressive strength s	degree of mixedness α compressive strength σ
85	2 f.b.	Holt & Freer-Hewish 1998, 2000,…	Holt & Freer-Hewish 1998, Holt et al. 2000,…

93	Fig. 6.29a	(Larsson 1999)	(Larsson, R. 1999)
100	Fig. 6.37 fig. cap.	(Isobe 1996)	(Isobe et al. 1996)
103	Fig. 6.44b fig. cap.	(Kitazume and satoh 2003)	(Kitazume & Satoh 2003)
104	fig. cap.	(Bachy 1999)	(Bachy 1996)
106	11 f.t.	(Larsson S. 1999, …	(Larsson 1999b, …
108	fig. cap.	Fig. 6.41	Fig. 6.50
109	12 f.b.	Omine et al. (1998)	Omine et al. (1998a)
109	7 f.b.	Porbaha et al. (1999)	Porbaha et al. (1999a)
109	2 f.b.	Larsson & Axelsson (1994)	Axelsson & Larsson (1994)
112	2 f.b.	Ca2+	Ca^{2+}
114	2 f.b.	aij	a_{ij}
138	Table 8.5 footnote	The w/w_l -ratio is…	1) The w/w_l -ratio is…
171-198	footnote	Sifficient mixture quality	Sufficient mixture quality
1 	Fig. 10..3		
177	1 f.t.	(Larsson 1999, …	(Larsson 1999b, …
180	2 f.b.	average length	averaging length
180	fig. cap.	average length	averaging length
188	3 f.b. 2 f.b.	coefficient of variation - " -	blade rotation number - " -
200	ref.	reference is missing	Barnes, H.A., Hutton, J.F. and Walters, K. 1989. An Introduction to Rheology. Rheology Series, Vol. 3. Elsevier. 199 pp.
206	ref.	Karsastanev, D….	Karastanev, D….
213	ref.	Sheller, P.O. and Reitmeiert, W. 2000.	Sheller, P.O. and Reitmeier, W. 2000.
216	ref.	Viggiani, C.	should be deleted

f.t. = from top, f.b. = from bottom
fig. cap. = figure caption, ref. = reference

Preface

The present thesis is concerned with mixing processes having application to ground improvement by deep mixing. Since there are no extensive works published on this subject field, a great part of the work consists of a literature survey with particular emphasis on literature on the process industries. This review forms a basis for a description and discussion of the mixing process and factors affecting the process in connection with deep mixing methods. The thesis also presents a method for a simple field test for the study of several influential factors in the mixing process of lime-cement columns. The influence of a number of factors on the mixing process of lime-cement columns for deep mixing has been studied in two field tests using statistical multifactor experiment design. The conept of sufficient mixture quality, i.e. the interaction between the mixing process and the mechanical system, is discussed in the last section.

The work was carried out at the Division of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm. The project is part of an industry-wide R&D programme run by the Swedish Deep Stabilization Research Centre. The author is employed at Tyréns AB in Stockholm and has worked on the project as a industrial PhD-student. The project has been supervised by Professor Håkan Stille and Associate professor Sven-Erik Rehnman.

The project was financed by the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Deep Stabilization Research Centre (SD), Tyréns AB, the Royal Institute of Technology, LCM, Hercules Grundläggning and Skanska.

The laboratory tests presented in Larsson et al. (1999) was performed as a MSc thesis project by Maria Walter assisted by the author. The special laboratory equipment was designed by the author and constructed by Elis Svensson, Division of Soil and Rock Mechanics.

The field test at Arboga (Chapter 7) has been performed and coordinated in conjunction with another SD-project, Axelsson (2001). The test columns were installed by LCM. The sampling was performed by the author with assistance from Morgan Axelsson, Elis Svensson and Per Delin, Division of Soil and Rock Mechanics. The laboratory tests were performed by the author and Anders Ekström, Department of Land and Water Resources Engineering.

The field tests at Håby and Strängnäs (Chapter 8 and 9) have been performed by LCM and Tyréns AB in connection to deep mixing works for highway projects. The test set-up at Håby was designed by the author and Bengt Nilsson. The test columns were installed by Mikael Svadling assisted by Leif Sämsgård and Bengt Nilsson. The test set-up at Strängnäs was designed by the author, Marcus Dahlström and Bengt Nilsson. The test columns were installed by Leif Sämsgård assisted by Bengt Nilsson. The field testing was performed by Marcus Dahlström and the author. The statistical analyses are performed by the author. A MSc thesis project by Per Hedman and Mari Kuokkanen was performed in parallel to the field test in Strängnäs presentded in this thesis.

Chapter 2 to 7 are taken, except from minor revisions, from Larsson (2000a) that was reviewed and translated into English 2002 by Kim Bastin. The translation was financed by the US National Deep Mixing (NDM) Program, Tyréns AB, and the Swedish Deep Stabilization Research Centre.

Royal Institute of Technology

Author's acknowledgement

My warmest thanks go to my supervisors Professor Håkan Stille and Associate professor Sven-Erik Rehnman. A special warm thanks to Professor Bengt Broms for his most active interest in the project. I will thank Thord Sjödahl, my colleagues, the management and foundation at Tyréns AB for their support. The clarifying discussions and valuable comments on paper and report manuscripts by Per-Evert Bengtsson, Helena Eriksson, Lars Olsson, Sven Hansbo, Jan Ekstöm, Göran Holm, Magnus Karlsson, Mats Carlsson, Bengt-Arne Torstensson, Helen Åhnberg and Staffan Hintze, have been most helpful in my work. Thanks to Göran Wallmark and Leif Säfström for their inspiring interest for deep mixing.

I wish to express my sincere appreciation to the help given by all those who have contributed to this work. In particular, I wish to thank Morgan Axelsson for the good collaboration, Elis Svensson and Per Dehlin for their assistance in laboratory and in the field, Anders Ekström who carried out laboratory work, Jan Lindgren who did editing work with parts of the thesis, the personal at the library at the Swedish Geotechnical Institute for their most kindly help, Bengt Nilsson and Marcus Dahlström and the staff of the LCM who performed the field tests at Håby and Strängnäs. Maria Walter, Mari Kuokkanen and Per Hedman for their excellent work with their MSc-theses.

Many thanks to all colleagues and the staff of the Division of Soil and Rock Mechanics who could stand my appearance for several years.

I sinceraly thank my mother, sister with family, and my deceased father who have encourage my work.

I dedicate this thesis to my family for their love and encouragement. My wife Jennie and my son Alfred are a tremendious source of joy and stability. They had to patiently endure my work for a long period of time and are therefore sincerely thanked.

Stockholm
November 2003

Stefan Larsson

Royal Institute of Technology

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7. Assessment of mixture quality: Field test in Arboga

8. Uniformity of lime-cement columns: Field test in Håby

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10. On the concept of sufficient mixture quality

Summary

The lime-cement column method in deep mixing, where lime and cement are mixed into the soil to form columns with a hardening effect on the soil, has been used extensively in the Scandinavian countries to reduce settlements and stabilise soft soils. The method is under rapid development with new applications such as the stabilisation of deep excavations and high embankments. These new applications may require a better mixture quality and better control over the mixing process in the stabilised soil. Both clients and contractors are in need of methods for evaluating the mixture quality. Different applications may require different properties and thereby different mixture qualities. Although the method has been used for over 25 years and has become a large-scale industry, knowledge about the fundamentals of the mixing process is limited. There is also a lack of methods for investigating the different parts of the mixing process.

The main objectives of this study are:

to provide a foundation to assist development of the mixing process in deep mixing, by making a contribution to knowledge of the basic mechanisms in the incorporation of binding agents into soil

to develop a methodology for the study of several influential factors in the mixing process of lime-cement columns for deep mixing

to improve knowledge concerning factors that influence the uniformity of lime-cement columns

to relate the mixing process to the mechanical system and to discuss the concept sufficient mixture quality

The thesis begins with a presentation of an extensive literature survey in the process industry. Mixing operations are used widely in industrial production processes where physical and chemical changes occur. Present knowledge of the various mixing processes is mainly based on investigations by the chemical industry relating to the manufacture of pharmaceuticals, paper, plastics, ceramics and rubber. In spite of extensive research over a long period, there is still a lack of fundamental understanding of complex mixing processes. The first three chapters deal with mixing mechanisms, basic mixing operations and equipment, and assessment of the mixture quality, respectively. The focus is on mixing of particle suspensions and laminar mixing mechanisms. The principal conclusion from this part of the thesis is that the literature survey provides a key implement for the primary purpose, describing and discussing the mixing process in the deep mixing method.

The process of mixing is highly dependent on the properties of the materials concerned. When different types of materials are mixed, it is important to have a thorough knowledge of the rheological properties of the materials. When these are known, it is possible to forecast the mechanisms which are essential for mixing and thereby to determine which mixing processes should be chosen. Normally, the behaviour of particle suspensions is very complex. With a dry binder, the soil mixture becomes even more complex. The viscous elastic properties of a soft soil reduce the movements around the mixing device. Relative motions between different elements in the mixture, which are a prerequisite for mixing to occur, only take place in a narrow volume around the mixing device. Another problem lies in the difficulties of measuring the rheological properties of a clay soil during very rapid deformation. Basic knowledge is lacking and the technique becomes empirical.

The main part of the thesis deals with the application of deep mixing. The mixing process is very complex, with many phases and several factors that influence the process and the results. Although it is difficult to distinguish the different mechanisms during a mixing operation, it is important to understand how they

affect both each other and the outcome. The different parts of the mixing process are described on the basis of the dry mixing method, used in the Scandinavian countries. An important conclusion is that the first part of the process, the distribution of the binder from the mixing device into the soft soil, is most critical for the process to perform as required. The influence of various factors on the mixing process is described and discussed. Unfortunately, no extensive studies have been published concerning mixing processes in deep mixing methods. Most of the studies referred to in this thesis are fragmentary and of very limited scope.

In co-operation with a parallel project, a large number of samples were taken from a number of lime-cement columns that had been extracted at a test site in Arboga. The purpose was to study the dispersion of binders in the columns by measuring the binder content in the samples. The discussion deals with the possibility of applying statistical analysis and mixing indices to measure the mixture quality when using dry deep mixing. The results indicate that the sample size has considerable influence on the evaluated mixture quality, i.e. there exists volume-variability dependence. It is also shown that it is difficult to draw conclusions concerning the dispersion of binder when using only a few samples, since the dispersion may vary over the column volume. With more extensive knowledge, it might be possible to assess the mixture quality without increasing the number of samples.

The influence of a number of factors on the mixing process of lime-cement columns for deep mixing has been studied in two field tests in Håby and Strängnäs respectively. The influence of several factors was investigated using statistical analysis of variances ANOVA, based on two- and 2^n-factor experiments. The effects of retrieval rate, number of mixing blades, rotation speed, air pressure in the storage tank, and diameter of the binder outlet on the stabilisation effect and the coefficient of variation determined by hand-operated penetrometer tests for excavated lime-cement columns, were studied. Based on the results from the analyses presented, the main conclusions were;

a) It is possible to study at the same time the influence of several factors affecting the mixing process. The two field studies illustrate the importance of performing a sufficient number of tests when studying influencing factors since the strength is highly stochastic with large variations.

b) The upper pair of mixing blades, in connection with the binder outlet hole, has a significant and determining influence on the binder dispersion. The study showed that the binder is incorporated and spread in the cavity formed by the mixing blades during rotation.

c) Pneumatic fracturing, as a mixing mechanism, had a minor influence on the binder dispersion.

d) Neither the rotational speed nor the diameter of the binder outlet hole had a significant effect on the stabilisation effect and the coefficient of variation.

e) The number of blades and the retrieval rate are shown to exhibit significant influence on the stabilisation effect and coefficient of variation. The two factors can be linked to the coupled factor “Blade rotation number”, which is the total number of mixing blades passing during one meter of shaft movement. The study indicates that the stabilisation effect and the coefficient of variation is a function of the logarithm of the Blade rotation number.

f) The study indicates that the stabilisation effect and the coefficient of variation is a function of the logarithm of the Blade rotation number.

g) The strength and deformation properties of the soil have a major influence on the strength of the columns and the coefficient of variation. According to an empirical correlation, the coefficient of variation depends on the quotient between the water content and the liquid limit.

h) The visual examination appeared to be a complementary tool to the hand-operated penetrometer. The visible clumps and layers of unmixed binders reflected the coefficient of variation as a measure of the mixture quality.

In the last section the mixture quality has been discussed with respect to respect to the mechanical system, the scale of scrutiny, and the correlation structure of the strength over column cross-sections. The correlation structure and the scale of scrutiny have been evaluated based on the results obtained from the field tests at Håby and Strängnäs Based on the consideration of an averaging failure, with a parallel failure system, the variability obtained from small scale tests were reduced with respect to a variance reduction factor. The variance reduction factor depends on the scale of scrutiny and the scale of fluctuation, which in this case were determined by experimental semivariograms.

Statistical analysis of variances, ANOVA, were performed in order to investigate whether the retrieval rate, the number of blades on the mixing tool, the type of mixing tool, the rotational speed; the air pressure in the storage tank, or the diameter of the outlet hole of the mixing tool have an influence on the scale of fluctuation. The section also briefly consider design consideration with respect to the mixing process, the influence on the strength magnitude from an economical point of view and some considerations concerning production quality assessment.

Based on the results from the analyses presented, the following conclusions can be drawn;

a) Different types of correlation structures can be obtained between different columns in spite of the fact that they were equally installed. The mechanical mixing work does not significantly influence the type of correlation structure.

b) The results from the analysis of variances, ANOVA, show that none of the investigated factors have a significant influence on the scale of fluctuation.

c) The results are an indication that the mechanical mixing work influences the spatial correlation structure, expressed as the scale of fluctuation, in a relatively small scale, only a few centimeters. The observations from the tests indicate that the spreading and incorporation of the binder in the early stage of the mixing process are the crucial factors and have the determining influence on the binder dispersion and the spatial correlation characteristics over the column cross-section.

d) The evaluated scale of fluctuation is in the same range at the two test sites, 0-0.3 m. The reduction factor with respect to the coefficient of variation, evaluated from the hand-operated penetrometer tests, is approximately in the range 0.5 to 0.3 for a column section where the considered area is in the range 25% to 75% of the column area.

e) A simple consideration shows that the possibility to utilize variance reduction and the assignment of the sensitivity factor have a major influence on the determination of the partial factor of safety.

f) The most rational course of action to increase the strength magnitude and to improve the mixture quality is to provide the mixing tool with more blades or construct mixing tools that achieves more mixing work. It is not considered profitable to increase the mixing work with respect to the retrieval rate.

g) The most suitable method for production quality assessment is still column penetration tests and reversed column penetration since a relatively large volume is tested. Single test from small size tests or small size samples can give misleading results due to large variabilities. The test or sample size for single test should preferable have the same size as the scale of scrutiny.

The analysis shows that it is not possible to give general recomendations concerning the installation parameters, as the retrieval rate and the mixing tool design. Design values for strength properties depends on the mechanical system, the scale of scrutiny, the spatial correlation structure, and the concept of safety, i.e. the concept of sufficient mixture quality is problem specific. In the case were the columns are prefarably axial loaded, the mixing process may have a minor influence on the strength variability due to the variance reduction. However in the case were the columns are laterally loaded and the axial load is relatively low, the mixing process may have a major influence since the variance reduction may be insignificant.

Definitions

DEFINITIONS - PROCESS INDUSTRY

The definitions of rheology are not strictly used in geotechnical engeneering today. The reason for this section is to state a number of definitions that are subsequently used in the thesis. The definitions are partly taken from Harnby et al. (1992) and Barnes et al. (1989).

Agglomerate	A collection of primary particles and aggregates which are connected at their ends and corners is called an agglomerate. Its surface area is not much less than the total surface area of its constituents.
Aggregate	Aggregates are groups of primary particles connected by their surfaces. An aggregate has a surface area that is less than the total surface area of its constituent particles.
Bingham plastic fluid	A fluid which differs from a Newtonian fluid in that the linear plot of shear stress against shear rate does not pass through the origin.
Dough	A non-Newtonian material having elastic and viscous flow properties.
Diffusive mixing	Natural or spontaneous mixing. The components blend by themselves.
Dilatant fluid	With this type of fluid, the apparent viscosity increases as shear rate is increased.
Disperse	To distribute (become distributed) through a liquid in the form of fine particles.
Dispersion	A chemical mixture of fine particles dispersed in a liquid.
Dispersive mixing	Mixing in which the size of the ultimate particles is reduced.
Distributive mixing	Mixing by redistribution through slicing and replacing.
Dynamic viscosity	The viscosity μ (Pa s) is now called the dynamic viscosity.
Flocculation	Suspended particles bound together by weak structures in a liquid
Fluid (adj. and noun)	Liquid.
Flow	In this report: material in motion

Granular viscous material	A suspension having both the properties of a solid and viscous flow properties
Intensity of segregation	The intensity of segregation (I_S) is a measure of the difference in concentration between neighbouring lumps in a mixture. It describes the effect of molecular diffusion in the mixing process.
Laminar mixing	Reduction of the scale of segregation or layer thickness by laminar deformation (shearing, stretching, slicing and folding).
Layer thickness	The average distance between adjacent boundary layers of materials mixed by laminar mixing mechanisms.
Liquid	(n.) A substance in the melted state. (adj.) In the melted state.
Macromixing	Mixing by turbulent or laminar motion on a scale larger than the smallest layer thickness or eddy size
Micromixing	Mixing by molecular diffusion on a scale smaller than the smallest layer thickness or eddy size
Mixing time	The time it takes to mix from a given initial state to a prescribed final mixing quality, i.e. the time required for the mixture of the component substances to reach a specified degree of uniformity.
Molecular diffusion	Reduction in the intensity of segregation. The transport or movement of individual molecules through a fluid by the random motion of individual molecules. E.g. calcium ions which react with the silica and aluminium in clay minerals over a long period.
Newtonian fluid	A fluid in which the shear stress is proportional to the shear strain is classed as a Newtonian fluid.
Paste	A non-Newtonian dispersion with a high concentration of solid particles in a liquid. The shear stress in the material is not proportional to the shear rate.
Plastic fluid	Plastic fluids are characterised by a yield stress which must be overcome in order for movement to take place.
Pseudoplastic fluid	With this type of fluid, the apparent viscosity varies inversely as the shear rate.
Rheology	The study of the deformation and flow properties of materials.
Scale of segregation	The scale of segregation (L_S) is a measure of the size of unmixed lumps of pure consistency.
Shear rate	The velocity gradient of a fluid under shear or elongation. $\dot{\gamma} = \frac{du}{dxdt} = \frac{dv}{dx} \quad \left[\frac{m}{ms} = s^{-1}\right]$

Suspension	Fine particles of an insoluble substance uniformly dispersed in a liquid or gas.
Thixotropic fluid	These fluids display a reversible decrease in shear stress over time at constant shear rate.
Turbulent mixing	Reduction of the scale of segregation by random turbulent movement of the material.
Residence time	The time which an element spends in a mixer etc. between entry and exit.
Viscoplastic fluid	These fluids behave in part as a viscous liquid and in part as an elastic solid, i.e. they can exhibit elastic recovery.
Viscosity	Internal friction, resistance to flow (from Latin *viscosus* 'sticky').
Viscous fluid	A fluid having high viscosity (sticky, thick-flowing)
Viscoelastic material	A material having both elastic and viscous properties. The material shows elastic recovery from the deformation that takes place on movement.
Wetting	Replacement of gas (or vapour) with a liquid from the surface of a solid.
Yield stress	The minimum stress required to break up structure of a material sufficiently to produce movement. The yield stress of a suspension is such that its properties resemble those of a solid as long as the stresses in the material do not exceed the yield stress.

DEFINITIONS - DEEP MIXING

The definitions related to deep mixing are partly taken from CEN/TC 288 (2002) and EuroSoilStab (2002).

Admixture	A substance added to the mixture for the purpose of improving its properties e.g. petizer, fluidifier, retarding agent
Mixing process	The mixing process involves mechanical disaggregation of the soil structure, dispersion of binders, fillers and additieves in the soil, and molecular diffusion.
Binder	Chemically reactive materials that reacts with the soil and/or the ground water for the purpose of binding particles together as a coherent mass
Binder content	The weight of dry binder introduced per unit volume of soil to be treated
Blade rotation number	The total number of mixing blades passing during 1 m of shaft movement. The conception has also been named "mixing cycles per meter".

Cement slurry	A mixture of dry cement and water creating a cement slurry in which bentonite, gypsum, or other additives may be included
Column	A pillar of treated/stabilised soil manufactured in situ by a mixing tool.
Column stabilisation	Deep mixing by means of forming columns of stabilised soil. The stabilisation can be done by forming different patterna.
Dry deep mixing	A mixing process of the soil and a binders with or without fillers and admixtures in dry powder form
Filler	Non-reacting material e.g. sand
Wet deep mixing	A mixing process of the soil and a slurry consisting of water, binders with or without fillers and admixtures
Mixing tool	A tool used to mechanically mix the binder with the soil. Normally consisting of one or several rotating units equipped with blades, paddles, propellers, and/or augers.
Penetration	The phase of the mixing process in which the mixing tool is delivered to the appropriate depth.
Penetration rate	Vertical movement of the mixing tool per revolution of the rotating unit(s) during penetration
Retrieval	The phase of the mixing process in which the final mechanical mixing and retrieval of the mixing tool take place
Retrieval rate	Vertical movement of the mixing tool per revolution of the rotating unit(s) during retrieval
Rotation speed	Number of revolutions of the rotating unit(s) of the mixing tool per unit time

Publications

The thesis is presented as a monograph but parts of it have been published in journal- and conference papers.

Larsson, S., Rehnman, S-E. & Walter, M. 1999. Laboratory method for design and development of the dry jet mixing method. Proc. of the 12th ECSMGE, Amsterdam, Vol. 3, pp. 1533-1538.

Larsson, S. 1999a. The mixing process at the dry jet mixing method. Proc. Int. Conf. on Dry Mix Methods for Deep Stabilization. Stockholm, pp. 339-346.

Larsson, S. 2000b. The mixing process for chemical soil stabilisation – an owerview. Proc. 12th Nordical Geotechnical Meeting, Helsinki, pp. 241-250. (in Swedish)

Larsson, S., Axelsson, M. & Rehnman, S-E. 2000. On the assessment of the mixing quality when using the dry jet mixing method. Proc. 4th GIGS, Int. Conf. on Ground Improvement Geosystems, Helsinki, Finland. pp. 99-108.

Larsson, S. 2001. Binder distribution in lime-cement columns. Ground Improvement, Vol. 5, No. 3, pp. 111-122.

Larsson, S., Dahlström, M. and Nilsson, B. 2002a. Uniformity of lime-cement columns for deep mixing – a field test. Submitted to Ground Improvement 2002-12.

Larsson, S., Dahlström, M. and Nilsson, B. 2003a. A complementary field study of the uniformity of lime-cement columns for deep mixing. Submitted to Ground Improvement 2003-11.

The following reports have been presented during the project

Larsson, S. 1997. Mixing mechanisms when using the dry jet mixing method. Work Report No. 3, Swedish Deep Stabilization Research Centre, Linköping, 89 pp. (in Swedish)

Larsson, S. 2000a. Mixing Processes for Ground Improvement by Deep Mixing. Report 6, English Translation July 2002, Swedish Deep Stabilization Research Centre, Linköping, 200 pp. Originally published as Licentiate Thesis 2052, Div. of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm.

Larsson, S., Dahlström, M. and Nilsson, B. 2002b. A study of influencing factors on the mixing process for deep stabilisation by lime-cement columns – field test at Håby. Work Report No. 23, Swedish Deep Stabilization Research Centre, Linköping, 80 pp. (in Swedish)

Larsson, S., Dahlström, M. and Nilsson, B. 2003b. A complementary field study of the uniformity of lime-cement columns for deep mixing. Work Report No. 27, Swedish Deep Stabilization Research Centre, Linköping, 28 pp.

Two MSc thesis have been presented within the project:

Walter, M. 1998. Kemisk stabilisering av jord – en studie av inblandningsprocessen (Chemical stabilization of soil – a study of the installation process). MSc thesis 98/9. Div. of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, 62 pp. (in Swedish).

Hedman, P. and Kuokkanen, M. 2003. Hållfasthetsfördelning i kalkcementpelare - Fältförsök i Strängnäs (Strength distribution in lime-cement columns - Field tests at Strängnäs). MSc thesis 03/06. Div. of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, 47+59 pp. (in Swedish).

Other papers that have been presented during the project which are not directly included but with a content that are related to this thesis:

Larsson, S. 1999b. Shear box apparatus for modelling chemical stabilised soil- Introductory tests. Proc. of the Int. Conf. on Dry Mix Methods for Deep Soil Stabilization, Stockholm, Sweden, pp. 115-121.

Larsson, S. and Broms, B.B. 2000. Shear box model tests with lime/cement columns – some observations of failure mechanisms. GeoEng2000, Melbourne, CD, 6 pp.

Axelsson, M. and Larsson, S. 2003. Column penetration tests for lime-cement columns in deep mixing - experiences in Sweden. Proc. 3rd Int. Conf. on Grouting and Ground Treatment, New Orleans. ASCE, Geotechnical Special Publication No. 120, pp. 145-163.

1. Introduction

1.1 BACKGROUND

The deep mixing method is today accepted world-wide as a ground improvement technology in order to improve the permeability and strength- and deformation properties of the soil. Binders, such as lime or cement are mixed with the soil by rotating mixing tools. The stabilised soil, often produced column shaped, has a higher strength, lower compressibility, and lower or higher permeability than the virgin soil. Experience has been positive and the method has great development potential. The method is undergoing rapid development, particularly with regard to its applicability, cost effectiveness and export potential.

The aim of the mixing process in deep mixing is to transport and distribute the binder in such a way as to produce uniform columns with the required function properties. Increasingly stringent demands are made on the uniformity of properties along the length and across the section of the produced columns. There is also a particular requirement for uniformity of properties between the columns in a structure. In order to improve the production process and to improve the possibility to predict the mixing quality, we need a better knowledge of the basic theories and mechanisms involved in the incorporation of binders, such as lime and cement, into soil. The knowledge is limited concerning influencing factors on the mixing process and the influence on the improved soil properties.

The Swedish lime column method was introduced in the mid 1970s, but then only quick lime was used as binder. Lime-cement columns were mainly used to reduce settlements and to increase stability for relatively low embankments. The stabilised soil was assumed to interact with the surrounding soft soil, i.e. the stability calculation method was based on the assumption that the columns and the surrounding soft soil behave as a composite material. The development of deep mixing methods, extended fields of application, the concept of safety, and the fact that stabilised soil is inhomogeneous, demands for improved design methods, such as probabilistic approaches. Probabilistic design require knowledge concerning the uniformity of the stabilised soil, and a proper assessment of the variability of the stabilised soil properties, and thereby an increased knowledge of the mixing process. The interaction between the mixing process, sufficient mixture quality and the mechanical system has not been well investigated. The concept of mixture quality is not well defined and the volume-variability dependence is little known.

1.2 OBJECTIVES

The main objectives of this study are:

to provide a foundation to assist development of the mixing process in deep mixing, by making a contribution to knowledge of the basic mechanisms in the incorporation of binding agents into soil;

to develop a method for the study of several influential factors in the mixing process of lime-cement columns for deep mixing;

to improve knowledge concerning factors that influence the uniformity of lime-cement columns;

to relate the mixing process to the mechanical system and to discuss the concept sufficient mixing quality.

1.3 SCOPE AND STRUCTURE

The thesis is presented as a monograph. However, some chapters are written as manuscripts for journal submissions and text recur therefore in different chapters.

The subject field is not traditionally geotechnical engineering. To reach the objectives the project is therefore performed interdisciplinary. Present knowledge of the various mixing processes is mainly based on investigations by the chemical industry relating to the manufacture of pharmaceuticals, paper, plastics, ceramics and rubber. The thesis presents, in Chapter 2 to 4, an extensive literature review with particular emphasis on literature on the process industries:

> **Chapter 2**, Mixing mechanisms, deals with basic theories and mechanisms of mixing, particularly of liquids and solids.
>
> **Chapter 3**, Mixing equipments in general, is a review of the basic designs of mixing equipment used in the process industries for mixing liquids and solids.
>
> **Chapter 4**, Mixture quality, is a compilation of simple statistical analyses and mixing indices for the assessment of the mixing quality of different types of mixtures.

Chapter 2 to 4 are included in the thesis in order to create a comprehensive picture of different types of mixing processes in a wide range of applications outside the scope of traditional geotechnical engineering. The review has a rather extensive range than those directly applicable to deep mixing. The knowledge concerning mixing process in connection to the process industry has not been treated before in literature concerning deep mixing. These chapters can be read briefly as an introduction and to understand chapters concerning mixing processes for deep mixing, Chapter 5 to 10. Chapter 2 to 4 can also be read in detail in order to deepen the understanding of mixing processes and to inspire the development of the mixing process for deep mixing.

> **Chapter 5**, Rheology, reviews and discusses some of the available knowledge of the rheology of soft soils in an approach to a better understanding of mixing mechanisms in deep mixing.
>
> **Chapter 6**, Deep mixing, describes and discusses the mixing process, mixing mechanisms and factors influencing the process of incorporating binding agents into loose soils. It further discusses the mixing equipment used in deep mixing.

This review, and a review concerning issues related to soil stabilisation, forms a basis for a description and discussion of the mixing process and factors affecting the process in connection with deep mixing methods. The discussion mainly comprehends column stabilisation in cohesive soils and particularly dry deep mixing, as used in the Scandinavian countries.

> **Chapter 7**, Assessment of mixture quality—field test in Arboga, presents a statistical analysis of mixing quality based on chemical assays of a large number of samples taken from four lime–cement columns. The chapter discusses the concept of mixture quality.

The main purpose of the investigation presented in Chapter 7 was to obtain an increased knowledge concerning binder dispersion in lime-cement columns. The investigation is the foundation for the investigations on mixing process influencing factors.

Two conference papers have been published concerning the discussion of the mixing process based on Chapter 2, 4, 5 and 6, Larsson (1999) and Larsson (2000b). The field test in Arboga, Chapter 7, and parts of Chapter 4 has been published in a conference paper, Larsson et al. (2000), and in a journal paper, Larsson (2001).

A method for the study of several mixing process influential factors of lime-cement columns is used in two field tests. Chapter 8 and 9 are of classic character where a number of hypotheses are tested by statistical analyses.

> **Chapter 8**, Uniformity of lime-cement columns - field test in Håby, presents the methodology using statistical multifactor experiment design for the study of several influential factors in the mixing process of lime-cement columns. This chapter is written as a manuscript for a submitted journal paper, Larsson et al. (2002a).
>
> **Chapter 9**, Uniformity of lime-cement columns - field test in Strängnäs, presents results from a complementary field test by the proposed test methodology. This chapter is also written as a manuscript for a submitted journal paper, Larsson et al. (2003a).
>
> **Chapter 10**, On the concept of sufficient mixing quality, discusses the link between the mixing process and the mechanical system for lime-cement columns. The concept of sufficient mixing quality is considered with respect to the mechanical system, the scale of scrutiny, and the correlation structure, i.e. how the variation of properties from one point to another in space. The analysis is based on the results from the two field tests in Håby and Strängnäs. This concluding chapter can be considered as the synthesis and is, according to the author, the most essential part of the thesis.

Chapter 7 to 10 includes separate discussions and conclusions. No separate conclusion chapter has therefore been written. Limitations in connections to the field tests are stated in the respective Chapters. Proposals for further research are given under the respective discussion sections.

The thesis comprehends conceptions from geotechnical engineering, the process industry, and statistics. It has been chosen to use the abbreviations that normally are used in the respective discipline. However, these disciplines occasionally use the same abbreviation, but in different meaning. An abbreviation section has therefore been omitted. Abbreviations are explained in the text under respective section. Some definitions used in the process industry and for deep mixing are explained in a separate section.

2. Mixing mechanisms

2.1 INTRODUCTION

Mixing and homogenization is an important process in numerous industries, e.g. the food, chemical engineering, paper, rubber and concrete industries. The principal purpose of mixing processes is to bring about changes in physical, chemical and biological properties.

> "The term *mixing* is applied to operations which tend to reduce nonuniformities or gradients in composition, properties, or temperature of material in bulk. " *(Uhl & Gray 1966).*
>
> "The objective of mixing is homogenization, manifesting itself in a reduction of concentration or temperature gradients, or of both simultaneously, within the agitated system... Rapid mixing necessitates motion of the ingredients." *(Štìrbáèek & Tausk 1965).*

Movement produced by e.g. mechanical mixing may be necessary e.g. in order to break up aggregates so that solid particles can disperse in a liquid. The different forms of movement constitute the mechanisms of mixing (Nienow et al. 1992). Mixing takes place between two materials when they come in contact with each other and are deformed so that the contact area between them increases. High-viscosity liquids have high resistance to deformation, and molecular movement and diffusion are low. Relatively large forces are necessary to overcome this resistance. Mixing also takes place when materials are cut into smaller elements and redistributed. A satisfactory mixing process produces a mixture of the required uniformity in the shortest possible time and at the lowest possible cost in terms of machinery, power and labour.

A uniform distribution of ingredients may be required e.g. to produce a final product with a certain texture or to bring about a desired chemical reaction. Requirements for uniformity in a mixing process vary depending on the requirements on the final product or function.

The present chapter sets out to review the basic mechanisms involved in mixing, particularly that of liquids and suspensions. Since soft soils are suspensions, and generally highly concentrated suspensions, the emphasis is placed on laminar mixing mechanisms. The process of dispersion of solid particles in liquids is also touched upon.

The literature cited in this chapter comes primarily from the process industries, where the available research on mixing mechanisms has been done. Mixing mechanisms and mixing processes in connection with deep mixing will be discussed in Chapter 6.

2.2 CLASSIFICATION OF MIXING MECHANISMS

A general classification of mixing processes is independent of the product or industry. Mixing processes can be classified as follows (Nienow et al. 1992):

1 Single-phase liquid mixing

2 Liquid-liquid mixing

3 Solid-liquid mixing

4 Gas-liquid mixing

5 Three-phase contacting

6 Solids mixing

Dry deep mixing by means of columns of lime, lime-cement, and cement involves solids (lime and cement particles), a concentrated clay suspension, and a gas (air). The phases differ greatly in their chemical and physical properties, and as a result these systems have extremely complex properties which can vary under different conditions.

While most types of mixing equipment are used to mix materials having a range of flow properties, the materials' properties are important to the design of the mixing plant. It may be that each type of equipment provides optimal performance with only a narrow range of mixture properties.

Rheology is the study of the deformation and flow properties of materials. From a rheological viewpoint all materials will flow if one waits long enough. Liquids (fluids) to be mixed may be classified as (Lindley 1991a):

1. Newtonian
2. non-Newtonian
3. Viscoelastic

Some simple models of flow are discussed in Appendix A.

Additional materials classifications might be (Lindley 1991a):

1. Cohesive solids
2. Powders
3. Sticky solids
4. Dry solids

2.3 CLASSIFICATION OF FLOW TYPES

Suspensions, such as clay suspensions and suspensions of lime and cement particles in clay, show properties that differ from those of Newtonian fluids, i.e. most relatively concentrated suspensions have non-Newtonian or viscoelastic characteristics.

In an incompressible material the characteristics of plane flows (relative movement between the elements of the material) can be described by two parameters: the rate of deformation ε and the rate of rotation ω. A number R which characterizes the flow type is written as (Giesekus 1983):

$$R = \frac{(\varepsilon^2 - \omega^2)}{(\varepsilon^2 + \omega^2)} = \frac{(1 - r_0^2)}{(1 + r_0^2)} \tag{2.1}$$

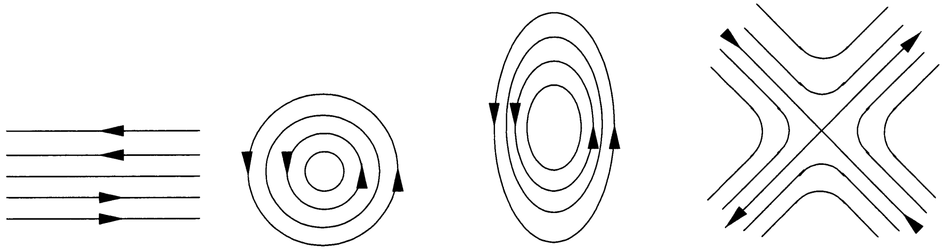
where $r_0 = \omega / \varepsilon$

Two classes of flow types are defined as:

hyperbolic flows:	$0 < \omega < \varepsilon$	$0 < r_0 < 1$	$0 < R < 1$
elliptic flows:	$\varepsilon < \omega < \infty$	$1 < r_0 < \infty$	$-1 < R < 0$

The limiting cases of these are:

pure shear flow:	$\omega = 0$	$r_0 = \infty$	$R = 1$
simple shear flow:	$\omega = \varepsilon$	$r_0 = 1$	$R = 0$
pure rotational flow:	$\varepsilon = 0$	$r_0 = \infty$	$R = -1$



(a) Simple shear (b) Pure rotation (c) Elliptic (d) Pure shear

Fig. 2.1 Types of plane flow (after Giesekus 1983).

Simple shear flow can be conceived as a relative sliding between rigid layers of infinitesimal thickness, see Fig. 2.1. The distances between particles remain constant for all particles situated in the same layer and change only if they are situated in different layers. The rate of rotation is equal to the rate of deformation.

In a mixing process in a non-Newtonian liquid there is usually a combination of all types of flow. The rheological behaviour of the material depends on the type of flow (Giesekus 1983). Thus in a mixing process, different parts of the mixture may show different rheological behaviour.

2.4 AGGLOMERATION AND SEGREGATION

Since mixing processes involve different materials having different rheological properties, it is important to be aware of factors that influence the properties of the mixture. Particles of materials which tend to agglomerate have poor flow characteristics. Particles agglomerate or adhere to one another because of interacting forces. The following mechanisms can lead to agglomeration (Coulson et al. 1979):

a) Mechanical interlocking: masses of long, thin particles may become totally interlocked.

b) Surface attraction: these include Van der Waal's forces; substantial bonds may be formed (high specific surface to volume ratio).

c) Plastic welding: results from high pressures which may develop in small contact area between irregular particles.

d) Electrostatic attraction: movement of fine particles can result in charge build-up.

e) Effect of moisture. Moisture collects near points of contact between particles and results in surface tension effects. It may also partially the particles, which then act as a bonding agent on subsequent evaporation.

f) Temperature fluctuation may result in changes in particle structure and greater cohesiveness.

Perfect mixing is the state in which all the parts of the mixture have the same composition.

Segregation occurs because of differences in particle size, density, shape and/or resilience. Size difference is the most important; density sometimes is important; other effects are generally unimportant. The following mechanisms lead to segregation (Williams 1983):

a) Particle trajectories where different size particles have different velocities.

b) Percolation of fine particles where fine particles move between gaps in the particle mass.

c) Rise of coarse particles on vibration.

2.5 FORCES AND MECHANISMS CAUSING MIXING

The fundamental processes for the transport of materials in a mixing process are: momentum transfer in mobile media, heat transfer, and mass transfer (Geankoplis 1993).

Molecular transport process produce transfer or movement of a given property by molecular movement through a system or medium (Geankoplis 1993). The properties transferred may be mass, heat or momentum. Each molecule in a system possesses a given quantity of mass, heat or momentum associated with it. If there is a concentration gradient of the between one region and an adjacent region, transport of this property will take place. The flux will be proportional to the concentration gradient and inversely proportional to the resistance.

The pattern of movement around an impeller is generally very complex. However, according to Metzner & Otto (1957), the resistance to the impeller can be examined by comparison with simple flow situations. In laminar flow around a sphere there is no separation of the flow and viscous dissipation of energy is the controllable factor. The total force on the sphere is due to the shearing forces on the surface and the differences in pressure between the front and the rear of the sphere. The pressure differences are due to the viscous dissipation of energy in the fluid stream (Metzner & Otto 1957).

The mixing mechanisms can be summarized as follows (Lindley 1991a):

a) Turbulence and diffusion for low viscosity liquids.

b) Breaking and recombining, deformation, laminar flow, shear flow and streamline flow for very viscous liquids.

c) Convection, diffusion, and shear for dry, non-cohesive solids.

Turbulent mixing

For mixing to take place there must be relative movement between particles or flow elements. When the flow rate increases the flow becomes turbulent. Mixing of materials takes place through either spontaneous motion (diffusion or free convection) or forced motion (Šterbácek & Tausk 1965). External forces must be applied to overcome the forces of resistance in the mixture. These forces are: inertial forces which resist changes in direction or velocity, and viscous resistance or shear forces. For liquids of low viscosity in which turbulence has developed, inertial forces offer the greatest resistance to mixing.

Turbulent flow is a hydrodynamic process in which eddies are produced. The elements move not only in parallel layers but also on erratic paths. This promotes mixing in that not only molecules but also fluid elements pass between the individual layers. The analysis of the turbulent flow in e.g. a mixing vessel is very difficult because of the rapid three-dimensional motions. To determine whether the flow is turbulent or laminar one can use the *Reynolds number* criterion, but determining the Reynolds number is very difficult. For mixing processes in vessels the maximum value of the Reynolds number for laminar flow is Re = 10–20.

Turbulent motion can be considered as a superposition of a spectrum of velocity fluctuations and eddy sizes in the mixture. The relation between shear stress and shear rate in turbulent flow can be written as (Šterbácek & Tausk 1965)

$$\tau = (\mu + \varepsilon)\frac{dv}{dy} \qquad (2.2)$$

where μ is the viscosity (laminar internal friction), ε is the eddy viscosity, and dv/dy is the shear rate or shear velocity gradient. The eddy viscosity e is not constant for a fluid at a given temperature. It is not constant in all parts of the fluid, but varies from small values at the periphery of the flow to high values in the centre. For fully developed turbulence the influence of laminar friction m may be neglected and the above equation can be written as

$$\tau = \varepsilon \frac{dv}{dy} \tag{2.3}$$

The mixing of suspensions and solid-liquid systems are dependent on large eddies which contain a large amount of energy, so-called anisotropic turbulence (Nienow et al. 1992). Large eddies have large velocity fluctuations of low frequency and are of a size related to the geometry of the mixing tool. Eddies are of great importance for both distributive and dispersive mixing.

Like the internal friction, the diffusion rate also increases as the flow becomes more turbulent.

Laminar mixing

The mechanisms that bring about mixing are laminar and turbulent flow, eddy diffusion and molecular diffusion. Internal forces and shear forces are responsible for reduction in particle size and hence an increase in interface area between the components. If aggregates, (strongly bonded lumps) are present in the material, laminar mixing acts as a dispersing process, i.e. high shear velocities break up the aggregates, bringing about homogenization.

If rapid mixing is necessary, the ability of the mixing method to deform the materials becomes important (Gray 1963). Some fluid movements are more effective than others for deforming and mixing viscous materials.

A flow pattern is desirable that produces movement throughout the entire volume to be mixed. In viscous liquids the kinetic energy of the moving fluid is consumed by the viscous drag. Viscous liquids need to be pushed into and out of all parts of the volume by a moving surface or moving fluid. This displacement should be done in a way which rapidly deforms the shape of and extends the area between the materials being mixed (Gray 1963).

The mechanisms which can be active in laminar flows are laminar shear, extensional flow, distributive mixing, molecular diffusion and shear stresses (Edwards 1992). Laminar flow is normally associated with high-viscosity liquids. At typical rates of energy input, viscosities greater than about 10 Pa s are required if the flow is to be truly laminar (Nienow et al. 1992). High-viscosity liquids are as a rule rheologically complex. Under laminar flow conditions, intermediary forces quickly die out under the action of the high viscosity. The mixing divice must therefore occupy a large part of the volume to be mixed. Close to the tool high shear rates exist where fluid elements can be deformed and stretched by laminar flow. The mixing quality is determined by the total shear, which is the product of shear velocity and time. Mixing is improved by a combination of high shear forces and long residence time.

Laminar shear

In laminar shear there is elongation and increase in the area of a plane which is perpendicular to the direction of shear, see Fig. 2.2.

In order to set up a relation between deformation in laminar motions and the mixing quality of a two-component mixture, we may treat the layer thickness as a measure of the state of the mixture. If S represents the area between two components and t the thickness of the layer, the relation shown in Fig. 2.3 is obtained.

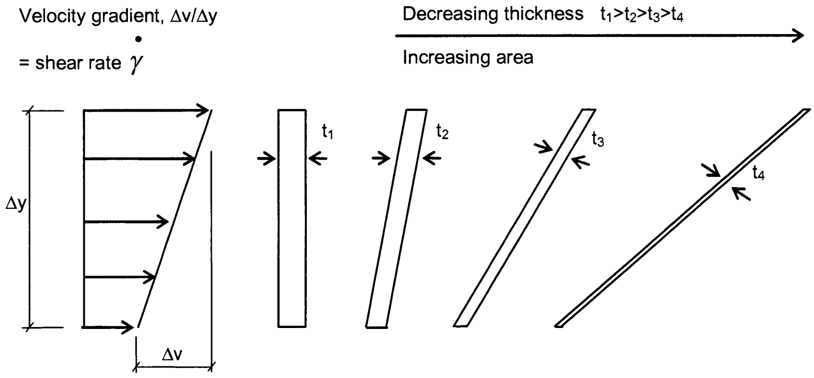


Fig. 2.2 **The thinning of fluid elements due to laminar shear flow (after Nienow et al. 1992).**

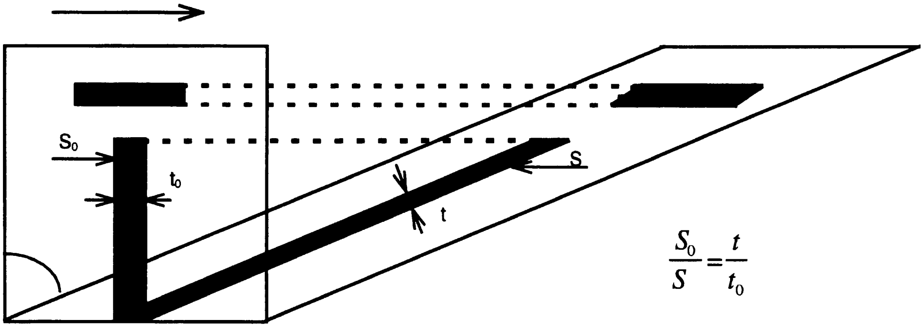


Fig. 2.3 Laminar shear flow (after Hold 1982).

A general analysis of mixing in laminar shear flow was presented by Spencer and Wiley (1951). The process is illustrated in Fig. 2.4, and it can be shown that the ratio of the final to the initial interfacial area is given by (Hold 1982):

$$\frac{S}{S_0}=\sqrt{1-2\gamma\cos\alpha\cos\beta+\gamma^2\cos^2\alpha} \tag{2.4}$$

where: S = interfacial area per unit of mixture (m^2/m^3)
S_0 = interfacial area before shearing, area per unit of mixture (m^2/m^3)
α = angle between the normal to the original plane and the *x* axis (rad)
β = angle between the normal and the *y* axis (rad)
γ = net strain (-)

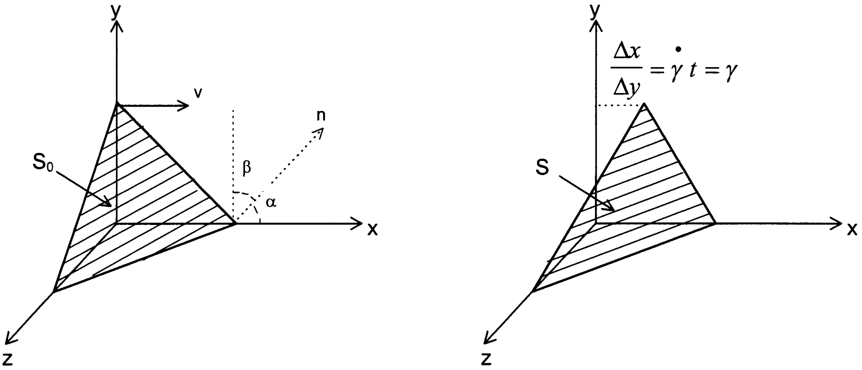


Fig. 2.4 Increase in interfacial area between parallel plates in laminar shear flow. (after Hold 1982)

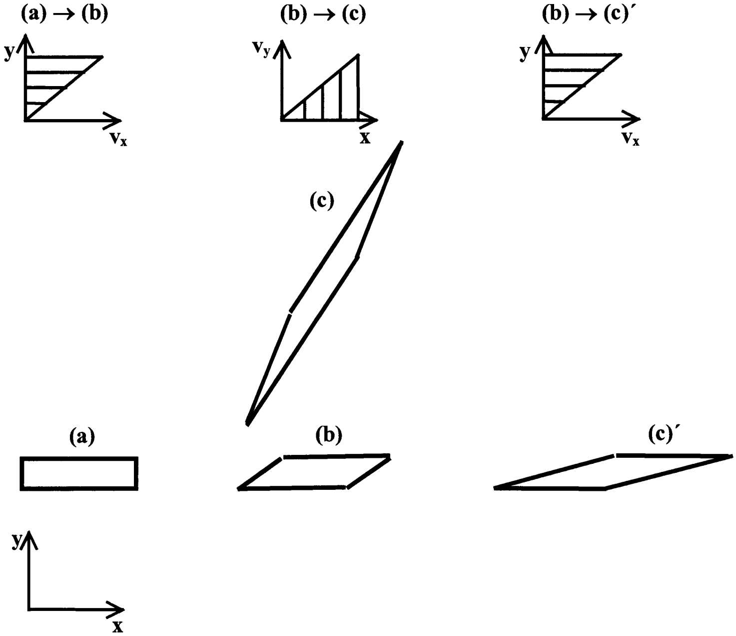


Fig. 2.5 Effect of simple shearing with change in direction. Two consecutive simple shearing steps at right angles (after Edwards 1992 and Hold 1982).

The influence of orientation is brought out by the equation above (Edwards 1992):

a) for surfaces initially parallel to the x,y plane

$$S/S_0 = 1 \tag{2.5}$$

that is, no mixing occurs;

b) for surfaces initially parallel to the x,z plane

$$S/S_0 = 1 \tag{2.6}$$

and again no mixing occurs;

c) for surfaces initially parallel to the y,z plane, i.e. perpendicular to the plane of shear

$$S/S_0 = (1 + (\dot{\gamma} t)^2)^{1/2} = (1 + \gamma^2)^{1/2} \tag{2.7}$$

giving an increase in interfacial area between the components and hence an improvement in mixing.

For very large deformations g Hold (1982) shows that:

$$S/S_0 = (1 + \gamma^2 \cos^2 \alpha)^{1/2} \cong \gamma \cos \alpha \tag{2.8}$$

The interfacial area is increased if the direction of shearing changes during the shearing process (Hold 1982). It is therefore more advantageous to deliberately change the direction of shear than to apply a unidirectional shear field continuously. Simple shearing can thus be optimized by changing the direction of shear on each cycle, see Fig. 2.5. The increase in interfacial area can be optimized by changing the direction of shear so that it always maintains angles $\alpha = \beta = 45°$, see Fig. 2.4.

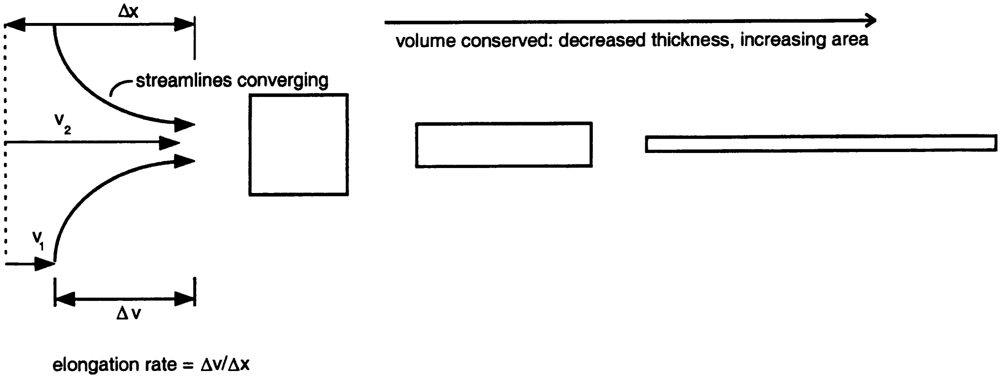


Fig. 2.6 The thinning of fluid elements due to extensional flow (after Nienow 1992).

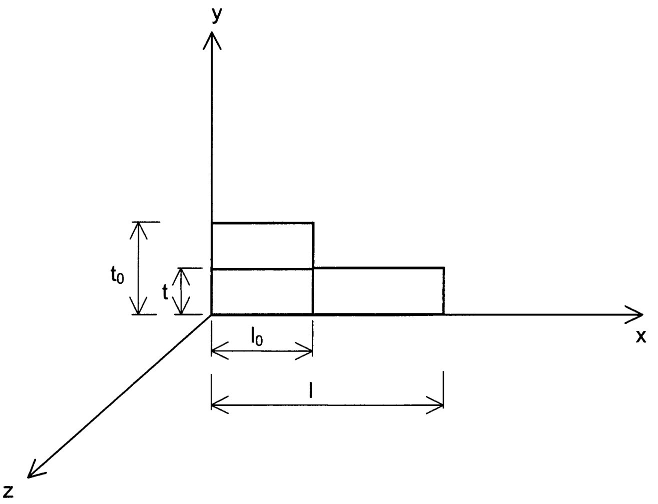


Fig. 2.7 Increase in interfacial area during idealized uniaxial extension (after Cheng 1979).

Extensional flow
In most practical applications there are generally also extensional flows, i.e. flows where the velocity increases in the direction of flow, see Fig. 2.6. Extensional strain produces stretching of the material due to changes in the flow geometry or acceleration of the flow, which reduces the thickness of the elements and thus improves mixing quality (Edwards 1992).

In uniaxial extension in the x direction, compression occurs in the *y* and *z* directions at half the strain rate in the *x* direction, see Fig. 2.7. The ratio of final to initial length of an elemental volume is given by (Edwards 1992):

$$l/l_0 = e^{\gamma_e} \tag{2.9}$$

where: l_0 = initial length of elemental volume (m).
l = final length of elemental volume (m).
γ_e = strain in extensional movement (-).

The ratio of final to initial width is given by (Edwards 1992):

$$t/t_0 = e^{-\gamma_e} \tag{2.10}$$

where: t_0 = initial width of elemental volume (m).
t = final width of elemental volume (m).

From this it follows that (Cheng 1979):

$$S/S_0 = e^{\gamma_e/2} \tag{2.11}$$

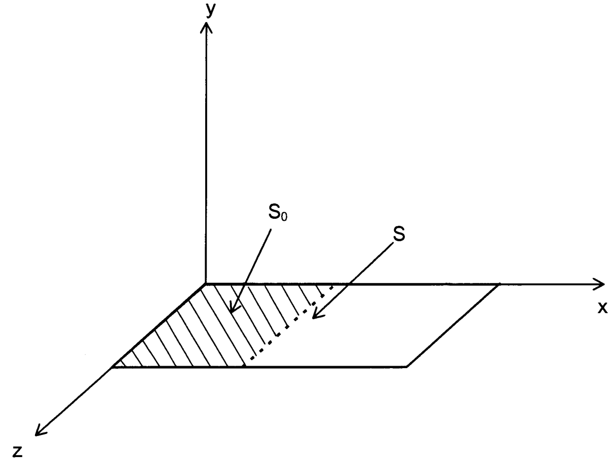


Fig. 2.8 Increase in interfacial area during planar extensional movement (after Cheng 1979).

For planar extensional flow the elongation in the *x* direction is accompanied by compression at the same rate in the y direction with no compression in the *z* direction, see Fig. 2.8. In this case the ratio of final to initial length of an elemental volume is (Cheng 1979):

$$S/S_0 = e^{\gamma_{pe}} \qquad (2.12)$$

where γ_{pe} is the strain in the *x* direction upon planar extensional movement.

If a comparison is made by the change in interfacial area produced in unidirectional shear, uniaxial elongation and planar extension, it is clear that effectiveness in generating new surface area increases in the order (Cheng 1979):

1) Unidirectional shear
2) Uniaxial elongation
3) Planar extension

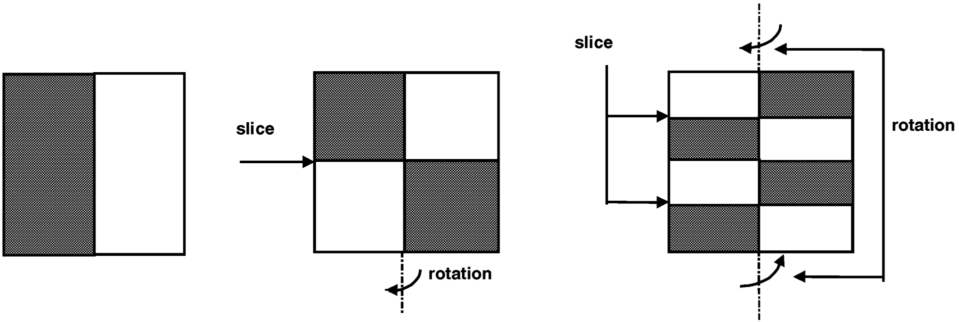


Fig. 2.9 Concept of distributive mixing by slicing and rotating (after Nienow et al. 1992).

In practical applications it is not possible to continuously elongate material: an elongational region must be followed by a compression zone. In mixing processes the material passes through different zones (Edwards 1992). If a mixer has zones of high shear or elongation, the components should pass through these zones as often as possible.

Distributive mixing

Blending by spatial redistribution due to slicing and replacing is illustrated by the idealized mechanisms shown in Fig. 2.9. The laminar flow through a unit, e.g. an in-line static mixer, produces a stream-splitting and hybridizing effect which reduces the striation thickness and increases the interfacial area between the components. This is called distributive mixing (Edwards 1992).

As Fig. 2.9 shows, the interfacial area between the two components increases and the striation thickness decreases. The mixing quality improves with each application of the mechanism. In the idealized situation shown in Fig. 2.9 the slicing and replacing mechanism is not accompanied by shearing or extension. It is advantageous for a mixing process to be designed to have zones in which the elements are subjected to shearing and extension, with the opportunity for reforming between these zones, i.e. a combination of laminar shear flow and distributive mixing.

Molecular diffusion

In high-viscosity fluids molecular diffusion is a slow process. Only when shear and strain have reduced the striation thickness to a low enough value does molecular diffusion become significant.

Solids

Solid particles range in size from fine powders to large particles varying in size, shape, density and roughness. Fine powders can be difficult to mix due to cohesive forces and coarser particles due to segregation. Mixing uniform, free-moving solids, a task intermediate between those aforementioned, is an easy matter.

The mixing of cohesive powders requires the mixture to be divided into smaller parts and each part to move freely relative to the mixture. Mixers producing high shear forces are preferable for such materials.

Three mechanisms account for the behaviour of solid particles during mixing (Perry et al. 1984):

1) Diffusion: random movements on a small scale. Individual particles move separately

2) Convection: random movements on a large scale. Lumps or groups of particles move together

3) Shearing

2.6 DISPERSION OF FINE PARTICLES IN A LIQUID

When fine solid particles are added to a liquid it is normally necessary to break down lumps of particles which are held together by either strong or weak internal forces. Suspensions are usually highly viscous and have non-Newtonian flow characteristics. The lumps are broken down by means of the shear stresses that are applied to the fluid.

A number of problems arise in connection with the dispersion of solid particles in a liquid when the particles are not adequately wetted, when air is entrained in the fluid, when agglomerates are difficult to break down, and when flocculation occurs.

A detailed analysis of the stress fields in dispersive mixing is very complex (Parfitt & Barnes 1992). The flow can involve zones of high shear and probably elongation alongside zones in which redistribution can take place. Although elongation is more effective, equipment which delivers high shear forces is easier to design.

Solid particles must pass through four states during conversion into a dispersion (Parfitt & Barnes 1992). The particles must be incorporated, the particle surface wetted, agglomerates broken down, and the particles stabilized against flocculation.

Incorporation

To obtain good mixing results with short mixing times it is important that incorporation takes place so that the incorporated powder is distributed evenly throughout the volume. This is particularly important when incorporating powders in materials having viscoelastic properties, high yield stress, and high viscosity, since it is difficult and time-consuming to disperse the material in the mixture during the distribution phase. Viscoelastic materials have high resistance to deformation and hence to movement. Good distribution of the binding agent means that the scale of segregation (see Chapter 4) is reduced at an early stage of the dispersion process.

Particles may be primary particles, aggregates or agglomerates. Aggregates are groups of primary particles joined at their faces and having a surface area less than the sum of the areas of their constituent particles. A collection of primary particles and aggregates which are joined at edges and corners is called an agglomerate. Its surface area is not much less than the sum of the areas of its constituents (Parfitt & Barnes 1992).

Interparticulate forces exist in dry powders. Van der Waals' forces are normally attractive and generally greater than electrostatic forces. At relatively high moisture contents a film forms which produces an attractive force between particles in contact. Larger amounts of water between the particles result in the formation of interparticulate water bridges which increase cohesion (Parfitt & Barnes 1992). The magnitude of the strongest forces, van der Waals' forces and gravitation, can be estimated. In general, the smaller the particles the greater is the effect of interparticulate forces.

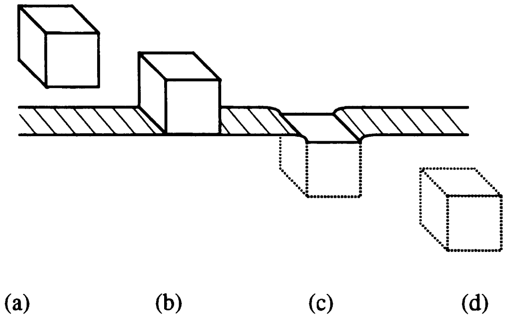


Fig. 2.10 Three stages of the wetting process: (a) to (b) adhesion; (b) to (c) immersion; (c) to (d) spreading (after Parfitt & Barnes 1992).

Wetting

When a powder is mixed with a liquid, the lumps of powder contain enclosed air which must be replaced with liquid (McDonagh & Heywood 1986). The liquid first engulfs the small particles, then the larger ones. Larger aggregates can also be engulfed by the liquid. The liquid will penetrate voids or pores in an engulfed agglomerate, but at a slower rate than the engulfing process. At a certain degree of penetration the bulk density of the agglomerate becomes greater than that of the medium, causing the agglomerate to detach. If liquid penetrates an agglomerate from all sides, the air pressure in the pores will increase until the agglomerate is disrupted. The characteristics of the wetting process are dependent on the properties of the liquid phase, the character of the surface, the dimension of the interstices in the agglomerates, and the pressure exerted on the components by the mechanical system.

Fig. 2.10 shows a small cube being immersed in a liquid. The wetting process takes place in three stages: adhesion, immersion and spreading (Parfitt & Barnes 1992).

No mechanical mixing is required during the wetting process if (1) the density of the powder is greater than that of the liquid, (2) the liquid wets the powder, and (3) the powder is not strongly agglomerated. The powder immerses in the liquid, the pores fill with liquid, and lumps fall apart releasing the enclosed air. If all these three conditions are not fulfilled, the wetting process must be assisted by mechanical mixing. Even with mechanical assistance, it is particularly difficult to release enclosed air when mixing a high-viscosity liquid. One way to avoid enclosed air is to premix the powder with a liquid of lower viscosity.

Breakdown of agglomerates

When the powder has been incorporated in the liquid and wetted or partially wetted, the next stage is to break down the remaining agglomerates by mechanical mixing (Parfitt & Barnes 1992). The disagglomeration is brought about by shearing, grinding, or impact. Disruption by shear relies on viscous drag. The shear force on a particle is directly related to the mean viscosity of the mixture. High shear stresses for this purpose can be achieved in e.g. roller mills or twin screw presses. High shear rate and high viscosity of the liquid are advantageous for achieving high shear. It may be remarked that it takes a great deal of energy to achieve high shear rates in a high-viscosity liquid. In viscous liquids where no mass transfer occurs between the solid and liquid phases the scale of segregation (see Chapter 4.4) is of great importance. When the scale of segregation has reached a low enough level, molecular diffusion can take over to reduce the intensity of segregation.

Depending on the rheological properties of the constituent materials and the type of mixing process, the efficiency of the dispersion process while agglomerates are being broken down is controlled by two mechanisms:

1. The effective strain and number of revolutions of the mixing tool or the number of circulations of the material
2. The shear rate, the intensity of agitation

Which of these parameters has the greater influence on the dispersion process depends on a number of factors, such as the rheological properties of the mixture and the mixing mechanisms active in the mixing equipment used.

In complex mixtures, such as the suspension of solids in a liquid during a dissolution, the distribution of the dispersed phase may depend on the intensity of the agitation (Rielly et al. 1994). Thus it is the agitation conditions and not the time of mixing that is important in determining the quality of the mixture, i.e. the rotational speed of the impeller is of great importance for the mixing quality.

In the mixing of thick suspensions, according to Schofield & Stewart (1982), the efficiency of the dispersion process depends on the effective strain and the number of revolutions of the impeller. E.g. for a

Z-Blade mixer the degree of deagglomeration was independent of the shear rate (speed of rotation) and depended solely on the number of revolutions. This means that one can estimate the number of revolutions required to break down agglomerates in small-scale experiments and then use this relation for equivalent larger-scale geometries.

In concrete manufacturing, Padgett (1996) writes that shear rate has greater influence on the properties of cement slurry than the total mixing energy. Laboratory mixers were compared with field equipment by measuring free water and thickening time at the same mixing energy. The results showed that there is little correlation between the total mixing energy and the measured properties of the cement slurry. On the other hand, the amount of free water is strongly dependent on the mixing device. One of the biggest differences between the field and laboratory equipment is the shear rate of the mixing process. The reason why the shear rate is more important than the total energy input lies in the forces required to break down the agglomerates that form during the wetting of the powder.

Schofield & Stewart (1980) in the course of a study of the breakdown of pigment in thick suspensions formulated hypotheses on the influence of effective strain and intensity of agitation. According to these authors there are three mechanisms by which agglomerates are broken down. In the first, the initial agglomerate breaks up into two or more smaller agglomerates. These smaller agglomerates will break down into still smaller units if they are subjected to a shear force which exceeds their binding force. Given sufficient time for all of the agglomerates to experience sufficiently large shear forces, under favourable conditions a final degree of deagglomeration will be achieved. Thus the deagglomeration process depends on the maximum strength of the bonds within the agglomerates and on the shear stress available. If the applied shear stress, or intensity of agitation, is high enough, all the agglomerates will be broken down into their fundamental particles. Another possibility is that a number of the fundamental particles (the smallest particles which can exist individually) which make up a large agglomerate become completely dissociated. The third possibility is that the fundamental particles are rubbed off the outside of the agglomerates. Summing up Schofield and Stewart's argument, agitation must be sufficiently intense and long-lasting for the agglomerates to be broken down to the extent required. Once this has happened, improvement of mixing quality depends on the effective strain.

We currently lack theories describing the basic mechanisms relating to effective strain and agitation intensity and the influence in general of these parameters on mixing processes. It is difficult on the basis of a literature review to draw general conclusions regarding the extent to which various parameters influence different mixing processes. Hence there is no alternative to carrying out trials for each mixing process and application.

Distribution

Distribution is the process whereby the broken-down agglomerates are distributed randomly through the liquid phase. This normally takes place simultaneously with deagglomeration. If the mixing process has not been designed so that deagglomeration and distribution take place concurrently, long mixing times may be expected to be required. Thus it is important that the solid phase is distributed through the largest possible volume at the incorporation stage. The distribution process works best if the mixture has low viscosity.

Stability of dispersion

When the powder is wetted, the agglomerates broken down, the particles separated and evenly distributed through the liquid, this state must be maintained and flocculation avoided. In many mixing processes this is a difficult problem. However, if the liquid is highly viscous and the powder of low density, stability of the dispersion is not a major problem, and it is therefore not discussed further in this thesis.

3. Mixing equipment in general

3.1 INTRODUCTION

According to the state of aggregation of materials, Šterbácek & Tausk (1965) distinguish between the mixing of gases, liquids and solids. The mixing of liquids can be further divided according to their consistency into the mixing of Newtonian liquids and the mixing of pastes, i.e. non-Newtonian liquids with high solids content.

According to Šterbácek & Tausk (1965) mixing equipment can be divided into four groups:

1 equipment for mixing gases;

2 equipment for mixing mobile liquids (Newtonian liquids);

3 equipment for mixing pastes and other non-Newtonian substances;

4 equipment for mixing solid loose substances.

The wide range of mixing equipment available reflects the enormous variety of mixing duties required in the chemical, paint, food, pharmaceutical and other industries. The present chapter deals with some of the types of equipment available, mainly in the process industries, for dispersion and dissolving in liquids and for the mixing of pastes and plastic materials. The types of mixing equipment discussed in this chapter span a rather broader range than those applicable to deep mixing. Equipment types relevant to the latter application are discussed in Chapter 6.

The literature reviewed and the illustrations reproduced here were in some cases published over 30 years ago – in particular, Šterbácek & Tausk (1965). The reason is that this work contains an excellent review of the basic designs of mixing equipment. More recent literature in many cases adds nothing new, apart from the development of static mixers and special forms of e.g. propellers and turbines.

3.2 DISPERSION AND DISSOLUTION IN LIQUIDS

General

There is an enormous variety of equipment for mixing different substances with liquids. Fields of application include the chemical, food, paint and pharmaceutical industries. A rapid mixing process requires effective motion achieved by convection. The motion of the material should be sufficiently intense to generate turbulence and turbulent diffusion. Regions of high turbulence are suitable for dispersive processes. The mixing of low-viscosity liquids is dependent on (Šterbácek & Tausk 1965):

1 degree of turbulence

2 rate of circulation

Most existing impellers transmit forces and momentum to the material by shear stress, i.e. at right angles or parallel to the motion of the impeller (Šterbácek & Tausk 1965). Paddles, turbines and propellers are examples of impellers belonging to this group.

There are various ways of imparting motion to the materials being mixed depending on their rheological properties. Concentrated suspensions generally have very complex rheology and may have both elastic and yield properties. Impellers are operated at different speeds depending on the characteristics of the materials to be mixed, see Table 3.1.

Table 3.1. The applications of different impeller types depend to a great extent on the viscosity of the mixture (after Edwards & Baker 1992).

Propeller		↑
Turbine	↓	
Paddle	viscosity increases	speed increases
Anchor		↑
Helical ribbon		
Helical screw	↓	

Propellers, turbines and paddles

Propellers, turbines and paddles are generally used for mixing relatively low-viscosity liquids and are operated at high rotational speeds, but they can also be used for mixing rheologically complex materials. When they operate in a tank they are usually of a diameter 1/4 to 2/3 that of the tank.

Impellers can be distinguished according to the flow pattern they produce: tangential (paddles), radial (turbines), axial (propellers), and compound flow, see Fig. 3.1.

Predominantly tangential flow is produced by paddles with straight blades and by broad blade paddles rotating at a speed such that no radial flow is caused by centrifugal force. Radial flow is produced by turbines and purely axial flow by propellers. Compound flow occurs, for example, with paddle mixers having tilted blades.

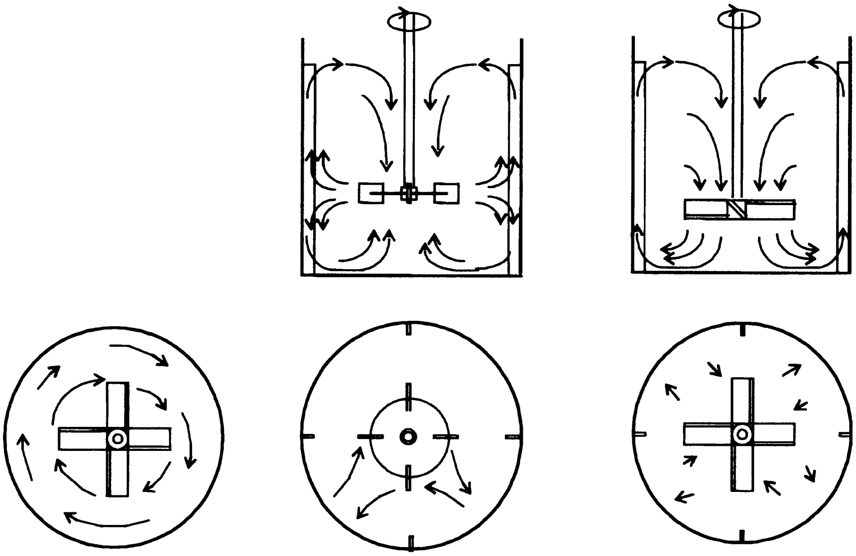


Fig. 3.1 Tangential, radial and axial flow (Štirbáèek & Tausk 1965).

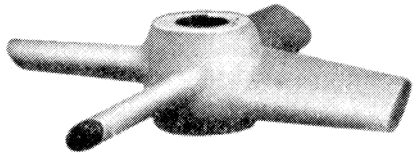


Fig. 3.2 Radial propeller mixer (Štìrbáèek & Tausk 1965).

Propellers

The commonest type of propeller is the marine type, often with three blades. Propellers work like high-speed pumps. Mixing is dependent on the motion of the fluid and hence the propeller's pumping capacity is critical.

With propellers mixing is achieved by the combination of two movements:

1. axial flow from the propeller;
2. helical turbulent flow.

Propellers can be used for mixing liquids with viscosities up to 2 Pa s (Šterbácek & Tausk 1965). They are suitable for rapid mixing, e.g. of low-viscosity emulsions. Propeller mixers are unsuitable for the suspension of heavy or rapidly settling substances and for the absorption of gases.
Radial propellers or axial turbines have a compound axial-radial flow. They consist of 4 – 16 flat or profiled blades mounted on a shaft at an angle of 10 – 25° with respect to the plane perpendicular to the axis of the shaft. Unlike ordinary propellers, the blades end in plane faces, see Fig. 3.2, which are the cause of the radial flow. These are high-speed mixers and are suitable for suspensions with viscosities up to 20 Pa s (Šterbácek & Tausk 1965).

Turbines

Turbines have vertically mounted blades and are of numerous different designs. They have been used as mixers for many years.

The turbine blades entrain and shed the fluid in a predominantly radial flow from the blades. Hence the shape of the mixing vessel is of great importance for the performance of the turbine.

The main advantage of turbine mixers is that they can be used over a wide range of viscosities and densities. There is no definite upper limit to the viscosity that can be mixed. Once turbulent flow has been achieved in the fluid ($Re > \approx 100$), viscosity is of little significance for the power consumption (Ulbrecht & Patterson 1985, Edwards et al. 1992).

The shape of turbine blades is dictated by the character of the flow and the purpose of mixing. For mobile liquids, vertical, flat blades are used. The blades may be tilted to improving pumping efficiency. When mixing high-viscosity substances it is advantageous to tilt the blades in the direction opposite to the direction of rotation. If the blades are tilted or profiled, the initial momentum will be less, which aids the transfer of energy from the blades to the fluid. Blades may be curved to reduce the flow away from the impeller and make the turbine easier to start up.

Turbines have a wide range of application including suspension, dissolving, chemical reactions, absorption of gases and heat transfer. They are less suitable, but can be used, for pastes and doughs.

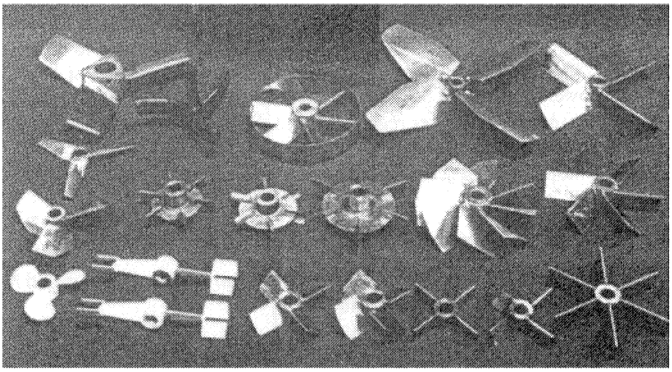


Fig. 3.3 Typical propellers, turbines and paddles (King 1992).

Paddles

Rectangular impeller arms, perpendicular or oblique to the axis of the shaft and driven by mechanical energy, fall under the heading of paddles. Paddles and turbines are distinguished from each other by the flow patterns they produce. With turbines, radial flow must dominate, with possibly some tangential flow, see Fig. 3.1.

Paddles have been known as a mixing device for a long time. Their main advantage is their simplicity and consequent low cost. Their main disadvantages are their small pumping capacity, their restriction to liquids with viscosities up to ~1 Pa s, and the limited axial flow from the blades (Šterbácek & Tausk 1965). Good blending is attained only in thin strata of liquid in the immediate vicinity of the impellers, where local eddies form on the upper and lower edge of the impeller.

When paddles are used for mixing a concentration gradient (stratification) often results in the fluid. This is a disadvantage, particularly when one of the components is added during stirring. This can be remedied by tilting the paddle blades by 30-45° to the axis of the shaft so that axial flow occurs. A combination of paddle and propeller can take the form shown in Fig. 3.4. Having the blades pitched in two directions produces both upward and downward axial flows, which is useful if circulation of the fluid is desired.

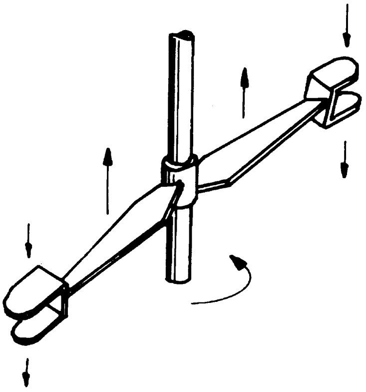


Fig. 3.4 Impeller with paddles pitched in two directions to produce circulation of the fluid. (Ulbrecht & Patterson 1985)

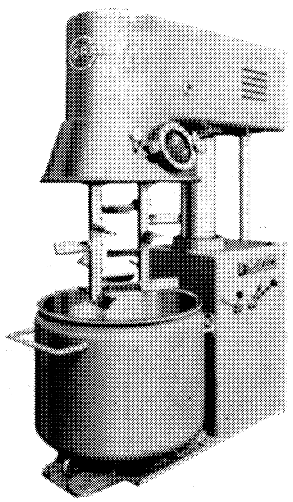


Fig. 3.5 **Mixer for pastes and suspensions. Two eccentrically arranged shafts with several paddles rotate in opposite directions. (Štìrbáèek & Tausk 1965)**

Broad paddle blades do not have these disadvantages because they generate predominantly tangential flow. These mixers are especially suitable for processes requiring uniform concentration, e.g. chemical reactions (Šterbácek & Tausk 1965). Holes may be drilled in the blades to improve shearing action. Disadvantages of broad paddles are that they are unsuitable for suspensions and for mixing viscous materials.

Since paddles predominantly act by tangential flow, problems may occur when the material and the paddle take on the same velocity gradients, i.e. the material is dragged around by the paddle without any appreciable degree of mixing taking place. This problem can be avoided by using several paddles rotating in different directions and/or at different speeds. When mixing viscous materials in vessels, the equipment may be designed as in Fig. 3.5. Two eccentrically arranged shafts, each with several paddles, rotate in opposite directions with the paddles overlapping. The fluid is thus kept in constant motion in continuously changing directions. This type of mixer places motion of the fluid ahead of high shear stresses.

Equipment for dispersing solid particles

The problems of dispersing solid particles in a liquid phase can vary greatly in difficulty and complexity. The dispersion process and its problems are described in Chapter 2.6.

There are numerous types of mixing equipment that can be used for dispersing powders in liquids, but only a few have been developed that are used specifically for dispersion (McDonagh & Heywood 1986). These categories of equipment are described briefly below.

i Vertical shaft mixers. Mixers using impellers mounted on a vertical shaft can vary widely in design and speed. Propellers, paddles, turbines etc. are used, and impellers can often be substituted and combined to obtain different mixing mechanisms at different stages of the process.

ii Horizontal shaft mixers. When mixing high-viscosity suspensions, horizontal mixers are often used to produce movement in every part of the vessel. Paddles, screws, kneaders or Z-blades may be used. Z-blades are described further in Chapter 3.3.

iii Mills. These are useful if the mixture contains agglomerates that are difficult to break down. Mills such as colloid mills, roller mills and ball mills can force the material into motion and produce high shear stresses.

iv Homogenizers. These are often used for low-viscosity materials in which there is no need for high shear stresses to break down agglomerates.

v Special powder-liquid contacting devices. A number of mixers have been developed which are specially suited for dispersion duties where the solid is difficult to wet. They can be divided into types where the liquid phase is sprayed into a falling stream of powder and types where the solid falls into thin liquid films. Both types produce a large interfacial area between the materials, thus avoiding large lumps of partially wetted particles. An example of such a mixer is shown in Fig. 3.6.

When designing or improving a dispersion process it is important to be able to describe and understand the individual stages of incorporation, wetting, disagglomeration, distribution and stabilization, see Chapter 2.6. The stages of the dispersion process may take place separately or concurrently; some may not occur at all. It is important to evaluate the role that each stage plays in each specific mixing application. Based on a description of the predominant mixing mechanisms and the difficulties of the dispersion process, effort can be focused on the most important stages of the process. Because of the generally very complex mixing processes, laboratory tests may be necessary to determine where the difficulties are (McDonagh & Heywood 1986).

Static mixers

Examples of static mixers are stationary or rotating units inserted in pipes, the components to be mixed being forced through the pipe (Godfrey 1992).

There are numerous types of static mixers and the range of applications is very wide, including both laminar and turbulent processes. Static mixers are often used to improve existing mixing processes, a static mixer being added for pre- or post-mixing.

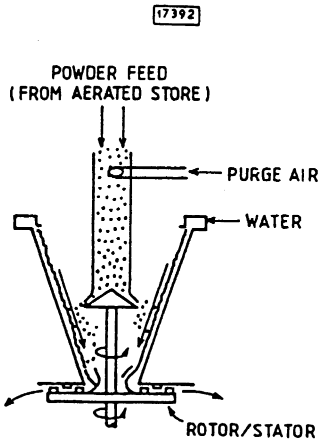


Fig. 3.6 **Wetting equipment. Powder is introduced into a fluid surface by e.g. a liquid. (McDonagh & Heywood 1986)**

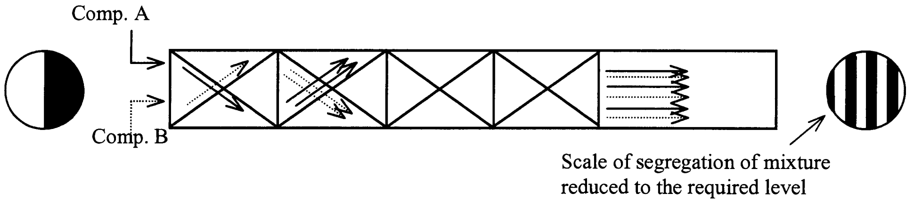


Fig. 3.7 Principle of an in-line static mixer.

The predominant mixing mechanism in laminar mixing is distributive, by splitting/slicing and folding/reorientation of the elements. This process reduces the volume of the individual regions of nonuniformity. The number of elements that are mixed depends on the difficulty of the mixing process. When dispersing solid particles in a liquid it is important that the mixer generates the shear forces required to break down agglomerates.

As with other types of mixing equipment, mixing quality is difficult to determine, making it difficult to compare different types of device.

Jet mixers

Jet mixing is employed for both gases and liquids. The principle is the same in both cases. The use of turbulent jets for mixing liquids is very common in the chemical industry.

Jet mixing is suitable for the mixing of mobile liquids, when it is generally combined with a pump. Turbulent jet mixers can give very short mixing times of seconds or less. Several nozzles may be used for more effective mixing, and the method is often combined with mechanical mixing.

The fluid discharging from a nozzle assumes the shape of a cone enlarging with the distance from the orifice, see Fig. 3.8. This is caused by the following circumstances (Šterbácek & Tausk 1965):

1. The flow of fluid displaces the fluid in the vessel in front of the orifice. The fluid adjacent to the jet is entrained into a motion parallel to the flow through the transfer of momentum from the jet to the surrounding fluid. This transfer of momentum is effected by the shear stresses between the fast-moving and the stagnant layers and by the turbulent penetration of elementary particles from the jet into the surrounding fluid. If we neglect the internal friction, the kinetic energy is constant, i.e.:

   $$\sum M_0 v_0 = \sum M_1 v_1$$

   where M_0 and v_0 are respectively the mass and the velocity of the jet stream and M_1 and v_1 are respectively the mass and the velocity of the entrained fluid. The velocity of the entrained fluid is smaller than the velocity of the stream itself, and each layer of the fluid set in motion entrains the adjacent layers. The cross section of the moving stream increases with distance from the nozzle and its velocity decreases towards the periphery of the cone.

2. As the surrounding fluid is entrained into the stream a decrease in pressure is produced in its original place. This decrease causes further fluid to be sucked into this space and likewise set in motion by momentum transfer from the jet.

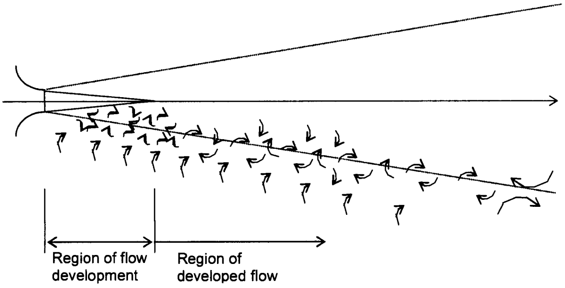


Fig. 3.8 A jet and its flow behaviour (after Štìrbáèek & Tausk 1965).

The entrainment of fluid into the moving stream results in a turbulent boundary layer at the periphery of the cone in which active mixing takes place. The thickness of this turbulent boundary layer increases proportionally to the distance from the nozzle, and this consumes some of the momentum in the core of the jet. The gradual increase in the thickness of the boundary layer leads to an enlargement of the cone and a constriction of the core, which finally disappears at a certain distance from the nozzle.

3.3 MIXING OF PASTES AND PLASTIC MATERIALS

General

There are numerous types of mixers and processes for mixing solids and pastes. The mixing of plastic materials forms a transition between liquid mixing and the mixing of solids. Commonly a mixer is versatile and can be used not only for viscous liquids or thin pastes but also for low-viscosity liquids. The same applies to certain mixers adapted for pastes which can also be used to mix solids. Thus there are no clear boundaries between different types of mixing equipment. Other mixers break down solid agglomerates in pastes and plastic masses and thus have the character of mills (Šterbácek & Tausk 1965).

Mixers for pastes and plastic materials are found especially in the chemical industry (rubber products, plastics, ceramics, drugs, soap etc.) and in the foodstuff industry.

Mixing pastes and plastic materials is considerably more difficult and complex than mixing liquids. The higher the consistency the slower is the flow of material, and hence the potential for turbulent flow is limited. Mixers are generally designed so that the impeller passes through the entire volume to be mixed, since it is difficult to produce mass flow throughout the volume.

Mixers for high-viscosity materials generally have very complex flow patterns. There are regions with high shear forces (where the material is stretched) and regions where the material is redistributed (folded). It is generally very difficult to analyse these mixing processes quantitatively in terms of idealized mixing mechanisms.

For most of the above equipment types, with the exception of mills and kneaders, the primary flow pattern is tangential, i.e. the flow follows the mixing element as it rotates about its axis. Helical mixing elements, steeply tilted paddles and propellers also generate an axial flow component, producing a helical primary flow. Centrifugal forces generated by tangential flow create a secondary, radial flow. In a viscoelastic material this secondary flow is counteracted by elastic forces.

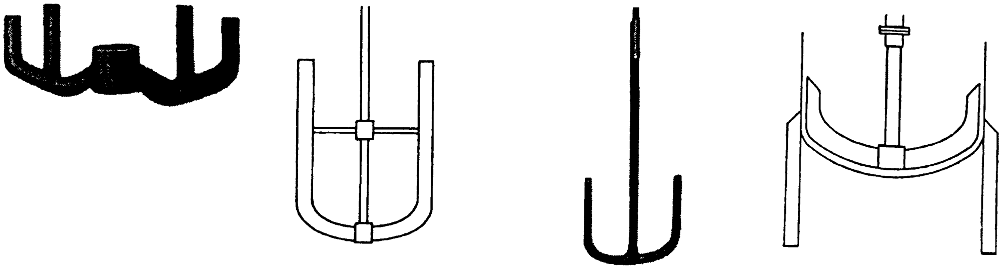


Fig. 3.9 Some typical anchor agitators. (Štìrbáèek & Tausk 1965)

Anchor agitators

The most common type of equipment for mixing pastes is paddle mixers designed so as to secure movement in mixtures of high consistency. Anchor agitators are the most common mixer of this type. The majority of these mixers have vertical arms in addition to horizontal arms to promote vertical movement of the mixture, which is difficult to transmit e.g. in plastic materials. Anchor agitators produce large circulation patterns. In general the impeller has a diameter of the same order as that of the vessel and is situated close to the bottom. Fig. 3.9 shows some typical anchor agitators for mixing in vessels.

In order to produce eddies throughout the fluid or a number of regions of shearing, the mixing elements may be formed as rakes. These are particularly suitable for mixing plastic materials. To increase the shearing action they can be provided with two sets of arms. Either both impellers may move in opposite directions or one impeller may be fixed while the other rotates. See Fig. 3.10.

Anchor agitators are particularly suited for combination with horizontal arms. One popular combination has an anchor and paddles with double motion, see Fig. 3.11. The paddles may be vertical or inclined. This combination permits the two mixers to move in opposite directions and at different speeds. This design is particularly suitable when the mixture has a relatively low initial viscosity which develops into pastes or plastic materials on account of reactions. During the first stage mixing is carried out by the paddles, and as thickening proceeds the anchor takes over.

Helical mixers

To improve circulation in a mixture helical ribbons or screws may be used. These mixers operate at a slow speed and do not generate high shear rates, relying instead on their pumping capacity to reach every part of the vessel. Helical mixers are well suited for mixing materials with high yield points and viscosities, since they produce axial and tangential movements while at the same time cutting through the material. This is an advantage when mixing materials that tend to stick to the mixer blades.

Helical impellers are considered more effective for mixing viscoelastic materials than anchor or multi-paddle impellers (e.g. Nagata et al. 1972). The reason is that when e.g. paddles rotate in a viscoelastic material the energy consumption is high in the immediate vicinity of the blades, but forces cannot propagate through the mixture because of its viscoelastic behaviour. As a result, mixing takes place near the blades, but just outside this region the mixture does not move at all. Viscoelastic behaviour is discussed in Chapter 5, Rheology.

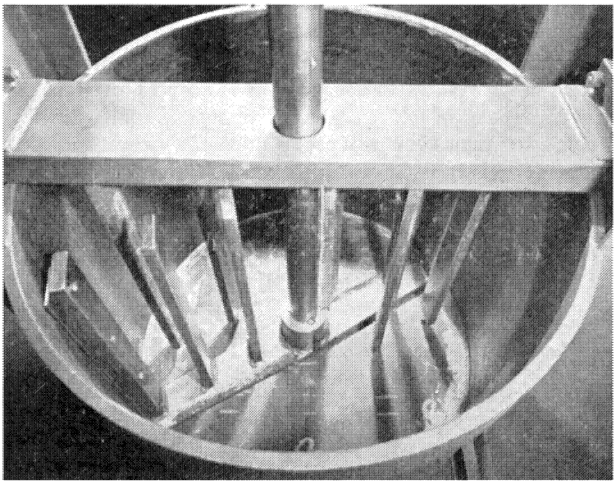


Fig. 3.10 Anchor agitator with two sets of arms, one rotating and the other stationary. (Štìrbáèek & Tausk 1965)

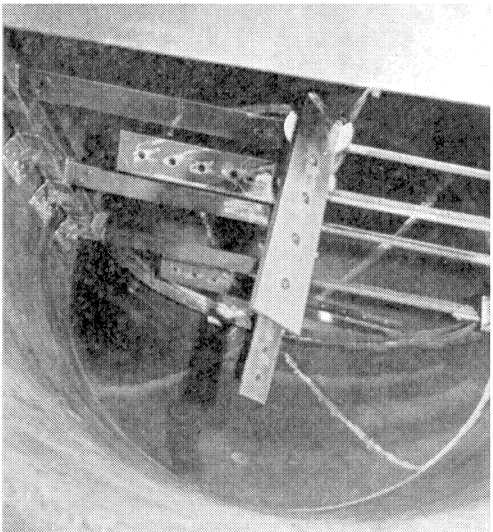


Fig. 3.11 Anchor combined with paddles. (Štìrbáèek & Tausk 1965)

Helical ribbons are particularly used in horizontal mixers where recirculation of the flow is desired. This is achieved by combining two ribbons operating in opposite directions. These mixers are particularly suitable for mixing loose solids but are also used for mixing liquids with e.g. powders. The mixing efficiency is increased by driving the material to the sides, after which it falls back into the main flow. Helical screws are used to produce strong axial flow in high-viscosity materials.

Mixers can also be designed with paddles arranged in the form of a helix. The material is forced out to the sides as well as along the tank. These mixer types are used e.g. for mixing paints (Šterbácek & Tausk 1965). Fig. 3.13 shows a mixer of this type used for mixing soil and cement for sub-grade soils.

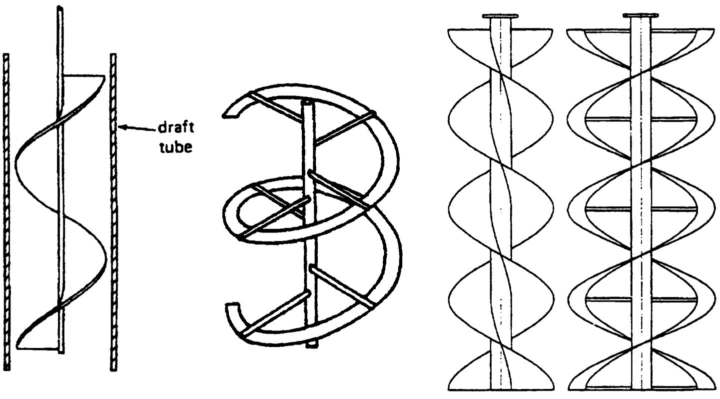


Fig. 3.12 Helical mixers (Parfitt & Barnes 1992, Silvester 1985).

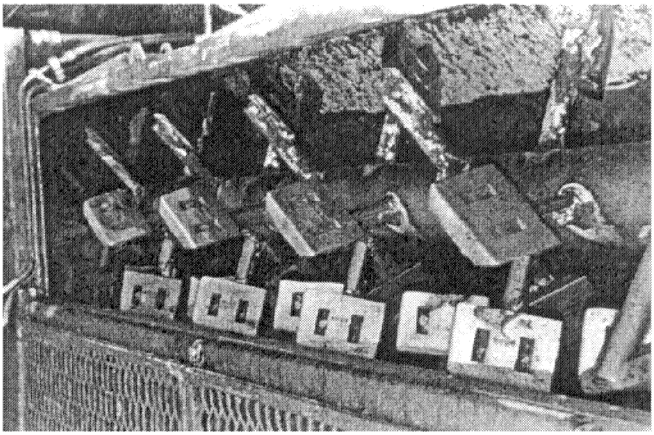


Fig. 3.13 Helical mixer with paddles for mixing soil and cement (Mueller 1991).

Kneaders

Kneaders, Z-blade and sigma-blade units are generally used for mixing high-viscosity liquids, pastes, rubbers, doughs etc. which cannot be handled by anchor impellers or helical ribbons. The clearances between the blades and between blade and vessel are small in order to produce high shear stresses in the material. The blades cut through the entire vessel volume. These mixing machines generally have the form of horizontally mounted tanks.

The mixing procedure for the dispersion of solids is usually as follows. First a part of the liquid is put in the tank. With the mixing device running, the solid components are then added with sufficient liquid to form a paste. In this first phase the liquid components are merely mixed with the solids. During the course of the kneading the agglomerates in the paste are broken down. High shear stresses occur between the blades and between the blades and the walls. It is important that the paste consistency be sufficient to generate the necessary shear stresses. High shear stresses are also necessary to aid wetting.

Two paddles may be used which rotate in opposite directions, arranged so that their paths overlap. Common shapes of paddles are shown in Fig. 3.14.

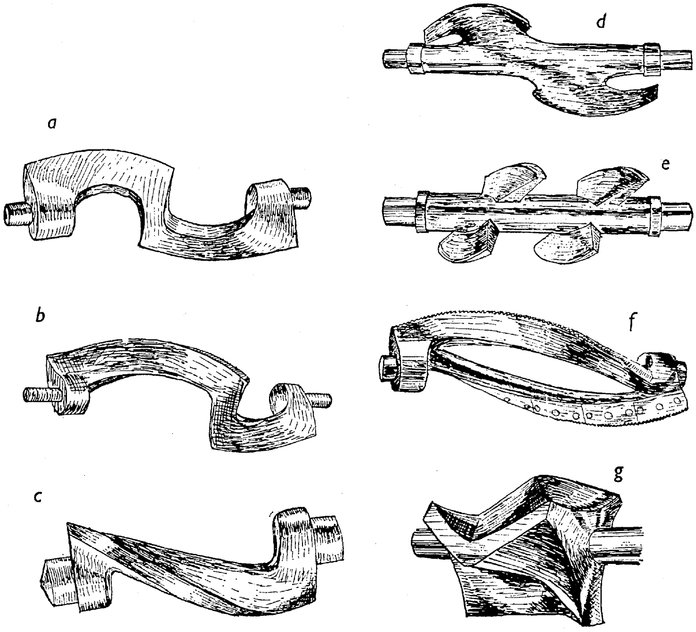


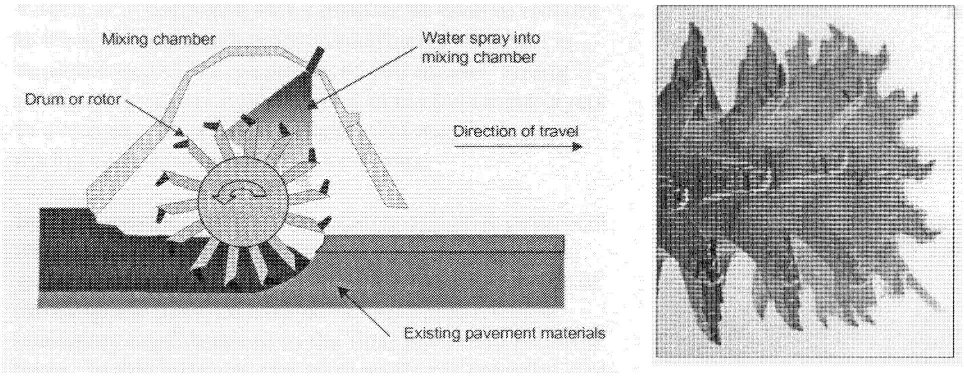
Fig. 3.14 Various types of kneaders (Štìrbáèek & Tausk 1965).
a: Mainly used in the chemical industry
b: Used for thin pastes
c: Suitable for the dispersion of paints and pigments in plastic materials and for the dispersion of water in rubber
d: Used for kneading very stiff materials in small quantities
e: Used for kneading very stiff materials in large quantities
f: Used for homogenizing fibrous materials
g: Suitable for kneading rubber

Mills

In many applications involving the dispersion of solids, conventional mixers are unable to achieve high enough shear forces in the material to break down agglomerates. This problem may arise if e.g. the components being mixed have widely differing rheological properties. Such applications may be handled by means of mills, in which dispersion is achieved by shearing and crushing of the agglomerates.

Mills are used for soil stabilizers for mixing soil and cement for sub-grade soils. A milling and mixing drum is located in a mixing chamber as shown in Figure 3.15a. The drums can also be supplied with an integrated binder spreading system in the front of the chamber (Vorobieff & Wilmot 2001). Different types of teeths is used as shown in Fig. 3.15b.

Fig. 3.16 shows the ranges of application of various types of mill and their principal mixing mechanisms, i.e. whether the solids are dispersed by crushing or shearing.



a)

b)

Fig. 3.15 **a) Mixing chamber with mixing drum (AustStab 2000b).**
b) Teeth for reclaimer/stabilizer (AustStab 2000a).

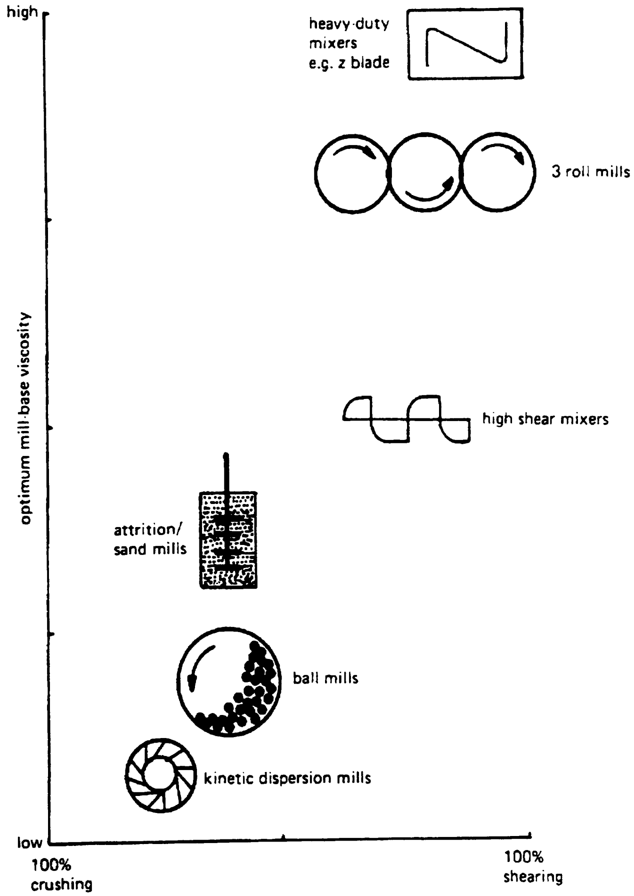


Fig. 3.16 Crushing and shearing in dispersion equipment (Edwards & Baker 1992).

4. Mixture quality

4.1 INTRODUCTION

The assessment of mixture quality is central to any investigation of mixing. The measurement of degree of mixedness or required mixing time requires the measurement of mixture quality. Similarly in the study of mixing mechanisms it is necessary to be able to describe the state of the mixture. When a mixture has some industrial application and its properties depend on how well mixed it is, the mixture quality is an essential part of the product specification (Schofield 1974).

When is a mixture well mixed? Traditionally the answer can be that a mixture is well mixed when it is good enough for its purpose. This does not generally mean that it is homogenous. On a sufficiently small scale, practically all mixtures are heterogeneous. Thus the term homogeneity is difficult to define. Numerous researchers have discussed and written on the concept of homogeneity or the perfect mixture. Poux et al. (1991) review some twenty articles on the subject. One example of a definition is offered by Fan et al. (1970), who define a homogeneous mixture as one in which the content of all constituents is uniform in every part of the mixture. The concept of homogeneity is generally unsuitable and inadequate to characterise e.g. suspensions, mixtures of solids, pastes and other complex mixtures. Indeed, it means different things in different process industries. Thus the concept is only useful when associated with a suitable scale.

Many criteria have been developed to assess mixture quality (Nienow et al. 1992). This is understandable given the very broad application of mixing processes, such as the formation of emulsions, solid dispersions, dry powder mixing etc. It is unfortunate that no universally applicable definition of mixture quality exists.

The concept of mixture quality arises in many contexts. Among the simplest to consider are mixtures of two dry solids. Here mixture quality is used to evaluate the outcome of mixing (e.g. concentration variances). Mixture quality is more difficult to define when e.g. a chemical reaction is involved. The mixing process is then often evaluated on the basis of factors, such as the product's rheology, compressive strength, colour, taste, temperature etc.

When assessing mixture quality it is necessary to distinguish between the distribution of the components in the mixture and special characteristics. Many factors are involved besides the efficiency of the mixing process. When assessing the quality of a process it is important to focus on the most important results for the product. To assess the effectiveness of the operation it may be necessary to use a number of indirect measurement methods to assess a specific result, as mixing equipment may perform several functions simultaneously, e.g. breaking up agglomerates and distributing solids.

The purpose of this chapter is to provide an overview of methods for assessing the homogeneity or degree of mixedness of a mixture. The theories are mainly taken from scientific journals dealing with the process industries. The types of mixture considered are mixtures of liquids, solids, and combinations of different phases.

Chapter 7 presents a study which evaluates mixture quality in a Swedish ground improvement project using the dry deep mixing method. In this study the dispersion of binder in the stabilized soil is considered as the basis for the evaluation of mixture quality. The concept of sufficient mixture quality for deep mixing is dicussed in Chapter 10.

4.2 DESCRIBING THE QUALITY OF A MIXTURE

Mixing is a random process in which materials are systematically distributed and rearranged (Sommer 1981). The resulting distribution of particles or components can be described statistically. Generally an expression for the degree of mixedness is intended as an indication of the variations existing in the mixture. For example, the coefficient of variation can be used as an expression for mixture quality. After a very long mixing time the concentration will be uniform throughout the entire volume.

A sample taken from a mixture can only approximately reflect the distribution of the components of the mixture. The more samples are analysed, the better the approximation will be. When the number of samples analysed is small, the error assumed in the statistical analysis will be large. This error is expressed as a confidence interval defining the bounds within which the statistical value lies. The size of the confidence interval depends on the number of samples analysed and on the statistical reliability.

An example from Rielly et al. (1994) is reproduced below to illustrate the difficulties of characterizing a mixture. Fig. 4.1 shows the difference between a non-random and a random mixture of particles. Both mixtures are divided into 36 parts or sub-volumes each containing 16 white and 16 black particles. For a mixture to be homogeneous, the composition of each sub-volume must be the same. Fig. 4.1b shows a homogeneous, non-random distribution of 50 % white and 50 % black particles. The probability of a mixing process distributing the particles in this way is very small. It is more likely that the best a mixing process can achieve is a distribution such as shown in Fig. 4.1a, where each sub-volume consists of different numbers of white and black particles. An analysis of just one sample of this mixture would give a result indicating that the white and black particles were not fully mixed. However, further random mixing would not result in any improvement.

Complete mixing could be defined as the state where all samples extracted from the mixture contain the same proportions of components, or the same properties, as the whole mixture. On this basis, the mixture in Fig. 4.1b shows the complete mixing of two components. Such a mixture is not possible to realize in practice. The mixture in Fig. 4.1a does not consist of eight white and eight black particles in every sub-volume, although the particles are randomly distributed. This example shows that it is not possible to define complete mixing without considering variations in composition or properties and the size of the sample.

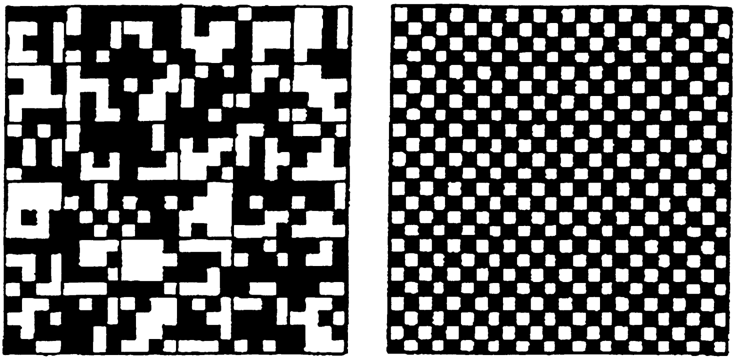


Fig. 4.1 a) Random mixture of particles. b) Non-random mixture of particles. (After Lacey 1943 and Rielly 1994)

4.3 SCALE OF SCRUTINY

The quality of a mixture depends on the scale on which it is examined (Lloyd 1981). A mixture, e.g. a suspension, may appear to be homogeneous when viewed by eye. When observed under the microscope, however, it becomes apparent that the particles are not evenly distributed. Thus the degree of homogeneity can only be determined once a suitable scale of scrutiny has been established. The appropriate scale of scrutiny itself depends on the application of the product. In mixtures where molecular diffusion is involved as a mixing mechanism, it must also be remembered that mixing may continue even though mechanical mixing has stopped. In such a process mixedness improves with time, and hence the time at which the mixture quality is assessed will influence the result. Thus the size of the samples taken from a mixture must be related to the mixing process and to the end use of the product. In practice the appropriate scale of scrutiny has to be estimated, however the concept is a useful one for defining mixture quality. An established scale of scrutiny limits the size or volume of samples to be analysed in order to assess the quality of a mixture.

The scale of scrutiny related to ground improvement by deep mixing is further discussed in Chapter 10, On the concept of sufficient mixture quality.

4.4 SCALE AND INTENSITY OF SEGREGATION

An objective definition or measurement of mixture quality must describe the distribution of the components in the mixture and how the interfacial area between the components has progressed (Schofield 1974).

Danckwerts (1952, 1953) proposed two criteria for mixing, which can be discussed qualitatively and quantitatively. The first is the scale of segregation, which is a measure of the size of unblended lumps of pure consistency and is a measure of average size. As lumps are displaced and broken down, the scale of segregation is reduced. The other criterion is intensity of segregation, which describes the effect of molecular diffusion in mixing. It is a measure of the difference in concentration between neighbouring lumps in the flow. See Fig. 4.2.

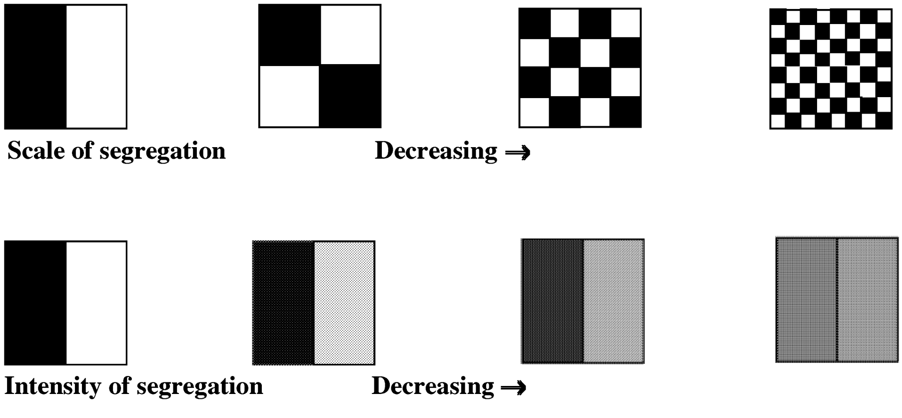


Fig. 4.2 Scale and intensity of segregation. (after Poux et al. 1991)

Consider a mixture of two liquids A and B. The concentrations of the liquids at any point are denoted by a and b respectively. The mean concentrations of the liquids in the whole mixture are $\bar{a}$ and $\bar{b}$ respectively. Thus:

$$a+b=1, \quad \bar{a}+\bar{b}=1 \tag{4.1}$$

Thus for a mixture consisting of liquid A only, the concentrations will be $a=1$ and $b=0$. The coefficient of correlation can be defined as

$$R(r)=\frac{\overline{(a_1-\bar{a})(a_2-\bar{a})}}{\overline{(a-\bar{a})^2}} \equiv \frac{\overline{(b_1-\bar{b})(b_2-\bar{b})}}{\overline{(b-\bar{b})^2}} \tag{4.2}$$

where a_1 and a_2 are the concentrations of liquid A at two points, 1 and 2, a distance r apart. The coefficient of correlation *R(r)* provides information about the average of the product of the concentration differences from the mean, at position 1 and 2. The denominators are called the variance of a (or b) and are sometimes written as σ_a^2 or σ_b^2 (which are equal). The coefficient of correlation *R(r)* normally assumes values between 0 and 1.

According to Danckwerts (1952) there are two ways of measuring the scale of segregation in a mixture, one based on distance and the other on volume. The length scale of segregation S is defined as

$$S=\int_0^\infty R(r)dr \tag{4.3}$$

The length scale of segregation S is the area under the curve *R(r)* in Fig. 4.3 (the concept is introduced in geotechnical statistics as "the scale of fluctuation" by Vanmarcke 1977, see Chapter 10). The volume scale of segregation V is defined as 2π times the area under the curve $r^2 R(r)$,

$$V=2\pi\int_0^\infty r^2R(r)dr \tag{4.4}$$

The scale of segregation is a useful concept for mixtures of coarse materials in which individual particles remain separate with no chemical bonding between them. However, the concept gives little information about the intensity of segregation. In mixtures of fine-grained materials molecular diffusion must be considered.

In order to allow for molecular diffusion in a mixture Danckwerts (1952) presented a second definition of degree of mixedness based on the concentration variance of a component of the mixture. The mean concentration and the variance of component A of a mixture are written as

$$\bar{a}=\frac{1}{n}\sum_{i=1}^{n}a_i \tag{4.5}$$

$$\sigma^2=\frac{1}{n-1}\sum_{i=1}^{n}(a_i-\bar{a})^2 \tag{4.6}$$

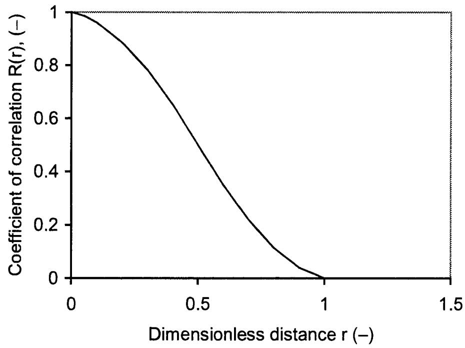


Fig. 4.3 Coefficient of correlation of a mixture. (after Danckwerts 1952)

where a_i is the concentration of A in sample i and n is the number of samples. The variance σ^2 describes the variation of the concentration of A in the mixture, but it represents only an estimate of the true variance. For a completely segregated mixture the variance is (Lacey 1943):

$$\sigma_0^2 = \bar{a}\bar{b} = \bar{a}(1-\bar{a}) \tag{4.7}$$

The intensity of segregation is defined as (Danckwerts 1952)

$$I = \frac{\sigma^2}{\sigma_0^2} = \frac{\sigma^2}{\bar{a}(1-\bar{a})} \tag{4.8}$$

According to the concept of intensity of segregation, $I = 1$ for a completely segregated mixture and $I = 0$ for a homogeneous mixture. The effects of changes in scale of segregation and in intensity of segregation are shown in Fig. 4.2. As the intensity of segregation decreases the mixture becomes more diffuse, while a decrease in the scale of segregation reduces the size of the mixed particles, making the mixture more homogeneous.

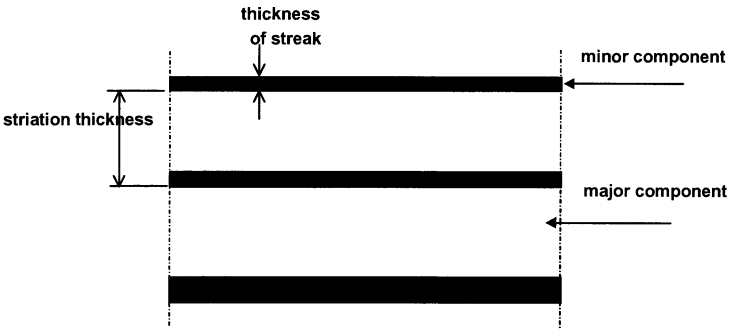


Fig. 4.4 Striation thickness as a measure of mixture quality. (Edwards 1992)

In systems involving chemical reactions, mixing on the microscopic scale is important, as otherwise the reaction will only take place on the surfaces of lumps in the mixture. In e.g. jet mixing the scale of segregation is reduced by turbulent motion, while the scale of segregation is reduced by molecular diffusion. When solid particles are added, their particle size will influence the scale of segregation and how it is reduced.

In laminar mixing of two materials the striation thickness can be a measure of mixture quality (scale of segregation) as shown in Fig. 4.4. The striation thickness can be related to the efficiency of molecular diffusion between the two materials (intensity of segregation) so as to give an idea of the requisite mixedness for the specific application.

Thus the outcome of mixing depends on the scale of scrutiny adopted. If a coarse mixture will give satisfactory results, molecular diffusion will play a minor role. Molecular diffusion is a slow process and difficult to bring about effectively in the laminar mixing of viscous media, e.g. thick suspensions.

4.5 MIXING INDICES

Based on the concepts of scale of segregation and intensity of segregation according to Danckwerts (1953), numerous mixing indices have been developed. Most mixing indices are mainly useful for the mixing of solids. Some forty different mixing indices have been tabulated by Poux et al. (1991) and comparisons between them have been made by Fan and Wang (1975), Fan et al. (1979), and Rielly et al. (1994).

Danckwerts' definition of intensity of segregation assumes that a perfect mixture has a concentration variance equal to zero. However, a small concentration variance will still exist because the number of particles in a sample taken from a mixture is finite. For a completely random (stochastic) mixture of equally sized particles the concentration variance is (Lacey 1954):

$$\sigma_R^2 = \frac{\bar{a}(1-\bar{a})}{n_p} \tag{4.9}$$

where n_p is the number of particles in each sample and $\bar{a}$ is the mean fraction of component A in the mixture.

In mixtures of any type (Poux et al. 1991)

$$\sigma^2_R > \sigma^2 > \sigma^2_0 \tag{4.10}$$

Assume that in an initial stage the binary components are completely segregated with a concentration variance σ_0^2. Lacey (1954) here defines a mixing index as

$$\begin{aligned} M &= \frac{The \quad mixing \quad that \quad has \quad occurred}{The \quad mixing \quad that \quad can \quad be \quad achieved} \\ &= \frac{\sigma_0^2 - \sigma^2}{\sigma_0^2 - \sigma_R^2} \end{aligned} \tag{4.11}$$

According to Lacey's mixing index a fully segregated mixture has a value of zero and a fully random mixture a value of one. When mixing liquids the concentration variance σ_R^2 of a fully random mixture may be assumed to be zero and we obtain a mixing index defined as (Miles 1962):

$$M = 1 - \frac{\sigma^2}{\sigma_0^2} \tag{4.12}$$

Miles' mixing index is relatively insensitive to different mixture qualities since a poorly dispersed mixture will have a concentration variance closer to σ_R^2 than to σ_0^2. That implies that this index generally lies within the range 0.75 – 1.0 regardless of the degree of dispersion. A more sensitive mixing index is defined as (Rose & Robinson 1965):

$$M = 1 - \frac{\sigma}{\sigma_0} \tag{4.13}$$

A number of similar mixing indices have been presented in the literature and are tabulated by Poux et al. (1991). Some of these are shown in Table 4.1. The common feature of these mixing indices is that they are mainly applied to mixtures of solids. The analysis is developed on the assumption that the mixture is a binary system of particles of equal size and density. Practical mixtures consist of particles that differ in size and density, which means that the concentration variance of a fully random mixture σ_R^2 will vary depending on whether the analysis is based on numbers of particles or weights of particles.

Table 4.1 Mixing indices for binary mixtures based on statistical analysis. (after Poux et al. 1991)

Author(s)	Expression	Fully segregated $\sigma = \sigma_0$	Fully mixed $\sigma = \sigma_R$
Lacey (1943)	$M = \frac{\sigma_0 - \sigma}{\sigma_0 - \sigma_R}$	0	1
Lacey (1954)	$M = \frac{\sigma_0^2 - \sigma^2}{\sigma_0^2 - \sigma_R^2}$	0	1
Miles (1962)	$M = 1 - \frac{\sigma^2}{\sigma_0^2}$	0	1
Rose & Robinson (1965)	$M = 1 - \frac{\sigma}{\sigma_0}$	0	1
Ashton & Valentin (1966)	$M = \sqrt{\frac{\ln\sigma_0^2 - \ln\sigma^2}{\ln\sigma_0^2 - \ln\sigma_R^2}}$	0	1

A number of mixing indices have been developed which are not based only on the definitions of σ, σ_0 and σ_R. Indices have also been presented which are based on experimental work. A number of such mixing indices are presented in Table 4.2.

In the context of chemical stabilization for sub-grade soils a measure of the efficiency of mixing is used (Assarsson 1972, Sherwood 1993). Samples of field-mixed stabilized soil are divided into two equal portions, where one is re-mixed in a laboratory mixer, and then preparing strength test specimens from both halves. The mixing efficiency is given by

$$Mixing \quad efficiency = \frac{Strength \quad field \quad mixed \quad material}{Strength \quad re-mixed \quad material} \times 100\% \tag{4.14}$$

Table 4.2 Mixing indices (after Poux et al. 1991).

Author(s)	Expression	Comments
Legatt (1951)	$M = \frac{\sum (x_i - \bar{x})^2}{\bar{x}}$	
Izykowski (1956)	$M = \frac{\lvert x_i - \bar{x} \rvert}{n\bar{x}}$	
Coulson & Maitra (1950)	$M = 1 - X$	X: percentage unmixed
Lastovtsev et al. (1962)	$M = \sqrt{\frac{\sum (C_i - C_0)^2 n_i}{C_0^2 (n-1)}}$	C_0 : concentration of constituents for an ideal mixture C_i : concentration of constituent i n : number of samples n_i : number of samples at concentration C_i
Adams & Baker (1956)	$\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{n-1}$	
Iinoya et al. (1985)	$M(t) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left[\frac{x_i(t)}{x_\infty} - 1 \right]^2}$	$x_i(t)$: volume fraction or concentration of specified particles detected by the ith probe at time t x_∞ : expected value in the final homogeneous mixture
Gray (1957)	$\sigma^2 = \frac{1}{N-1} \sum (I - \bar{I})^2$	I : probe meter reading $\bar{I}$: average probe meter reading.

The efficiency of mixing can also be assessed by comparing the strength of laboratory prepared samples with the strength of samples taken from the site. The efficiency of mixing is expressed as K_h (Kézdi 1979):

$$K_h = \frac{\sigma_{u,field}}{\sigma_{u,lab}} \times 100\% \tag{4.15}$$

where $\sigma_{u,field}$ is the 7-day strength of samples stabilized and compacted in the field and $\sigma_{u,lab}$ is the 7-day strength of samples stabilized and compacted in the laboratory under similar conditions. According to Baghdadi & Shihata (1999), K_h is usually in the range 60 – 80 %.

4.6 MEASUREMENT OF MIXTURE QUALITY

The theoretical methods presented in sections 4.4 and 4.5 provide a basis for assessing the homogeneity of a mixture. Such an assessment should be based on the concepts of scale and intensity of segregation or on some defined mixing index. The measurement of homogeneity requires sampling and the result is influenced by e.g. the number of samples, the sample size, the measurement method and the analytic method.

The number of samples taken from the mixture is related to the analytical method used. The fewer samples are analysed, the more uncertain will be the estimate of the homogeneity. If the number of samples is small, the confidence interval of the average can be estimated to a known probability by using the Student *t*-distribution (Johnson 1994). Published tables give the *t*-distribution as a function for the error probability. With a larger number of samples the value of *t* decreases and the permitted probability increases. However, statistical analyses of concentration variance require a relatively large number of samples. Poux et al. (1991) recommend taking 20–40 samples from a mixture to obtain correct information on the homogeneity.

Samples must be taken at different points of the mixture to give a global view of the mixing process. To provide a satisfactory view of the homogeneity, samples must therefore be taken according to an established method depending on the mixing process. Suitable sampling methods may thus vary from one mixing process to another. Harnby (1972) presented a sampling method based on random sampling which guarantees that samples will be taken from representative points of the mixture.

What is the influence of particle size on mixing quality? Poole et al. (1964) showed experimentally that particle size has an effect on the coefficient of variation of the mixture. The experiments indicated a linear relationship for a variety of mixtures. Bourne (1968) showed that the variance of a mixture depends not only on particle size but also on particle shape. However, for complex mixtures of solids in which chemical reactions take place there are no published theoretical relationships concerning the effect of particle size.

An estimate of homogeneity utilizing concepts of mixing index is based on the ability to estimate concentration variances. On the assumption that sampling errors and analytical errors are independent of each other, the concentration variance of a mixture can be written as (Yip and Hersey 1977, Orr 1979):

$$\sigma^2 = \sigma^2_{mix} + \sigma^2_{analysis} + \sigma^2_{sampling} + \sigma^2_{purity} \tag{4.16}$$

where σ^2_{mix} = the variance due to the mix
$\sigma^2_{analysis}$ = the variance due to the analytic method
$\sigma^2_{sampling}$ = the variance due to the sampling method and sample size
σ^2_{purity} = the variance due to the sample purity

The contribution of sampling method and analytic method to the total error can be substantial (Yip and Hersey 1977, Orr 1979). When studying e.g. the effect of a mixing process on homogeneity it is therefore important to be able to estimate the influence of the analytic method and the sampling method and to ensure that samples are not contaminated.

There are numerous ways of measuring homogeneity in a process. Some parameters often measured and used in the process industries to assess homogeneity and process conditions are (AIChE 1987):

- mixing time
- density
- particle size distribution
- agglomeration
- yield properties
- chemical/physical properties
- temperature
- pressure
- flow rate
- volume
- phase proportions

Mixing time is the time required for the mixture of constituents to reach a specified degree of uniformity. The mixture is then said to be mixed (Edwards 1992). The criterion is used especially in the mixing of miscible liquids. When assessing the result of mixing it is important to give careful consideration to the technique used to assess homogeneity. Often the mixing time is given by the process (e.g. a retrieval rate of a given number of mm/revolution in deep mixing) and it can be highly subjective. A mixing time is only meaningful if the mixture quality achieved at the end of the process is well-defined.

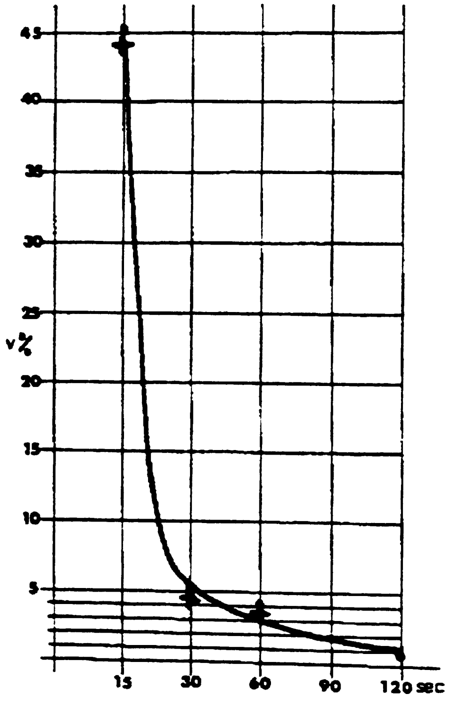


Fig. 4.5
The coefficient of variation as a function of mixing time for one test point in a mixing process (after Ries 1978).

Because of the difficulty of measuring and estimating the scale of segregation in the mixing of liquids, it is common to use very simple statistics, comparing the concentration variance at a number of points with the mean (reference value). One way is to measure the concentration of e.g. a tracer material and study e.g. the change in the coefficient of variation over time, Fig. 4.5. Practical mixing times can be measured by a number of techniques, e.g. acid-base indicators, variations in electrical conductivity, temperature variations and light absorption techniques (AIChE 1979, Edwards et al. 1992).

Mixer performance is difficult to characterize because a mixer often performs several functions simultaneously. Mixers are generally assessed on the basis of the finished product, often for reasons of practicality. Numerous criteria are used to define a well-mixed product or a state of uniform dispersion, and often they have no direct relation to the distribution of concentration or phase proportions in the mixture. Practical methods for measuring the scale and intensity of segregation of well-mixed samples are not part of ordinary routine analysis. Too often the mixing process is assessed on the basis of properties of the product which are dependent on other factors besides the efficiency of mixing. An example of this is the practice of assessing degree of mixedness on the basis of strength parameters.

In e.g. mixtures of viscoelastic materials, concentrated suspensions, mixtures of complex substances, and/or mixtures involving relatively rapid chemical reactions, it may be difficult to measure properties during the actual mixing process.

A commonly used way of assessing a mixing process is to investigate the energy input per unit volume. In viscous fluids the viscosity and rotation speed have little effect on the number of revolutions per unit volume required in order to achieve mixing (Godfrey 1985). Godfrey writes that the mixing process depends only on the number of revolutions of the impeller. The relationship between mixture quality and mixing time is linear. Homogeneity is independent of the viscosity, but it can be reduced by either pseudoplastic or viscoelastic behaviour. According to Godfrey (1985), both power consumption and mixing time are important for homogeneity. The energy required to achieve a specified homogeneity can be expressed as a product of power consumption and mixing time as follows (Lindley 1991b):

$$E_w = P_0 \times t_m \qquad (4.17)$$

where: E_w = total energy, Nm
P_0 = power input, W
t_m = mixing time, s

In mixing processes where the properties of the product are a function of the energy input per unit volume it is important to carry out small-scale trials with similar geometry and thus study the mixing process to scale.

When studying mixing results the documentation of conditions is important. Apparently minor factors can have major effects, e.g. the measuring apparatus used and where it is located. Measurements of mixing result should show data of following types (AIChE 1979):

- operating conditions
- description of equipment
- miscellaneous equipment performance characteristics
- feed characteristics
- product characteristics
- pressure, temperature, flow, and rotational speed data
- power data

In order to permit the development of methods for the measurement and analysis of the homogeneity of a mixture, it is important that all practical trials are very carefully documented. A study of the development of mixing indices and of methods for the measurement of various parameters in the process industries shows the importance of studies being published and discussed. The present literature review shows the amount of work and time that lies behind the knowledge available in the process industries. Thus it is important that a forum for discussion (written and open to scrutiny) be set up in the near future for the purpose of building up a system of suitable criteria for mixing and reliable measurement methods for estimating the state of a mixture.

5. Rheology

5.1 INTRODUCTION

In all processes in which different materials are being mixed it is important to know or at least have a good idea of the rheological behaviour of the input materials as a basic prerequisite to an understanding of the mixing process. There is a very wide range of processes, and they vary in the degree of precision with which the rheological data of the feed must to be specified in order for the product to meet specifications. In some processes the inputs must have the exact rheological properties for e.g. a chemical reaction to take place or for the correct circulation patterns to occur. In other processes it may be sufficient for e.g. the viscosity to be below a certain limit in order to guarantee circulation or turbulent flow.

With knowledge of the rheological properties of the inputs to a mixing process we can determine what mixing mechanisms are necessary in order for the product to have the desired properties. Knowing the required mixing mechanisms, suitable mixing processes can be determined. The rheology of the materials is thus the starting-point for all mixing process design.

Soft clays present engineering challenges because of the variation in their composition and properties. It is very difficult to determine the rheological behaviour of a clay e.g. in deep mixing. The mere fact that the geology and the water content can vary within the same locality makes the rheological behaviour of the soil during the mixing process difficult to predict. The present chapter reviews some of the available knowledge of the rheology of clays in an approach to a better understanding of mixing mechanisms in deep mixing.

Our knowledge of the rheological properties of suspensions consisting of combinations of clay, water, air, lime and cement is very limited. This is partly because these rheological properties are not studied and measured as part of the routine laboratory tests carried out ahead of deep mixing. The method in use today in Sweden (SGF 2000) for laboratory mixing of soil offers no way of investigating its rheological behaviour during the mixing process. Since the equipment associated with this method is invariably used in R&D projects, the result is that the rheology is very poorly known. Another reason is that it is difficult to make quantitative measurements of rheological properties with the technology and the equipment available today. These problems will be discussed in the present chapter.

5.2 RHEOLOGICAL PROPERTIES

Viscoelasticity

Clays are heterogeneous materials consisting of elastic and brittle solid components separated by surfaces of discontinuity from the liquid and air which occupies the void spaces. Clay has very complex rheological properties which are influenced by (Gillott 1987):

1. the physical properties of the water in close proximity to mineral surfaces, the amount of water and the compositions of the solutions present;
2. the extent of aggregation and cementation of the minerals;
3. the nature of the minerals;
4. the arrangement and packing density of the minerals;
5. mechanical, physical and chemical interaction of the minerals with each other and with entrapped pore solutions and air.

An ideal plastic material stressed beyond its yield value undergoes continuous and permanent deformation. Above a certain water content clays show plastic properties, while dry clays show little or no plasticity (Gillott 1987). The plasticity of a clay is affected by its mineralogical composition, the nature of the ions exchanged, the crystalline size, the size distribution of the minerals, the amount of water, and the geological history of the clay. In soil mechanics a plasticity index is used to describe the range of water content over which plastic properties are observed, Fig. 5.1.

All clay soils show time-dependent mechanical behaviour which may be described as viscoelastic (e.g. Hvorslev 1960, Adeyeri et al. 1970). When a viscoelastic material is subjected to mechanical stress, part of the energy is stored as elastic energy and the remainder is released as viscous energy, i.e. heat. The release of the latter energy results in permanent deformation, while the stored energy can contribute to damping and partial recovery from the deformation. A viscoelastic material thus possesses both elastic (Hooke's law) and viscous (Newton's law) properties. The simplest case can be described by the following relationship (Meyer 1874):

$$\dot{\gamma} = \underbrace{\frac{\dot{\tau}}{G}}_{\text{(Hooke's law)}} + \underbrace{\frac{\tau}{\mu_0}}_{\text{(Newton's law)}} \qquad (5.1)$$

where $\dot{\gamma}$ = shear rate ($d\gamma / dt$), s^{-1}

τ = shear stress, Pa

$\dot{\tau}$ = derivative of shear stress ($d\tau / dt$), Pa s^{-1}

G = shear modulus, Pa

μ_0 = viscosity at $\dot{\gamma} = 0$, Pa s

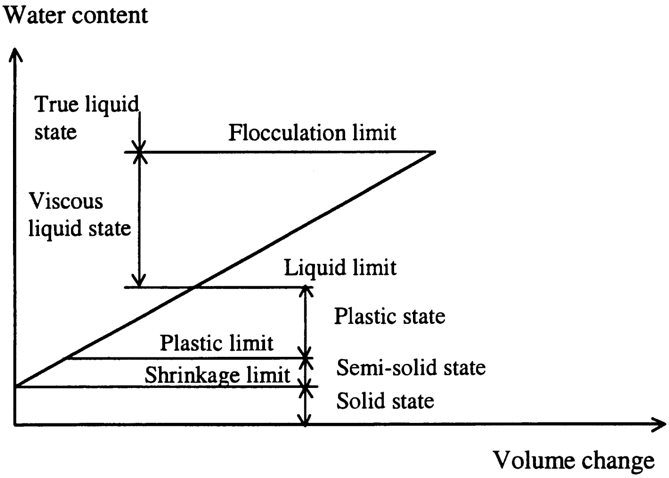


Fig. 5.1 **Relation between water content and volume change of a clay mineral (after Gillott 1987).**

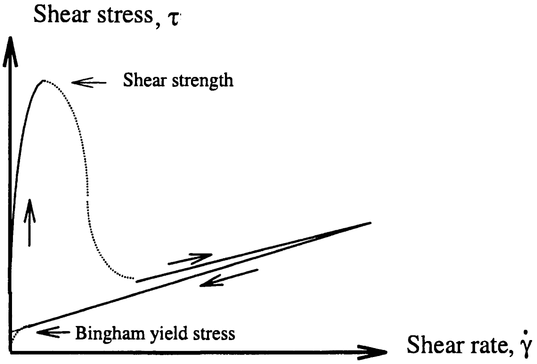


Fig: 5.2 **Schematic representation of structural breakdown of a viscoelasto-plastic material subjected to gradually increasing shear stress (after Walters 1980).**

Fig. 5.2 shows schematically the behaviour of an undisturbed viscoelasto-plastic material subjected to gradually increasing shear stress. Initially, structural breakdown competes with remoulding (Walters 1980, Nakajima 1994). The material deforms at an increasing rate as the stress increases. At the maximum stress the material can no longer be remoulded. The structure is so degraded that further deformation proceeds at an increasing rate even at low stresses. The properties of the material become increasingly liquid-like. The maximum shear stress in the figure corresponds well to the shear strength measured by e.g. a penetrometer or compression test.

Under laminar shearing the viscosity of a clay slurry is reduced due to the clay particles assuming a more parallel orientation (Gillott 1987). The release of entrapped water from the pores assists the structural breakdown under shearing. On the other hand, shearing reduces the size of the structures, which can increase collisions between the particles. In some systems this can have a dominating effect on the viscosity.

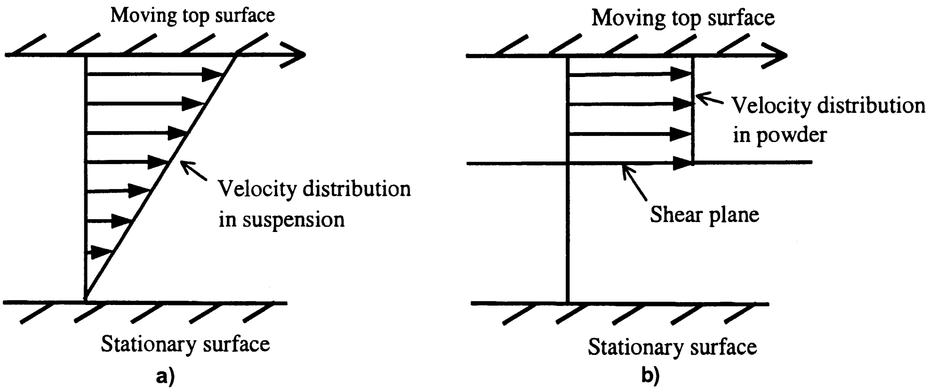


Fig. 5.3 **Velocity profile in shearing of: (a) a dilute suspension; and (b) a dry powder (after Heywood & McDonagh 1987).**

Granulo-viscous behaviour occurs when a mineral with high particle concentration has both solid and viscous flow properties (Cheng & Richmond 1978). Under shearing, viscous behaviour is described by a shear stress-shear rate relationship. This is independent of the normal stress unless the pressure is extremely high. Viscous materials are normally taken to be incompressible. Dry solids are characterized by the shear stress being dependent on normal stress and bulk density and independent of shear rate. They are further characterized by compressibility. Under shear a material having only viscous properties shows a continuous shear rate profile, while shearing of a dry powder results in a shear plane of only a few particles' thickness, see Fig. 5.3. The shear strength of a material with a high particle concentration can be expected to be dependent on both the shear rate and the normal stress. Under shear the shear rate profile may show numerous fluctuations. In practical terms this means that in e.g. thick suspensions, the transfer of force from an impeller is inhibited and it is difficult to produce the movements of materials that are necessary in order for mixing to occur (Nagata et al. 1972).

The development of slip planes and slip surfaces is also characteristic of clays undergoing rapid shearing motion. Fig. 5.4 shows the laminar shear mixing mechanism operating in a dense suspension, e.g. a clay. The figure shows the velocity distribution in the material with the top surface in motion while the bottom surface is stationary. Relative movement within the material, the precondition for mixing, takes place only at the slip surface itself and within a very restricted volume immediately above it. Above this volume the material moves as a rigid body, while below the slip surface no movement at all takes place.

Although in practice the movements and the mixing mechanisms around an impeller are more complicated than indicated in Fig. 5.4, the figure does explain why it is so difficult to produce movement in soil when mixing it with a binding agent: a mixing tool rotating in the soil only causes movement in the immediate vicinity of the blades. Because of the viscoelastic properties of the soil, forces and movement cannot propagate away from the impeller.

A slip surface can also develop close to the moving surface. This phenomenon occurs when the top surface is smooth or slippery. Influencing factors include the type of material, the particle size, the geometry, the velocity, the shear stresses acting on the surface, the particle concentration, the yield stress and the viscosity. In loosely consolidated soils in a plastic state the risk of slip is significant.

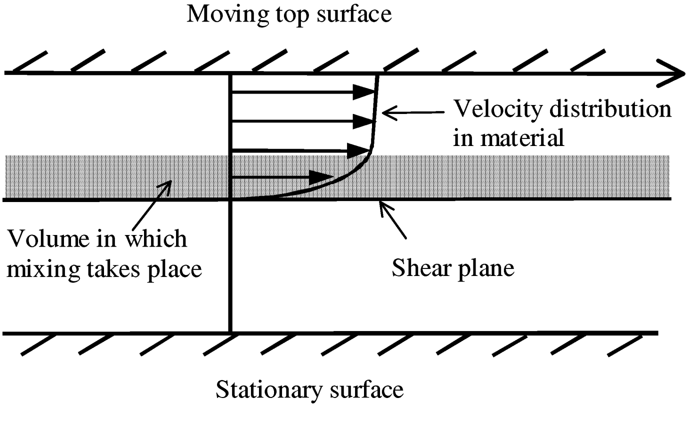


Fig. 5.4 **Laminar shear of a yield stress material with high concentration of solid particles.**

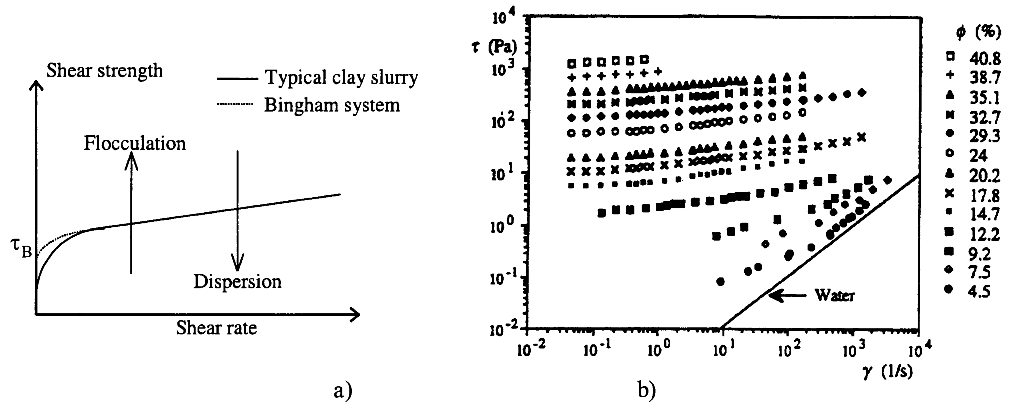
The theory of viscoelasticity is a well-established science, and there are numerous monographs which summarize the field and describe the properties of various materials (among them Drozdov 1998, Haddad 1995, Lakes 1998, Tschoegl 1989). A very extensive review of the properties of clays, rheological models and applications to engineering geology is that by Gillott (1987). Coussot (1997) has written a monograph which sums up present-day knowledge of the rheology of clay slurries with application to earth flows.

Factors affecting rheological behaviour

Even when a clay is dispersed to the point where it behaves as a liquid, it can still be difficult to set it in motion. The material will still have a yield stress which must be exceeded before movement can take place, Fig. 5.4.

Both hydrodynamic forces and non-hydrodynamic forces, such as the London-van der Waals forces, act in a suspension (Giesekus 1983). Non-hydrodynamic interactions take place between neighbouring particles as well as between particles and the liquid phase. At higher particle concentrations the non-hydrodynamic forces tend to take over and the behaviour of the suspension becomes non-Newtonian. The suspension has a yield stress which gives it the properties of a solid as long as the stresses in the material do not exceed the yield stress.

In a completely dispersed state and at high water contents, clay slurries may be regarded as having Bingham type flow behaviour (Nickel 1976; Locat 1992). Above the Bingham yield stress τ_B the shear rate increases rapidly with increasing shear stress, see Fig. 5.5. In clay slurries the strength of the interparticle bonds, the particles' mutual orientation and structure (Fig. 5.4), and the equilibrium particle spacing will be functions of the van der Waals-London forces and of the strength and thickness of the electric double layers on the edges and faces of the clay particles. These in turn are determined by the mineral type, the ionic properties and the concentration of electrolytes in the system (Nickel 1976). In most clay slurries the yield stress depends strongly on the clay concentration. It also depends on the electrolyte concentration, but this dependence varies in different slurries. An example of shear stress as a function of shear rate and particle concentration is shown in Fig. 5.5b.



a) b)

Fig. 5.5 a) Relation between shear stress and shear gradient for a Bingham system and a typical clay slurry (after Nickel 1976).
b) Flow curves for kaolin slurries with different particle concentrations f (Coussot 1997).

Clays show a wide range of shearing resistance depending on the water content. When the water content is high, clays behave as fluid suspensions, even though the interactions between the particles, ions and molecules in the suspension make the properties of clay unusual. Lower water content gives a higher consistency. The non-viscous behaviour of clays at water contents below the yield limit can be attributed to the interlocking of the clay minerals at contact faces (Allam & Sridharan 1984). In laboratory investigations of clay rheology it has been found that movement in the clay slurry decreases as water content decreases (Torrance 1986), i.e. the failure zone is limited to a part of the expected cross-sectional area.

Komamura & Huang (1974) studied the yield properties of clay soils with water contents both below and above the yield limit. They showed that the viscosity of a clay can decrease dramatically as the water content increases beyond the yield limit. This is attributed to an abrupt structural change at the yield limit. A sensitive soil rapidly loses shear strength when it undergoes movement, and the movement takes place at slip surfaces.

At the genesis of a clay the arrangement of the clay particles is assumed to be relatively open and loose packed. Changes over time render the open fabric out of equilibrium. However, the particles still cohere due to cementation, electrochemical bonding, pressure and interlocking caused by the mutual interference of particles which prevents free rotation. When the clay is disturbed or remoulded, the particles assume a more close-packed configuration which is closer to equilibrium with prevailing conditions. Since the water content is constant, the deposit becomes oversaturated and may flow like a viscous liquid (Gillott 1987).

Changes in pH have direct effects on the state of flocculation and the solubility of the mineral components (Bentley 1979). However, the influence of pH changes on rheology is small compared to that of the water content of the slurry.

Fig. 5.6 shows in principle how the viscosity of fluids is affected by different particle concentrations and shapes. Particle size and shape has a major effect on the rheological behaviour of a suspension. A system will normally contain particles of many different sizes and hence the particle size distribution plays a role. In addition, the particle size distribution can change over time, making the rheology of the process extremely complicated. For a given solids content there are certain optimal particle size distributions that give minimum and maximum viscosities.

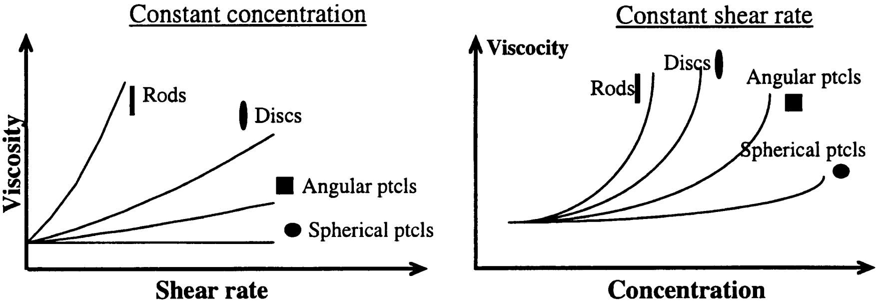


Fig. 5.6 **Effect of particle concentration and particle shape on rheological properties (after Mork 1994).**

Fine particles have a greater specific surface than coarse particles. Since the chemical reactions that take place on stabilization with lime and cement are largely surface reactions with clay minerals and water, this fact can have an influence on the outcome of stabilization. However, because molecular diffusion is a slow process it is very important that the solid particles are completely dispersed in the mixture.

In a range of applications additives, usually reactive chemicals, are used to change the rheological properties in order to make mixing processes and mixture handling easier or more efficient. Examples of such applications are rubber mixing (Grossman 1997), concrete manufacturing (Betonghandbok 1994), and industries in which materials are mixed in powder form (Kaye 1997).

When mixing binding agents with soft soils, additives may be used e.g. to disperse the soil so as to avoid aggregation. This gives the soil a fluid character. Aggregating additives may be used to produce a more granular structure with a lower yield stress. The choice of additives depends on a number of factors, but the main objective is to avoid plasticity of the mixture.

5.3 MEASUREMENT OF RHEOLOGICAL PROPERTIES

Quantitative measurements of the rheological properties of mixtures are a natural part of quality control, the development of mixing equipment, and research and development on the composition of materials for industrial applications in the process industries (Walters 1980). Rheological measurement methods have contributed to the development of injecting agents and concrete types (e.g. Håkansson 1993, Mork 1994). With regard to the rheology of soft soils there is a great deal of (geotechnical) literature describing the rheological behaviour of undisturbed sensitive clays, particularly at slow deformation rates. However, no studies have been published on the rheological behaviour of soft soils in the undisturbed or partially remoulded state at high shear rates.

According to Mork (1994), suspensions can be divided into three regions, see Table 5.1. Rheological properties within each region are measured with the instruments indicated in Table 5.2.

Table 5.1 Overview of particle systems (after Mork 1994).

Region I	Suspensions of low to medium concentration May be regarded as pseudo-homogeneous
Region II	Yield properties controlled by packing effects May exhibit granulo-viscous properties
Region III	Unsaturated, compressible three-phase materials Viscometers and rheometers often not usable

Table 5.2 Instruments used for different regions (after Mork 1994).

	Rheology	Geotechnics
Region	I + II	III (II)
Instruments used	Viscometer Rheometer	(1) Shear box (2) Shear cell (3) Triaxial compression apparatus

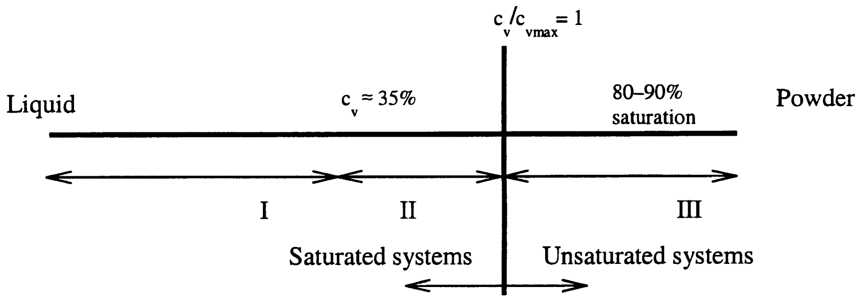


Fig. 5.7 Classification of systems based on particle concentration cv (after Mork 1994).

Fig. 5.7 shows how systems transition from pure liquid systems to powder systems. Cement paste and concrete systems, for example, fall within regions II and III. In region II the system may display granulo-viscous behaviour, i.e. the suspension may behave as a mixture of powder and water, leading to problems in the investigation of its rheological properties.

In order to study the rheological properties of systems in region III the usual instruments are the triaxial compression apparatus, the shear box etc. In rapid deformation events, slip surfaces form due to the material's viscoelastic properties e.g. as shown in Fig. 5.4.

Clay suspensions have particle concentrations that usually place them in region II or III in Fig. 5.7. They show non-Newtonian flow behaviour in general. Clays with water contents above the yield limit and in a completely remoulded state can be studied with rheological instruments such as rheometers. However, it is uncertain whether data from such tests agree with the behaviour of clays under natural conditions.

The rheological properties of sensitive clays have been studied by Canadian researchers (Locat & Demers 1988, Locat 1992, Coussot 1997). This research was done in conjunction with studies of remoulded material after major landslides. The velocity of landslides may be in the order of 10–20 m/s. Laboratory rheological tests were carried out in order to describe the relation between the index parameters of soils and their flow properties. The tests reveal very interesting relations between viscosity, yield stress, remoulded strength, and liquidity index. These relations are restricted to clay soils with water contents above the liquid limit (liquidity index >1). The relations can be used e.g. to evaluate the mobility of flow slides.

The formation of slip surfaces when a soft soil experiences rapid movement is one reason for the difficulty of carrying out rheological measurements. The same soil may have quite different rheological properties depending on the degree of remoulding.

5.4 RHEOLOGICAL PROPERTIES IN PARTIALLY REMOULDED STATE

The effect of complete remoulding of a clay can be described by its sensitivity. The sensitivity is defined as the ratio of the undisturbed shear strength to the shear strength in the fully remoulded state. The shear strength is determined by the unconfined compression test, the vane shear test or the fall-cone test. Nearly all normally consolidated and lightly overconsolidated clays show some sensitivity (Gillott 1987).

Söderblom (1974) proposed a new classification of quick clays. The background was that quick clays exist with different mechanical properties, i.e. they behave differently under external mechanical stress. Clays are usually termed quick clay if their sensitivity is greater than 50. Söderblom argued that clays can break down at different rates and that this fact should be taken into account in their classification.

An approximate classification of quick clays into groups was developed using a relative value called the rapidity number. Slow breakdown gives a low rapidity number and rapid breakdown a high one. To determine the rapidity number of a clay Söderblom used the Casagrande liquid limit test. A clay sample of height 40 mm and diameter 50 mm is dropped 250 times a distance of 10 mm. The sample is inspected visually and the rapidity number determined on a scale from 1 to 10, where $R_n = 1$ means that the sample is visually unaffected by the test and $R_n = 10$ means that the sample is totally liquefied. The rapidity number is thus subjectively determined and cannot be related to any soil parameter.

In an investigation of soil movements due to pile driving, Massarsch (1976) expressed the loss of shear strength after partial remoulding by a disturbance ratio. The disturbance ratio DR is defined as

$$DR = \frac{\tau_{undisturbed \quad soil}}{\tau_{partially \quad remolded \quad soil}} \qquad (5.2)$$

where $\tau_{undisturbed\, soil}$ is the undrained shear strength of the undisturbed soil and $\tau_{partially\ remoulded\ soil}$ the undrained shear strength of the clay after a certain degree of mechanical disturbance. Massarsch (1976) recommended using the disturbance ratio rather than the sensitivity in the analysis of piling problems in clay.

A further development of the concept of rapidity was presented by Tavenas et al. (1983). Research on the use of energy as a significant soil parameter (Tavenas et al. 1979) led into a study where the rapidity actually represents the energy required to remould clays. In a series of tests four different processes (two

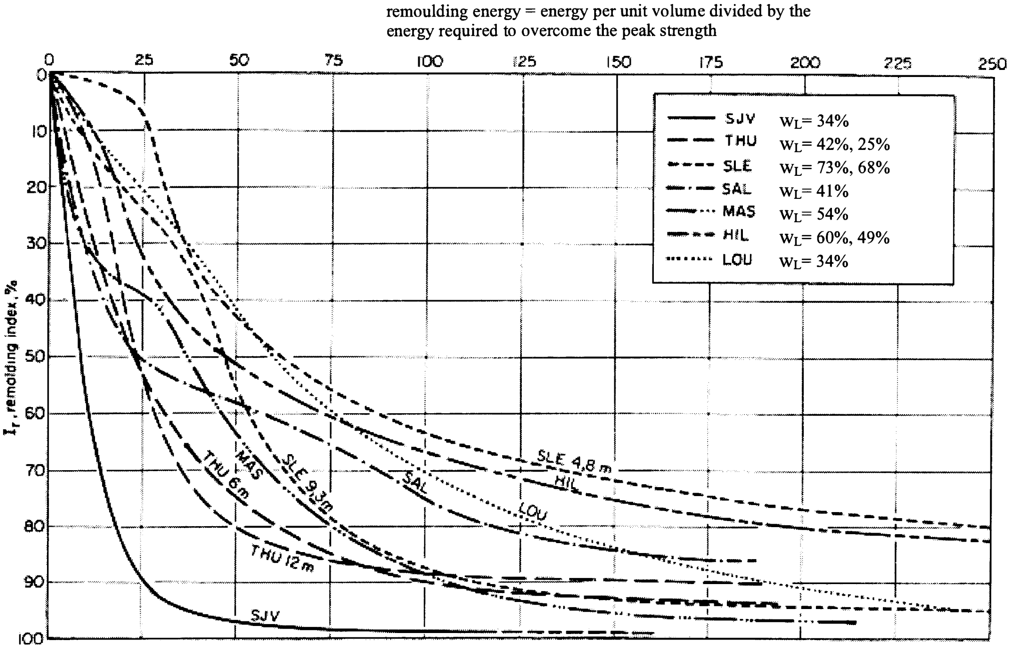


Fig. 5.9 **The relationship between the remolding energy and the remolding index for 7 tested clays (modified after Tavenas et al. 1983).**

kinds of impact processes, extrusion and shearing) was used to remould clays from Canada where landslides had occurred. In each case the energy impaired to the clay specimen was varied to investigate the relationship between the amount of energy dissipated and the resulting degree of remoulding. The degree of remoulding was expressed as a "Remoulding index" defined as

$$I_r = \frac{\tau_{undisturbed\ \ soil} - \tau_{patially\ \ remolded\ \ soil}}{\tau_{undisturbed\ \ soil} - \tau_{remolded\ \ soil}} \times 100 \tag{5.3}$$

The remoulding index I_r is equal to 0% for the intact clay and equal to 100% for completely remoulded clay. The remoulding index was evaluated with respect to fall cone tests. The remoulding energy was evaluated considering the energy required overcoming the peak strength of the undisturbed clay (the elastic part), since remoulding starts only after the initial strength of the clay has been overcome. Clays from 7 different sites were investigated. The results showed that the remoulding index is independent of liquidity index, remoulded strength or sensitivity. However, the results showed that the liquid limit seams to have an influence on the remoulding process, Fig. 5.8. The remoulding process was very variable in the different investigated clays. It took about 250 times the energy to overcome the peak strength, to achieve a remoulding index of 80% for clay with liquid limit of about 70%. The corresponding energy to achieve a remoulding index of 80% was 20-50 times the energy to overcome the peak strength, for clays with liquid limit equal to 25-35%. According to the authors, the reason why fine grained soils with a low liquid limit are easier to remould is that they contain limited amounts of clay minerals so that the interparticle bonds are of a rather brittle nature. Clays with higher liquid limits are more difficult to destroy since they contain higher amounts of clay particles and will present interparticle bonds of more plastic nature.

The disturbance ratio or the remoulding index can be used in relatively simple rheological studies of soils and their behaviour under the influence of mechanical stress, e.g. different degrees of remoulding. The effectiveness of different types of mixing tool can be studied in this way, since any significant mixing operation will increase the disturbance ratio of a soil. It is easy, for example, to carry out fall-cone tests or vane shear tests using miniature vanes in conjunction with laboratory tests in which soils are subjected to various amounts of mechanical work.

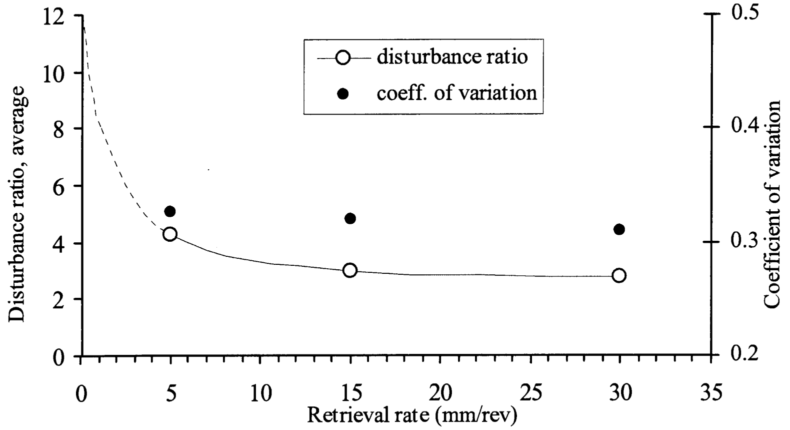


Fig. 5.9 **Disturbance ratio and coefficient of variation as functions of the retrieval rate of an impeller (author's experiments, Larsson 2000a).**

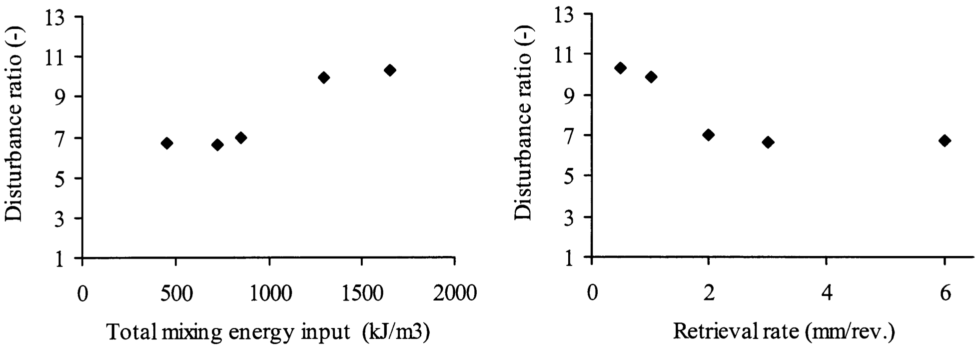


Fig. 5.10 **Disturbance ratio as a function of mixing energy input (author's experiments, Larsson et al. 1999).**

Larsson (2000a) reports, in an Appendix, a study of the effect of mixing energy on the disturbance ratio. This study comprised a series of trials in which the mixing tool was rotated in the earth at different retrieval rates without adding any binding agent. Vane shear tests were carried out on a number of column cross sections using a pocket vane of diameter 25 mm and height 50 mm in order to evaluate the disturbance ratio produced by the impeller. The trials were done on a grey, somewhat muddy clay with sulphide spots. This soil had very low rapidity, implying that it is relatively insensitive to remoulding. The results in Fig. 5.9 show that with the mixing tools currently in use for dry deep mixing in Sweden, it is difficult to break down the structure of a soil and thus change its rheological conditions during the mixing process. Notwithstanding a relatively large mixing energy, a retrieval rate of 5 mm/revolution, the disturbance ratio was only of the order of DR = 4. The disturbance ratio of a completely disrupted structure, which is equal to the sensitivity of the soil in question, is 12 – 13. According to this study, considerably greater effort is required to break down the soil structure.

The study of the influence of the mixing tool on the disturbance ratio was supplemented with laboratory trials. In the course of an investigation of the influence of the impeller on compressive strength (Larsson et al. 1999) a series of trials was carried out in which soil samples were mixed without binding agent. The study was done using the equipment and the soil reported in Walter (1998) and Larsson (2000a). The disturbance ratio was measured by the fall-cone test and can range from 1 to the value of the sensitivity of the soil, which was measured at 13. The soil studied is a sulphide clay with water content 107 %, liquid limit 100 % and fall-cone shear strength 14.7 kPa.

Fig. 5.10 shows the results of the laboratory tests, which again show that a large amount of mixing energy is required to fully break down the structure of the soil studied. However, the results show that the disturbance ratio after a relatively small amount of mixing is in the order of 7 which correspond to a remoulding index of approximately 93%.

5.5 RHEOLOGICAL PROPERTIES ON INCORPORATION OF LIME AND CEMENT

The rheology of suspensions is normally very complex. Solid particles such as lime and cement suspended in a clay slurry are a good example of a highly complex system. In dry deep mixing the rheological properties during the mixing process are also affected by chemical reactions.

There are no published scientific studies of the rheological properties of a soil while it is being mixed with cement and lime in deep mixing. Current knowledge of the rheology of such systems is empirical and all too often anecdotal in character.

We discuss below very briefly the chemical reactions that take place when soft soils are mixed with lime and with cement, and effects of the reactions on the rheological properties of the mixture.

Mixing with lime

The use of lime to stabilize soils dates back over 5000 years (Greaves 1996). The development of the surface stabilization technique took off in the 1940s in the USA, and it has since become widely used, particularly in road building. The use of lime in other foundation contexts has been described by e.g. Rogers & Glendinning (1996a), Sherwood (1993), and the British Lime Association (1990).

Numerous articles have discussed the lime-clay reaction mechanisms and changes in properties that occur on mixing lime with soil. Recent reviews of this work include Locat et al. (1990), Bell (1988), Sherwood (1993), West & Carder (1997), Janz & Johansson (2001), and Boardman et al. (2001). The reactions that occur are:

1 Hydration reaction;

2 Modification as a result of ion exchange;

3 Solidification as a result of pozzolanic reactions.

When quicklime, CaO, is mixed with a soil it absorbs moisture, forming calcium hydroxide, $Ca(OH)_2$. Since one kilogram of lime takes up 320 g of water the water content of the soil is reduced. The heat evolved by this reaction can also affect the mixing process. The dissolved calcium hydroxide is then available for ion exchange with ions in the clay minerals (Na^+, K^+, H^+). This second reaction, the ion exchange, cause flocculation and an immediate change in the plasticity of the soil and can have a major effect on rheological behaviour during the mechanical mixing stage. Depending on its initial water content, the properties of the soil may change dramatically. For fine graded soils, addition of lime generally decreases the plasticity of cohesive soils. The soils became friable and easier to work (e.g. Thompson 1968, Mateous, 1964).

When cohesive soils are mixed they do not disintegrate into elementary particles as granular materials do, but form striations or lumps whose size depends on the effectiveness of the mixing. It is well-known in surface stabilization that it is difficult to mix lime and cement with soft plastic soils (Petry & Wohlgemuth 1988). The addition of lime causes the structure to change to a more granular one. However, the immediate structural change in the lumps is confined to their surfaces (Lindh & Ydrevik 1978). The remoulded clay tends to form pellets with a surface coating of binding agent, and breaking down this structure can be difficult. A study by van Ganse (1974) showed that the initial reactions take place very quickly, within a few minutes after mixing in the case of laboratory samples. Another observation of interest from this study is that the lime–soil lumps that are formed retain their individuality to a large extent when the mixture is subjected to kneading and compaction. An aggregate-forming effect results in the soil absorbing more water, which may render mixing inefficient but can also promote compaction. The effect depends on the initial water content of the soil.

It is difficult to mix crusted clay effectively with lime. Experience from surface stabilization indicates that on mixing, the dry clay breaks up into large, hard lumps which are very difficult to pulverize (Lindh 1977). Pulverization is only possible with the addition of water. In order to obtain sufficient mixing, the mixing process can be carried out in a series of moment, as described by Krsul (1994). The binder is spread in two passes. In the first pass, half of the binder is mixed in a dry state. The rest of the binder is mixed in a second, wet mix. If the mixture has high clay content, a third mixing pass is carried out, in order to obtain a better moisture distribution.

Mixing with cement

Cement has a very positive effect on strength gain, particularly in soft soils, and its use has therefore been increasing in e.g. surface stabilization and deep mixing. The use of cement in surface stabilization is described by e.g. Sherwood 1993 and Portland Cement Association (1990).

As in the case of soil stabilization with lime, numerous articles have been published on the chemical reactions and changes in properties produced by the treatment of soil with cement. Recent reviews of this literature include Petry & Wohlgemuth (1988), Sherwood (1993) and Janz & Johansson (2001). Two main processes occur when cement is mixed with a soft soil. The primary process is hydration of the cement, causing hardening of the soil. The cement particles bind neighbouring lumps of soil together into a more or less continuous skeleton of hard material enclosing a matrix of unmodified soil. The hydration of cement results in the formation of calcium hydroxide, and the calcium ions react with the clay minerals. This secondary process also forms hardening materials.

The chemical reactions that take place on mixing cement with soil are much slower than the reactions with quicklime. It is therefore assumed that cement does not drastically alter the rheology of the system during the mixing process. However, the cement does affect the rheology inasmuch as adding a dry powder to the soil increases the particle concentration. The result thus depends very much on the effectiveness of the mixing process in disaggregating the soil and distributing the cement through it.

In surface stabilization projects in which clayey soils are to be treated with cement it is advisable to treat the soil with 1.5 – 2.5 % lime prior to cement stabilization (Cementa 1973). This is done because it is difficult to disaggregate clayey soils adequately *in-situ*. The addition of lime gives the soil a granular structure which can be more easily disaggregated with less machine effort. The drawback of this method is that it necessitates two distinct mixing steps and hence greater expense.

6. Deep mixing

6.1 INTRODUCTION

Deep mixing is a generic term for ground improvement methods in which binding agents, often lime and/or cement, are mechanically mixed with the soil. As a rule, the improved soil has better strength and deformation properties than the surrounding untreated soil. The mechanical mixing is generally done by rotating impellers of the paddle or helical type. A range of methods have been developed which today go under names such as "deep mixing (method)" (e.g. Terashi 1997, Porbaha 1998). In the Nordic countries compressed air is used almost exclusively as the medium for the transport of dry binder powder from the tank to the soil. This is known as “dry deep mixing”. Some Scandinavian literature uses the term “lime-cement columns”, “deep stabilization”, “dry jet mixing method”, “dry deep mixing”, or “column stabilisation”. The alternative today is to premix the binder, usually cement, with water to form a slurry, thus distributing the binder to the soil in liquid form. This is known as “wet deep mixing” and is the dominant technology in Japan and elsewhere. There is no clear distinction between surface stabilisation and deep mixing. However, CEN TC 288 (2002) specifies deep mixing as treatment of the soil to a minimum depth of 3 m.

The use of compressed air as the medium for transporting the binder has the advantage that it takes a relatively small amount of binding agent to achieve the requisite strength gain. Given that loose soils already contain a lot of water, it appears logical not to add still more water to the soil, as is done when the wet method is employed. However, the addition of air adds to the difficulty of the mixing process in a material, soft soil, whose rheological properties are already very complex. In the mixing process an air-borne binder complicates the dispersion process with regard to the wetting of lime and cement particles and the breaking up of agglomerates.

A series of operations and mixing mechanisms occurs in deep mixing. Compared with e.g. the mixing of two miscible liquids in a vessel, the mixing process that occurs in deep mixing is very complex and it is difficult to monitor the entire production process continuously. The wide variations in local geology, the difficulty of predicting the rheological properties of the mixture, field conditions affecting equipment etc. all make it difficult to monitor and study the mixing process and mixing mechanisms in the field.

The mixing process affects the physical and chemical properties of the columns, including:

1. Uniformity. The properties of columns can vary both along their length and across their section. Heterogeneities in various properties have been observed across column sections, e.g. grainy consistency, accumulations of binder along the column periphery, and tapered columns.
2. Strength gain and permeability. The main purpose of the mixing process is to disperse a binder in the soil. The potential strength gain and permeability of the column vary depending on how efficiently the binder is dispersed.

The review of present-day mixing procedures in the present chapter sets out from a division of the process into stages as in Fig. 6.1. The discussion is based on the principal method employed in the Scandinavian countries, using dry deep mixing. The phases of the mixing process are described and discussed. Factors that influence the mixing process are surveyed. A special section is devoted to mixing tools, mainly those used in Japan and Sweden. A concluding section examines some characteristic defects found in columns as a result of the mixing process.

6.2 HISTORICAL SKETCH

According to Bruce (1996) the original concept comes from the US, where in 1954 a single auger was used to mix binders with soil. A patented system was used in more than 30 projects. Handy & Williams (1967) reported the results of stabilizing soft soil at the "Aurora Avenue landslide" in Iowa, US. Five hundred drill holes of diameter 150 mm were filled with quicklime and water. A similar method had been used in 1960 in a highway project in Oklahoma, where drill holes of diameter 230 mm were filled with hydrated lime and water. The use of quicklime piles for stabilization has sinze been used world vide (e.g. Lutenegger & Dickson 1984). In the early 1960s an US patent on a mixing process where a rotating mixing tool provided by blades was used to mix cement slurry into the soil (Jasperse & Ryan 1992, U.S. Patent No. 3,023,585). However, deep mixing in its present form derives from development in Japan and Sweden.

Deep mixing, in its present form, was first presented in an international forum in 1975, when two papers were submitted to the same conference. One came from Sweden, Broms & Boman (1975b), and the other from Japan, Okumura & Terashi (1975). The method had been under development concurrently in the two countries (Okumura 1997). The first journal articles, by Broms & Boman (1979a and 1979b), focussed on applications, properties and design.

Development of the lime column method in Sweden began in 1967 under the leadership of Kjeld Paus. It was based on the *in-situ* mixing of soil with quicklime to form hardened columns of cohesive material (Boman & Broms 1975). Binding agents were investigated by laboratory tests at the Swedish Geotechnical Institute (SGI), and after development of a suitable installation procedure some trial columns were installed at the SGI test field at Skå-Edeby. The first equipment consisted of a drill rig mounted on a Volvo tractor, see Fig. 6.24a. The number of projects carried out in Scandinavia was fairly small until the end of the 1980s, when machinery development got properly under way. The development of the equipment currently used in Scandinavia has been described by Bredenberg (1999).

Concurrently with its development in Sweden, research and development on deep mixing had been in progress in Japan since 1967 in the form of laboratory and model scale tests (Okumura & Terashi 1975). These tests were run by the Port and Harbor Institute of the Japanese Ministry of Transportation with the aim of developing a method for the deep stabilization of marine clays under the sea floor. In Japan there has been a huge growth in the reclaiming of land from the sea by filling. The first Japanese project, using lime columns, was completed in 1974. The Japanese also developed the "wet method", in which the binder, usually cement, is premixed with water and injected into the soil as a slurry. The wet method in Japan was initially developed to improve the sea-bottom sediment. The first project using the wet method was completed in 1975 (Kawasaki et al. 1981), and in 1977 the CDM Association was set up to coordinate the development of the method in collaboration between industry and research institutes (Porbaha 1998).

In 1975 Japanese engineers began research and development into deep mixing using granular quick lime as binder agent (Chida 1982). Development of dry deep mixing during 1977 and 1979 was led by the Civil Engineering Research Institute of the Ministry of Construction in conjunction with the Japanese Construction Mashine Research Institute (Yang et al. 1998a). The first project was carried out in 1981 (Schaefer et al. 1997).

Deep mixing was highly successful in Japan and extensive research and development took place in the 1980s in the form of laboratory and field work. The method thus underwent rapid evolution and a relatively large number of organisations and companies have developed their own mixing processes, resulting in a variety of installation techniques. A review of eguippment currently used in Japan has been presented by Porbaha et al. (2001) and Terashi (2003).

In 1986 deep mixing was reintroduced in US in the form of a Japanese method for a liquifaction mitigation application at Jackson Lake Dam, Wyo (Bruce 1996, Jasperse & Ryan 1987, 1992), and Swedish practice has been represented in the US since 1997 (Bruce et al. 1998a). However, tests with lime columns were perform already in Florida 1992 (Hardianto & Ericson 1995). Development of deep mixing methods has also taken place in other countries e.g.; Italy (Paviani & Pagotto 1991); France (Harnan & Iagolnitzer 1994, Robert et al. 1994); England (Harnan 1993, Al-Tabbaa 2003); The Netherlands (Huiden 1999, Koehorst & van den Berg 1999, Vriend et al. 2000); Germany (Maisch et al. 1997, Scheller & Reitmeier 2000); Bulgaria (Evstaniev 1991); and in a number of countries in Asia e.g. China, India, Indonesia, Singapore, Taiwan, and Thailand (Porbaha et al. 1998b). An overview of practice worldwide can be found in Bruce et al. (1998b, 1999) and Porbaha (1998a).

A large number of general reviews have been presented during the years, primarily in connection to conferences. The Swedish lime-cement column method has recently been reviewed by Rathmayer (1997), Holm (1999, 2001, 2003) and Broms (1999a, 2000). Other similar methods, internationally named as "Deep mixing methods", have recently been reviewed by Okumura (1997), Porbaha (1998, 2000), Porbaha et al. (1998, 1999b, 1999c, 2000, 2001), Terashi (1997, 2001, 2003), Terashi and Juran (2000) and in a series of short papers by the Japanese Geotechnical Society (Yonekura et al. 1997). There are also today a number of design guides compiled in Europe (Tielaitos 1997, SGF 2000, EoroSoilStab 2002) and in Asia (CDIT 2002, JICA 1999). In Europe the CEN/TC 288 Working Group 10 has produced a draft of a standard for the execution of deep mixing (CEN/TC 288, 2002). These reviews and design guides deal with applications, properties of stabilised soil, control methods, design and equipment. Bruce et al. (1998a, 1998b, 1999) presented a proposition for a classification system of deep mixing. I spite of a great interest and a large amount of publications conserning deep mixing, few deals with the mixing process *in-situ* and influencing factors.

6.3 THE MIXING PROCESS

The mixing process in deep mixing is very complex, comprising many phases, and many factors influence the process and its result. It is difficult to clearly separate the different mechanisms involved in the mixing process, however it is important to understand how the mechanisms affect each other. Different mixing mechanisms are described in Chapter 2.

The purpose of the mixing process is to disperse the binder in the soil so as to provide the best possible conditions for the chemical reactions to take place. If all of the binder is to contribute actively to the improvement of the soil, the particles of binder must all be evenly dispersed throughout the volume of the column. Moreover, the binder should be evenly distributed over the column cross section in order to limit the dispersion of strength and deformation properties. Wide dispersion of the properties not only reduces the predictive value of laboratory tests but also complicates production control. The consequence may be a loss of control of the process and its results.

The manufacturing process in deep mixing is illustrated in Fig. 6.1. It can be divided into three principal phases:

1) penetration of mixing tool to the required depth;
2) dispersion of binder;
3) molecular diffusion.

Penetration of mixing tool

In the first phase of the mixing process the rotating mixing tool is driven into the soil to the desired depth. The insertion process can be executed in such a manner that the resulting remolding and disaggregation of the soil changes the conditions for subsequent phases. Total disaggregation (dispersed and feflocculated structure) can have a positive effect on the active mixing mechanisms by making it easier to produce the necessary movements in the soil for the mixing of the materials. The mixing mechanisms that may be affected are:

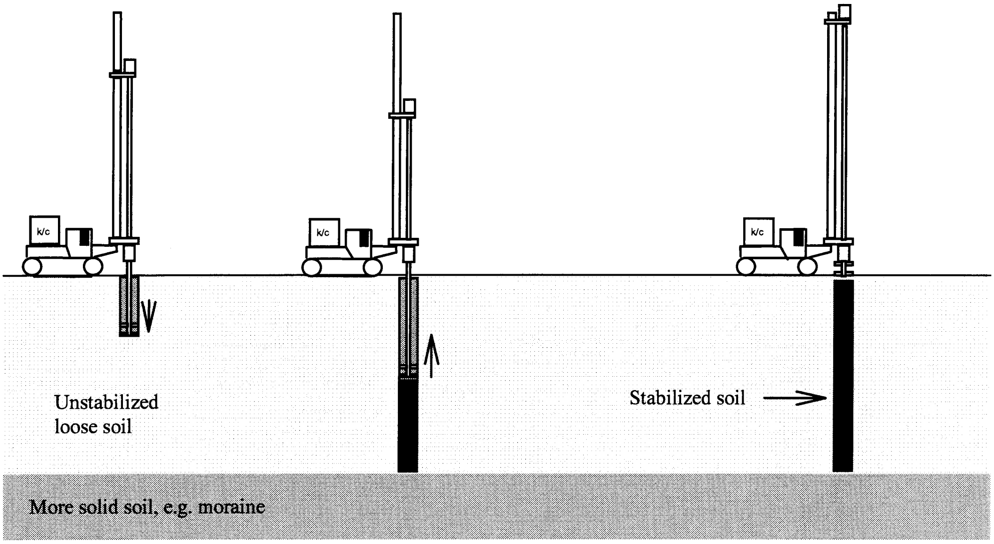
a) molecular diffusion. Disaggregation of the clay renders the clay minerals and the liquid phase more accessible for chemical reactions;

b) laminar mixing. The conditions for laminar mixing are improved by reducing the elastic drag of the clay suspension. Laminar mixing is an effective mechanism for disagglomeration and also promotes molecular diffusion.

In the current mixing procedure there is a risk that much of the energy used in the dispersion process is expended on remolding the clay. Laminar mixing is likely to be less effective as the clay can withstand deformation thanks to elastic drag and the high yield point (see Chapter 5.2).

However, it is not certain that complete disaggregation of the soil will exclusively positive effects on the strength gain. Complete disaggregation combined with poor mixing efficiency (high concentration variances) may result in the low shear strength of relatively massive striations and/or lumps impairing the overall strength properties of the column.

Existing mixing tools are equipped with paddles which are generally set at a small angle to the horizontal. This facilitates insertion of the tool as it requires little energy to penetrate the soil. The inevitable consequence, however, is that relatively little energy is expended on remolding the soil. It takes movement of the soil to produce the shear forces necessary for disaggregation. Large shear rates around the paddles



1) Penetration of mixing tool to desired depth

2) Dispersion of binder agent in the soil. Sub-phases:
- a) **incorporation and spreading of binder agent;**
- b) **wetting of dry binder particles;**
- c) **breakdown of agglomerates;**
- d) **distribution (and stabilizing of dispersion).**

3) Manufacturing completed. Mixing continues by molecular diffusion

Fig. 6.1 The mixing process in dry deep mixing (e.g. lime-cement columns).

can be produced by increasing their angle to the horizontal plane, causing forced axial and tangential movement, or "kneading", of the soil. High rotation speeds can also promote disaggregation. However, it may be difficult to drive the tool at a high speed when using steeply tilted paddles because the resistance and hence the shear forces are higher. It is also possible to increase the number of shear zones by e.g. drilling holes in the paddles, increasing the number of paddles, angling the blades in opposite directions, or using a tool in the form of a rake (i.e. with teeth).

An important issue is whether increasing the agitation energy during penetration of the tool actually improves conditions for the mixing process sufficiently to justify the extra cost it entails. It is uncertain today how much the result of mixing is affected by the input of agitation energy during penetration as compared with other factors. The tool is currently inserted at the rate of 100 mm/rev, and it is doubtful whether the soil structure is significantly affected. It is also doubtful whether it is economical to remold and disaggregate the soil before adding the binding agent.

The dispersion process

The process by which the binder is dispersed in the soil can be divided into four steps (basically based on a division of the dispersion process by Parfitt & Barnes (1992), see Chapter 2.6):

a) incorporation and spreading of the binder;

b) wetting of solid particles;

c) breakdown of agglomerates;

d) distribution.

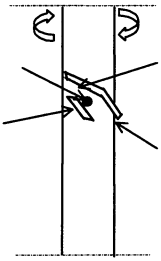
In practice the stages overlap and it can therefore be difficult to distinguish them by visual observation.

a) Incorporation and spreading of the binder

It is most important that the mixing tool is designed in such a way that the binder is spread as evenly as possible over the column cross section during the incorporation phase. This avoids major concentration variances, makes the breakdown of agglomerates easier, and avoids long mixing times, since the whole dispersion process take place during a short time of mixing. Due to the complex rheological behaviour of a clay suspension it is difficult to distribute a binder over a column cross section in a short time by mechanical mixing, see Fig. 5.4. It is therefore important that the binder is evenly spread over the cross section at an early stage of the mixing process.

In the Scandinavian countries binder is delivered in powder form from tanks via hoses to the mixing tool using compressed air as a transport medium. The binder is expelled through a hole in the Kelly rod just above the mixing tool, usually in the manner shown in Fig. 6.26. The binder is spread through the cavities formed in the soil by the rotating mixing tool, and to some extent by pneumatic fracturing caused by the air pressure. The size and shape of the cavities formed depends on the geometry of the mixing tool and the intensity of mixing, the air pressure, stress conditions in the soil, the rheological properties of the soil and the binder. In order to avoid large agglomerates (loosely bound lumps) and accumulations of binder it is very important that the binder is spread evenly over the entire column cross section in this phase of the mixing process.

The incorporation and spreading of the binder by compressed air is a mixing mechanism in itself, since it may produces relative movement of the soil and the binder (cf. Fig. 3.8). A relatively large energy input may takes place as the compressed air fractures the soil. Unfortunately our knowledge of this mixing mechanism is very limited. Better knowledge is highly desirable, as this mechanism can be a significant one for the mixing process. If the binder is spread evenly over the cross section at incorporation, the main task of the mixing tool will be breaking up the agglomerates that form, and the risk that the mixing tool will be unable to distribute the binder is reduced.



Expulsion of binder

Forward paddle creates a cavity through which the binder is spread over the cross section

A film of clay is pressed and stretched against the inside of the paddle, increasing the interfacial area between the clay and the binder.

Laminar shearing produces high shear stresses at the lower edge of the paddle, generating the compressive stresses necessary for liquid to penetrate the pores and release entrapped air from the agglomerates.

Fig. 6.2 In-principle design of an impeller paddle in which the binder is wetted in contact with a film of clay.

b) Wetting of solid particles

When a powdered binding agent is mixed with a soil, the lumps of powder contain entrapped air which must be replaced with liquid. In e.g. calcareous and cementitious reactions, liquid is drawn from the soil by diffusion. If the air is not to remain entrapped mechanical work to be done, but even with mechanical assistance the release of the air can be difficult if agglomerates or aggregates have formed. The wetting process is assisted by mixing tools which generate high compressive and shear stresses in the soil.

The wetting process cannot occur spontaneously because the lime and cement particles are not dense enough to sink into the clay slurry. The high particle concentration, the complex spreading process, the presence of air as a component, and the chemical reactions proceeding during the mixing process make the behaviour of the mixture extremely complex. As mentioned in Chapter 2.6, the wetting process is influenced by the properties of the liquid phase, the character of the surface, the dimensions of the interstices in the agglomerates, and the compressive forces exerted by the mechanical system on the components. The rheological behaviour of the clay (dependent on e.g. clay and water content) is also highly significant for the wetting process. Complete remolding of the clay releases water which is available for wetting the lime and cement particles. It also gives the clay particles a larger active interfacial area with the binder, which promotes molecular diffusion.

Fig. 6.2 shows an in-principle design of an impeller paddle shaped so that a film of clay is forced against the inside of the paddle while binder contacts the soil in the same region. The principle is adapted from equipment specifically designed for wetting solid particles, see Fig. 3.6. The binder is spread along the cross section of a cavity created by a forward paddle. The stretching of the film of clay along the blade increases the interfacial area between the components being mixed. Below the paddle, large shear stresses and movements are generated in the material, producing the necessary compressive stresses to force liquid into the pores and release the entrapped air from the agglomerates.

In dry deep mixing, particularly in soils with water contents below the liquid limit (liquidity index < 1), wetting problems in combination with inadequate mechanical mixing can lead to agglomeration and entrapped air in the columns. A way of avoiding air and increasing the efficiency of wetting is to premix the stabilizer with water, i.e. carry out mixing in two steps. This method, known as the "wet method", is mainly used with cement as binder agent. In applications where satisfactory performance depends on a high degree of homogeneity and where the liquidity index is less than unity wet deep mixing may be appropriate.

In the improvement of soft soils with a liquidity index greater than unity the wet method may have a negative effect on the mixing process, since lumps or portions of the soil may be entrained by the mixture without undergoing significant action by the mixing tool. It is important that the mixing tool is designed to produce high-intensity and if possible turbulent movement.

The wetting process is closely linked to the process of compacting the mixture of soil and binding agent. The capacity of the mixing tool to compact the mixture is all the more important when air is injected into the soil. The influence of the compaction process on mixing is discussed at the end of section 6.4.

c) Breakdown of agglomerates

Once the binder is incorporated and spread and the particles are wetted, the agglomerates that have formed should be broken down before the chemical reactions begin. Unless the particles are evenly dispersed in the mixture, large aggregates will form, resulting in concentration variances and poor mixture quality. Furthermore, if the particles are not dispersed, not all the particles of binder will make their full contribution to even strength gain throughout the stabilized volume.

Agglomerates are broken down by shearing or by generating large compressive forces. To produce sufficiently large shearing or compressive forces the mixture must be set in motion. For the effective breakdown of agglomerates in a mixture with dough-like properties, experience from process industries indicates that equipment with a kneading or grinding action should be used. A kneading action in the mixture may be produced by paddles mounted at a relatively large angle to the horizontal, ~45°, thus generating both axial and tangential motions. It is advantageous to generate movements in a number of directions because clayey soils have viscoelastic properties, entailing a risk that the mixing tool will only generate movement in the immediate vicinity of the blades, i.e. that the soil will "yield" in a thin shear plane close to the tool as illustrated in Fig. 5.4.

Depending on the rheological properties of the soil and on which mixing mechanisms are active, the efficiency of the mixing process is influenced mainly by the following two factors:

1) the effective strain in the mixture. This factor can be expressed as a function of the number of revolutions per metre (rev/m) or the retrieval rate (mm/rev) of the mixing tool;
1) the intensity of mixing or agitation. This factor can be expressed as a function of the rotation speed of the mixing tool (rev/min).

A hypothesis in this connection is that when the mixing intensity is sufficient to break down agglomerates, the effective strain is the most significant factor for better mixture quality. If on the other hand the mixing intensity is too low to break down the agglomerates, the effective strain is of little importance as the agglomerates are merely entrained with the mixture. According to this hypothesis it is the rheology of the soil that determines how far the retrieval rate and rotation speed of the tool influence the process.

In order to bring about the necessary movements and shear stresses in the mixture the mixing tool may be designed on the principle of an anchor agitator having two sets of arms operating in opposite directions, or as an anchor agitator combined with paddles operating in opposite directions (cf. Figs 3.5, 3.10, and 3.11). Such a tool could be of the in-principle design shown in Fig. 6.3. To produce large shear stresses in the material the paddles may run at different speeds, with the smaller paddle rotating at the faster speed (a higher shear rate results in higher shear stresses in a suspension with viscous properties). The tool produces both high shear stresses and movement, enabling the material to remould between successive shearings. The dominant mixing mechanisms are laminar shear and distributive mixing.

If a completely remoulded soft soil has a liquidity index > 1, under favourable conditions turbulent flow may be generated in the mixture. Turbulent flows result in effective circulation and high shear forces. If the viscous drag in the fluid is small, a larger proportion of the mixing energy will go into breaking down agglomerates. It takes relatively high rotation speeds to produce turbulent flow. At low speeds there is a risk that the tool will merely move the agglomerates around without breaking them up.

In Chapter 5 we discussed the difficulty of producing movements in materials with viscoelastic properties, due to the fact that the intermediate forces around the impeller rapidly die out. The impeller may not generate significant movement of the mixture, with the result that if the mixing time is too short, layers of

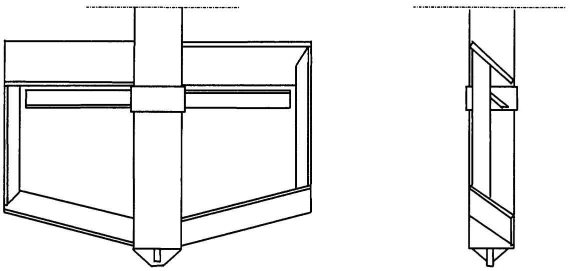


Fig. 6.3 **In-principle mixing tool design combining an anchor agitator with a paddle operating in the opposite direction.**

solid additive will be left in the soil. Hence it is important to design the mixing tool to produce forced movement of the materials and generate laminar mixing within a sufficient volume of soil around the tool. When a paddle is tilted at a small angle to the horizontal, one may expect it to cut through the clay without imparting movement to a significant volume of soil. The risk of poor results with a given tool is thus particularly great if the water content is close to the liquid limit and the soil has plastic properties, or if the clay is not sufficiently disaggregated.

In a process in which agglomerates are being broken down the fluid elements need to remould themselves between successive shear stresses. In a turbulent flow regime this is not a problem, since the elements are moving randomly in continually changing directions. In a viscoelastic soil, however, it can be difficult for the fluid elements to remould themselves if movement in the mixture is limited. This problem can be overcome by subjecting the mixture to continually changing directions of shear, with each shear stress operating in a different plane to the previous one, see Fig. 2.5. An in-principle design for such a mixing tool is shown in Fig. 6.4. This tool is moreover designed so that the blades generate alternate inward and outward radial movements in the mixture.

Shearing forces operating in different planes can also be achieved by equipping the paddles with teeth. These can also facilitate penetration of the dry surface crust during insertion. Yet another way of achieving a desirable shearing action is to provide the paddles with holes in order to obtain extensional flow with increased shearing capacity, see Fig. 2.6.

d) Distribution

Distribution is the process by which the disaggregated agglomerates are randomly scattered through the mixture. This normally takes place concurrently with the preceding process.

If the binder has not been adequately spread during the previous phases of the process, long mixing times may be expected, as it is difficult to generate movement in all soil types. Distribution of the binder is promoted by complete disaggregation of the soil, high water content, and low viscosity. It will only be successful with mixing tools that produce large movements in the soil.

Molecular diffusion

After the manufacturing process is completed and the column is installed in the soil, the mixing process continues by molecular diffusion. When concentration variances exist in an otherwise uniform solution, they tend to decrease over time and finally disappear. In a homogeneous system this process, known as diffusion, must ultimately result in uniform concentrations of all materials throughout the system.

The binders most commonly used today, lime and cement, differ in their diffusion properties. When lime reacts with water it produces calcium hydroxide, which diffuses in dissolved state and thus improves the

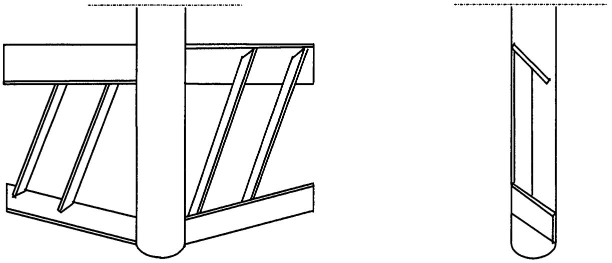


Fig 6.4 **In-principle design of a mixing tool which generates shear forces in continually changing planes.**

degree of mixedness. Cement on the other hand reacts with water to form products which harden and fill out the pores between the soil particles. Molecular diffusion is a minor mixing mechanism for cement, which thus requires a higher degree of dispersion than lime. Petry & Wohlgemuth (1988) write that cement is not a suitable binder for shallow subgrade stabilization of soft plastic soils unless the mixture quality is very good.

The diffusion of calcium from the column into the unstabilized surrounding soil, or from regions of the column with a high lime concentration into lumps of soil with lower concentration, depends on the water content, the mineral content, the permeability, the clay content and the void ratio (Thompson 1966). Seepage flow in the material presumably has a positive effect on lime migration, since water is a medium for molecular diffusion (Lindh & Ydrevik 1978).

Litterature review on molecular diffusion in soft soils

The molecular diffusion of calcium ions in soil as a mixing mechanism was demonstrated and discussed in the journal literature as long ago as 1939 by Jenny & Overstreet (1939). However, research did not take off until the 1960s, when lime stabilization began to come into more general use for the surface stabilization of terraces in road building. Perhaps the most comprehensive study from that time is Davidson et al. (1965). Notwithstanding numerous studies published since the 1960s, it remains unclear how molecular diffusion works as a mixing mechanism and how much effect it has in deep mixing. A survey of some of the studies of the molecular diffusion of lime in soft soil follows below.

Shen et al. (1997, 2003a) presented analyses of samples taken from the soft soil in between installed cement columns (wet method, 140 kg/m^3). The columns were of diameter 1140 mm and were installed in a grid at 1500 mm centres. The results showed that the disturbance in the soil caused by the installation process is quickly repaired by cation diffusion and a consolidation process caused by the dissipation of excess pore water pressure. Direct after installation the undrained shear strength in the surrounding soil decreased, but after ten days the strength regained and continued increasing in a long period. Both the field test and complementary laboratory tests showed property changes in the surrounding soil in a range of about 2 to 3 times the radius of the columns. The deep mixing of soft soil can causes vertical fracturing of the surrounding soil. The fractures can be explained by the excess pore pressure in the soil produced by lateral pressure from the injection of binder, and by the shearing of the soil caused by the mixing tool (Shen & Miura 1999, Shen et al. 2003b). The fractures form channels for binder migration and may account for the measurably elevated concentrations of cations well out in the surrounding unstabilized soil.

Mathew & Narasimha Rao (1997) studied the diffusion of calcium ions in a marine clay from India with a liquid limit of 63 % and a plastic limit of 22 %. In this laboratory study holes of diameter 50 mm were filled with quicklime. Columns were installed at 400 mm centres (triangular mech). Measurement of pH and lime content at points in between between the columns showed that lime had migrated throughout the soil volume. In 60 days the calcium oxide content had increased from 1 % to 2.5 % and the pH from 7.5 to 10.

Rajasekaran & Narasimha Rao (1996 & 1997) and Narasimha Rao & Rajasekaran (1996) studied the diffusion of lime from a central lime column (a hole filled with quicklime) of diameter 50 mm in a tank of diameter 600 mm. A marine clay from India was used having a liquid limit of 85 % and a plastic limit of 53 %. The calcium content of the soil was 0.2 %. Forty-five days after installation the calcium content ranged from an average value of 2.5 % 25 mm outside the column to 1.65 % at a distance equal to five times the column diameter. The authors conclude that the strength and compressibility behaviour were improved over a radial distance of 4 to 6 column diameters.

In the course of investigations into the suitability of lime columns for slope stabilization in England, Rogers & Glendinning (1994) presented results of a laboratory investigation into the diffusion of lime in a lower Lias clay. The soil was compacted in layers in a box of dimensions 1000×500×500 mm. A hole of diameter 50 mm was filled with quicklime. Samples were taken at various distances from the column on successive occasions. The results showed that migration of lime took place to a maximum distance of 20 – 30 mm from the column. In subsequent field trials, holes of depth 2.5 – 3 metres and diameters 63 mm and 200 mm were filled with quicklime (Rogers & Glendinning 1997, Rogers et al. 2000). The findings were similar: a zone up to 30 mm from the periphery of the column was noticeably stiffer and drier in character. Radial cracks of length ~50 mm and width 2 – 5 mm had appeared around the columns. Some larger cracks were observed, approximately 7-10 mm wide and 100 to 400 mm long. These cracks were filled with lime.

A number of studies of molecular diffusion have been done in connection with research on the surface stabilization of soft soils with lime. Fohs & Kinter (1972) carried out a study in which a lime slurry was placed in contact with small blocks of compacted soil. The results of this study showed that that migration of lime took place over a distance of 20 – 30 mm, i.e. in the same order of magnitude as the findings by Rogers & Glendinning (1994, 1997). A very extensive study of the diffusion of lime and cement in small lumps of soft soil was reported by Stocker (1975). The study shows that lime can migrate through lumps 40 mm thick.

In the course of an extensive investigation of the feasibility of stabilizing soft soils with polymetric hydroxy-aluminium, OH-Al, a study was made of changes in soil properties and pore-water composition outside stabilized columns (Bryhn et al. 1988). The columns were installed by the Swedish lime column method. Diffusion of cations, either added in the binder or resulting from ion exchange, increased the remoulded shear strength within a zone extending up to 86 cm from the column. On the other hand, a laboratory study of the diffusion of lime showed that OH-Al binder only affected a zone within 100 mm of the stabilized column (Bryhn et al. 1984). Similar tests using lime as binder showed that the zone affected by diffusion was only ~30 mm in thickness.

Åhnberg et al. (1995) carried out a series of laboratory tests in which lime-stabilized and cement-stabilized soil was placed in cylinders with unstabilized soil on either side. The results showed that calcium ion transfer was greater for the lime-stabilized than the cement-stabilized soil. An uncertainty in the results made it difficult to assess the extent of diffusion, but it was estimated at no more than a few centimetres. A thin layer of softer clay observed between the stabilized and the unstabilized soil was attributed to shrinkage of the stabilized material. The tests were followed up with field trials in which a Ljungskile clay was stabilized with 50 % lime and 50 % cement. Softer clay was observed in the immediate vicinity of the column and was considered to be due to a reduction in the salt content of the clay.

Joshi et al. (1981) presented a study in which a slurry of slaked lime was injected into slurries of bentonite and kaolin. Calcium ion migration was studied by strength measurements, scanning electron microscopy and X-ray studies. The results indicated an effect on strength in the soil up to ~30 mm from the calcium source. However, an elevation in the calcium ion concentration was detectable up to 75 mm from the source, indicating that the calcium ion migration front lies considerably further out in the soil than the front at which geotechnical parameters are affected.

In a study of the mixture quality of a number of lime-cement columns, reported in Chapter 7, the water content of the soil was measured just beyond the column periphery. A number of columns were recovered by means of a split sample tube of diameter 900 mm. Since the diameter of the columns was substantially smaller, 600 mm, an amount of relatively undisturbed soil was recovered along with the columns. The water content was measured in samples taken every 5 mm to a distance of 100 mm from the column. The results of four sampling sections are shown in Fig. 6.5. The properties of the soil and the installation data of the columns are reported in Chapter 7. The results show that the water content is affected within a zone up to 30 mm from the column, which agrees fairly well with the majority of the studies reviewed above. The surface of the clay that was in direct contact with the column, a zone of about 5 mm in thickness, was very stiff. The zone from 5 mm to 30 mm was also noticeably stiffer than the surrounding soft clay, Fig. 6.6. An interesting observation was that the water content was somewhat lower in the soil just outside the column than inside the column (0 – 5 mm). This may have been caused by the increase in pore pressure due to mechanical mixing, and by consolidation due to water transport from the soil into the column during hydration of the binder. The hardening material of the column itself increased in volume, subjecting the surrounding soil to radial consolidation. Thus the material of the column was consolidated to a lesser degree than the surrounding soil, resulting in the column having a somewhat higher water content.

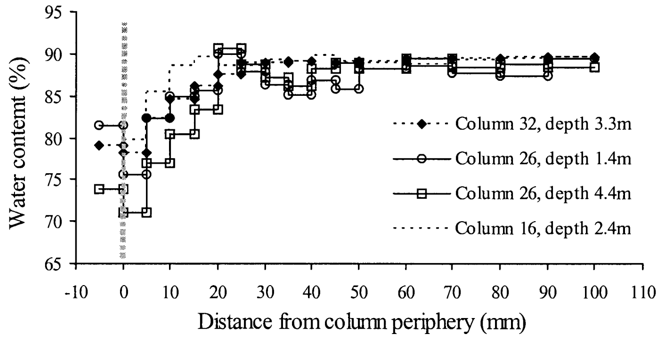


Fig. 6.5 **Water content measured in surrounding clay at various distances from column periphery (author's work, 1998).**

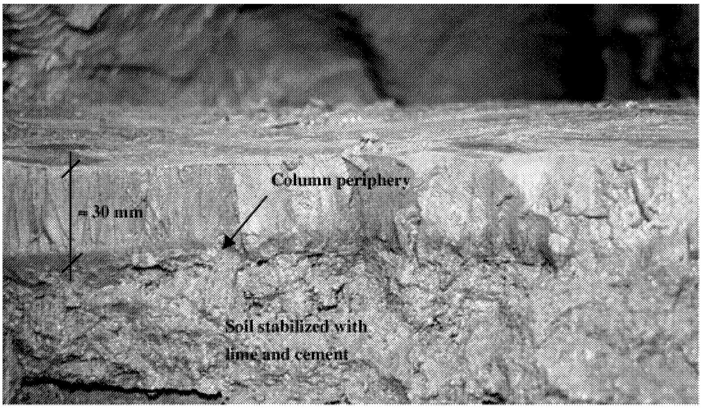


Fig. 6.6 **Boundary zone between column and surrounding soil (author's work, 1998).**

6.4 FACTORS AFFECTING THE MIXING PROCESS

The mixing process in dry deep mixing is a very complex one. A variety of factors influence the process and its results:

- the rheology of the soil, the binder, and the amount of binder;
- pressure conditions in the soil during column installation;
- the delivery pressure and the amount of air used;
- the geometry of the mixing tool;
- the mixing energy: the retrieval rate and rotation speed of the mixing tool;
- the consolidation stress, the compaction energy, the temperature, the availability of water and seepage flow, which affect molecular diffusion.

This section reports and discusses published studies on factors influencing the mixing process. An owerview of a number of studies reported in relation to deep mixing is shown in Table 6.1. As shown in the table, the focus has been on the influence of the mixing work and on comparisons of different mixing tools. The influence of factors such as the rotational speed, air pressure, the amount of air, compaction and soil rheology has not been well investigated.

Mixing energy

It is well-known today that the effective strain in the mixture (the retrieval rate of the mixing tool) has an influence on the mixing process and its results. In an early stage of development, Terashi et al. (1977) investigated the influence of the mixing work on the unconfined compression strength on laboratory specimens. A longer mixing time increases the effective strain and the dispersion of the binder in the mixture. Many studies have drawn this conclusion on the basis of laboratory-prepared specimens without subjecting this factor to any closer examination, e.g. Locat et al. (1990), Åhnberg et al. (1995). However, few studies have been carried out with the explicit purpose of investigating the influence of individual factors on the mixing process.

In the Scandinavian countries the retrieval rate (mm/rev) of the mixing tool is used as a measure of the mixing time. The effective strain in the mixture is a function of the retrieval rate. The intensity of mixing (agitation) is a function of the rotation speed. In Japan, on the other hand, the mixing time is measured in terms of the penetration speed (m/min), the retrieval speed, and the rotation speed. To provide a measure of the mixing time these parameters are combined as mixing cycles per meter *T*, given by (Yoshizawa 1997):

$$T = \sum M \times \{(N_d / V_d) + (N_u / V_u)\} \tag{6.1}$$

where ΣM = number of mixing tool blades
N_d = rotation speed of mixing tool during penetration (rev/min)
V_d = mixing tool penetration velocity (m/min)
N_u = rotation speed of mixing tool during retrieval (rev/min)
V_u = mixing tool retrieval velocity (m/min)

In Japan part of the binder is often delivered as the mixing tool is being inserted into the soil, particularly when binder in liquid form is used. The binder thus assists the remoulding of soil by the tool. Dry binder may also be delivered in this way in order to utilize the mixing tool more efficiently. To take account of the

Table 6.1 An owerview of a number of studies reported on factors influencing the mixing process for deep mixing.

Referens	Test		Binder	Mixing work	Binder type	Binder content	Rot. speed	Air pressure	Amount of air	Compaction /consolidaton	Soil reology	Mixing tool
Aalto & Perkiö (2000) and Aalto (2001)	M	UC, FC	C D	x					x	x		x
Aalto (2003)	F	UC, V,P	C, L		x						(x)	x
Abe et al. (1997)	F	UC										x
Al-Taabbaa & Ewans (1999) and Al-Tabbaa et al. (1999)	M	UC	C W,D	(x)		(x)					(x)	x
Asano et al. (1996)	L,F	UC	C,F,G, W		x	x						
Chida et al. (1982)	L	UC	C,L,S W,D	x	x							
Dong et al. (1996)	M	UC	C W	x			(x)					x
Enami et al. (1986a)		UC		x								
Hayashi & Nishikawa (1999)	L	UC	C D	x		x						
Hansson (2000) and Rogbeck et al. (2000)	F	P	L,C,S D	x	x		x					x
Hedman and Koukkanen (2003)	F	P	L,C D	(x)							(x)	
Johansson & Jons (1995)	F	P,V	L,C D	x								x
Larsson et al. (1999) and Walter (1999)	L	UC	L,C D	x	x							x
Mizuno et a. (1988)	F			x								
Muro et al. (1987a, 1987b)	M	UC	C	x	(x)		x					
Nishibayashi et al. (1988) Matsuo et al. (1996)	M	UC	C W		x	x						
Nishibayashi et al. (1985)	M	UC	C W	x			(x)					x
Nishibayashi et al. (1984)	M	UC	C W	x			(x)					x
Nishida et al. (1996)	L,F	UC	L D	x							x	

Test; L=laboratory test, e.g. dough mixer; M=model test; F=field test; UC=unconfiened compression test; V=vane test; FC=fall cone test; P=penetrometer tests
Binder; L=lime; C=cement; S=slag; F= fly ash; G=gypsum; D=dry; W=wet

fact that only part of the binder is delivered during insertion of the mixing tool, the following expression may be used to calculate the number of mixing cycles per column metre T (Hayashi & Nishikawa 1999):

$$T = \sum M \times \{(N_d / V_d) \times (W_i / W) + (N_u / V_u)\} \qquad (6.2)$$

where W_i = quantity of binder delivered during penetration (kg/m^3)
W = total quantity of binder (kg/m^3)

In Sweden the retrieval rate (mm/rev) of the mixing tool is used as a measure of the mixing time. The number of cycles per column metre T can be calculated as:

$$T = \sum M \times \frac{1}{s} \times 1000 \qquad (6.3)$$

where $\sum M$ = number of mixing tool blades
s = retrieval rate of mixing tool during withdrawal (mm/rev)

It will be noted that when investigating the effect of different rotation speeds in Japan, both the effective strain and the mixing intensity are varied. It is therefore difficult to separate these two parameters in Japanese studies, since the rotation speed is increased in order to obtain longer mixing times.

Muro et al. (1987a, 1987b) studied the effect of mixing time and rotation speed in a series of laboratory tests in which the mixing process was simulated by means of two types of equipment. The tests were carried out using kaolin and cement as binders. Fig. 6.7 shows the results, in which the degree of mixedness a is evaluated as a function of total number of revolution R. The degree of mixedness a in the figure is equivalent to the mixing index defined by equation 4.13 in Chapter 4. The water content of the mixture was used as a variable for evaluating the degree of mixedness. The initial water content of the kaolin was 70 %. The tests were carried out at three rotation speeds, 20, 40 and 60 rev/min. Mixing took place in a circular tank of diameter 160 mm and height 160 mm. The mixing tool was rotated in a horizontal plane, i.e. at zero pitch. The results show clearly that the mixing time or the total number of revolution has a major impact on the degree of mixedness, particularly at short mixing times.

Unconfined compression tests were carried out to investigate the effect of mixing energy on the strength of the laboratory-mixed soil. Fig. 6.8 shows the relations between degree of mixedness, mixing cycles, and unconfined compressive strength. The results of this study show that the degree of mixedness and the number of mixing cycles have a major impact on the compressive strength. Muro et al. (1987a, 1987b) proposed a exponential relation between the unconfined compression strength and the number of cycles. The degree of mixedness is proportional to the logarithm of the number of cycles. Similar results were reported by Baker (1954) from laboratory mixes of a clayey silt stabilized with cement.

Muro et al. (1987a, 1987b) also carried out mixing tests in order to investigate the relation between mixing energy and unconfined compressive strength when using a vertically reciprocating mixing tool in a container of diameter 157 mm and height 400 mm. Fig. 6.9 shows the relation between unconfined compressive strength, the modulus of deformation at half the ultimate stress, and the retrieval rate of the mixing tool.

Fig. 6.9 shows some results which are more difficult to interpret than those in Fig. 6.8. As the retrieval rate is reduced from 10 mm/rev. to 2.5 mm/rev the strength decreases slightly, only to increase as the number of mixing cycles is increased (the retrieval rate is decreased) further. There is also a significant

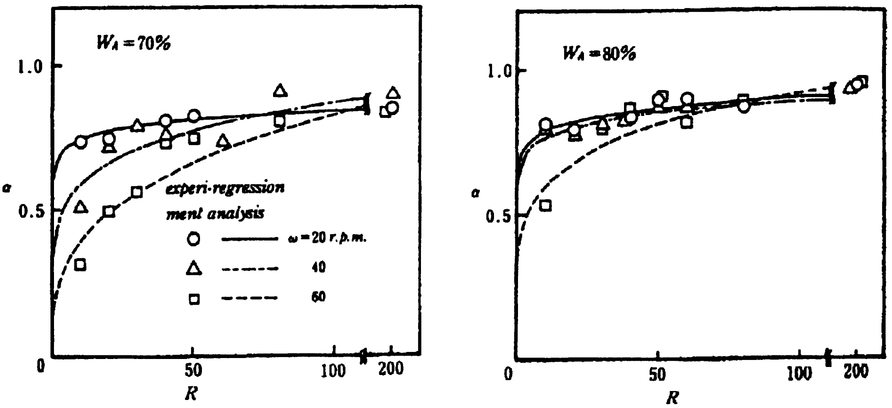
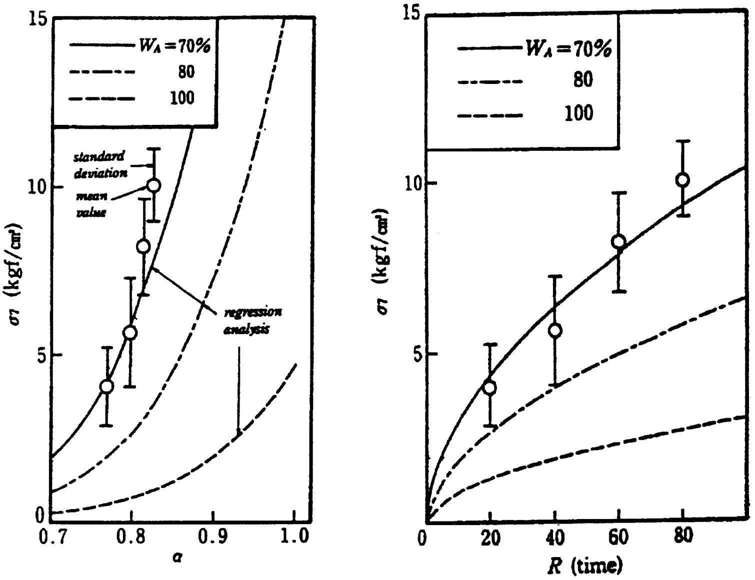
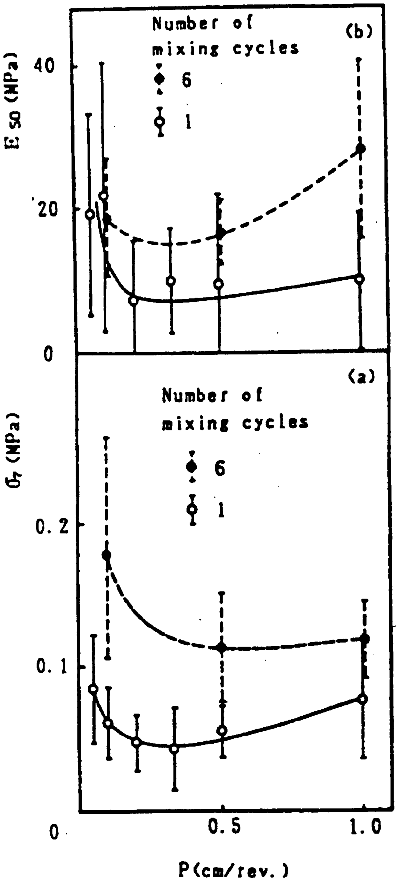


Fig. 6.7 Relation between degree of mixedness a and total number of revolution R. (Muro et al. 1987b).



a) b)

Fig. 6.8 a) Relation between compressive strength s and degree of mixedness a
b) Relation between compressive strength s and the number of revolution R
(Muro et al. 1987b).
(Note: 1 kgf/cm^2 = 100 kPa)



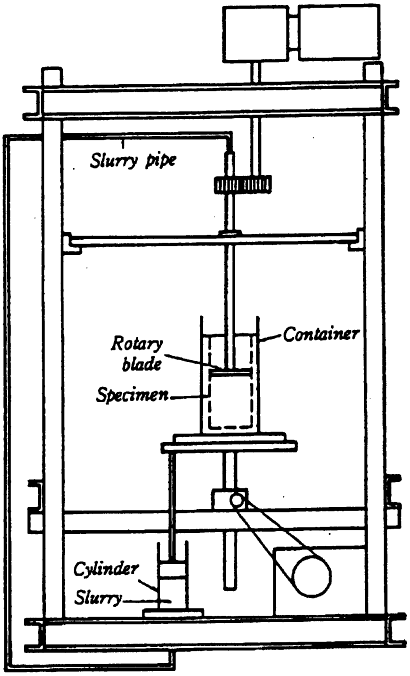


Fig. 6.9 **Relation between unconfined compressive strength s, modulus of deformation at half the ultimate stress E50, and the retrieval rate of the mixing tool P. (Muro et al. 1987a)**

increase in strength as the number of mixing cycles increases from one to six cycles. It is of course difficult to draw general conclusions from the tests, and the authors write that further studies are needed in order to understand the mechanical relations between degree of mixedness and the compressibility and strength parameters. That the degree of mixedness does have an effect on these parameters is clear, however.

Another interesting study of the effect of mixing energy on the degree of mixedness was reported by Nishida et al. (1996). Fig. 6.10 shows the results of mixing tests in which small cylindrical plastic beads were mixed with three clays differing in sensitivity. The degree of mixedness was determined by counting the concentration of beads in different parts of the mixture. In their study, too, the degree of mixedness was evaluated by the mixing index of equation 4.13. The tests showed that mixing energy has a major impact on mixedness at short mixing times, and that a higher degree of mixedness could be expected in clays of high sensitivity.

Yoshizawa et al. (1997) report on a number of interesting studies carried out in Japan, mainly in the 1980s. Fig. 6.11a shows the results of a comparison between different rotation speeds and their effect on the compressive strength of the stabilized soil. Fig. 6.11b shows the results of a comparison of different penetration velocities and their effect on compressive strength. These two studies show that the mixing time or number of mixing cycles have an impact on the strength of the stabilized soil. However, they do not show whether the rotation speed affects the result when the number of mixing cycles is kept constant.

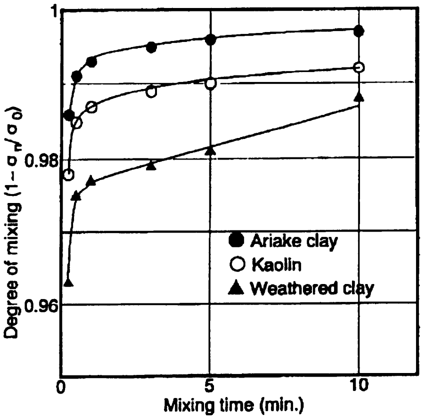
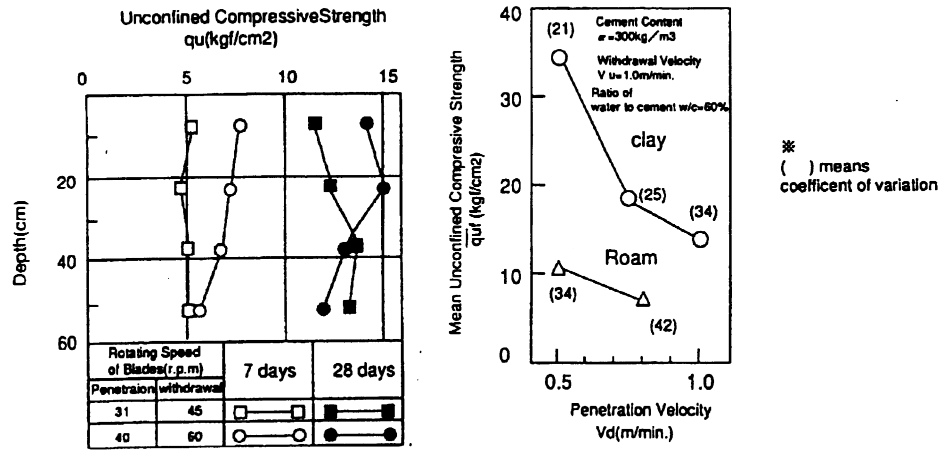
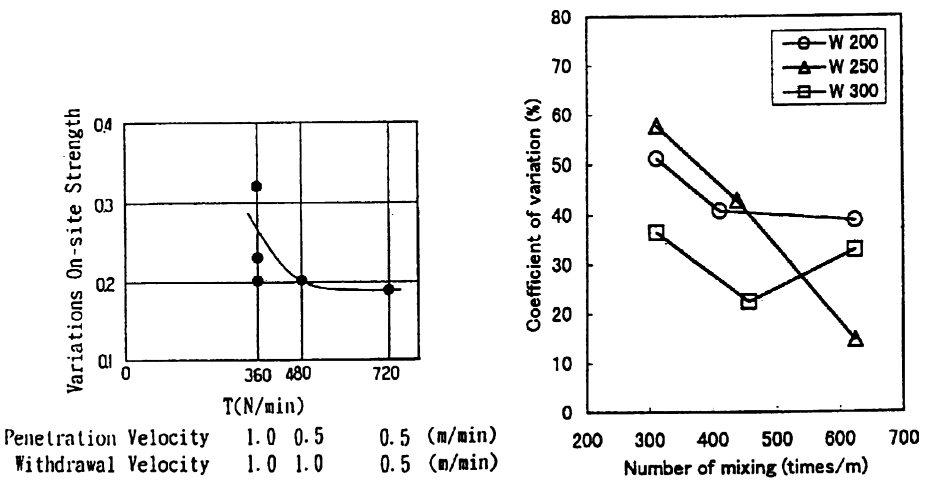


Fig. 6.10 Relation between mixing time and degree of mixedness. (Nishida et al. 1996)



a) b)

Fig. 6.11 a) Relation between rotation speed and compressive strength. (Yoshizawa et al. 1997 after Nishibayashi et al. 1985)
b) Relation between penetration velocity and compressive strength. (Yoshizawa et al. 1997 after Enami et al. 1986a)
(Note: 1 kgf/cm^2 = 100 kPa)



a) b)

Fig. 6.12 Relation between number of mixing cycles and the coefficient of variation of the strength achieved.
a) Yoshizawa et al. (1997) after Mizuno et al. (1988)
b) Hayashi & Nishikawa (1999).

Yoshizawa et al. (1997) also report results of strength measurements on samples from of stabilized soil which show that the coefficient of variation tends to fall as the mixing time increases, Fig. 6.12a. Hayashi & Nishikawa (1999) reported results from both laboratory tests and field trials in which the effect of mixing time on strength was studied in cement-stabilized peat. The investigation showed that mixing time had a significant effect on both strength and mixedness. As the number of mixing cycles increased from 300 to 600 rev/m, the coefficient of variation of the compressive strength fell from 40 – 60 % to 15 – 40 %, Fig. 6.12b.

Larsson et al. (1999) and Walter (1998) presents results from a study of the effect of mixing energy on unconfined compressive strength when mixing cement and lime–cement. A principal illustration of the equipment is shown in Fig. 6.13. Two different mixing devices was compared, where booth were of paddle type. The purpose for the comparison of two relatively equally devices was to study effects of small changes in the geometry. The incorporation of binder was performed by adding the binder in a vertical string just outside the centre of the soil sample. The deagglomeration and distribution of the binder was performed by letting the mixing device rotate throughout the mixture. The retrieval rate of the mixing device was varying and during the mixing operation the torque was measured. The compressive strength was used as a measure of mixture quality, on the assumption that strength will increase as the binder is better dispersed in the mixture. This study too indicates that mixing energy has a major impact on compressive strength at short mixing times, as shown in Fig. 6.14.

Omine et al. (1998a) treated cement-treated soil as a two-phase mixture consisting of improved and unimproved parts. In a series of laboratory tests the improvement rate (mixedness) was evaluated as the ratio of improved surface to total surface. The improved area was measured by means of a planimeter. A kaolin clay was treated with a cement slurry. Columns were manufactured in a cylinder of diameter 150 mm and height 150 mm. The results of this study showed that the improvement rate had a major effect on the compressive strength. A linear relation was obtained between compressive strength and the number of mixing cycles.

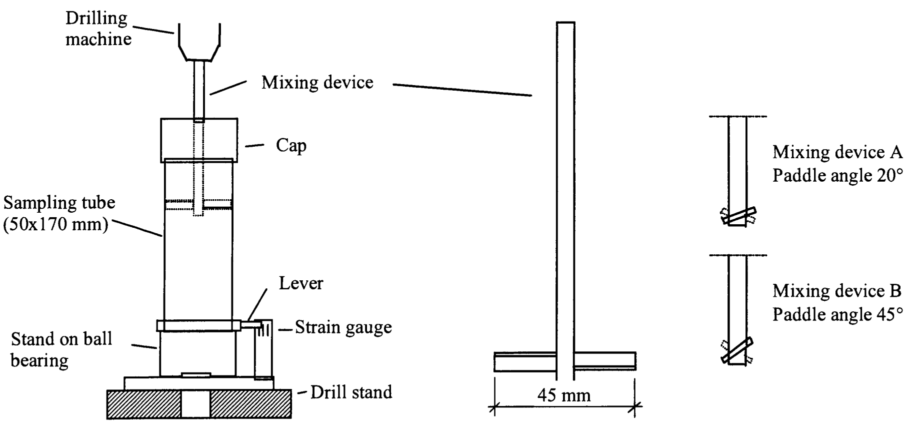


Fig 6.13 **Laboratory set up and the two mixing devises A and B (Larsson et al. 1999)**

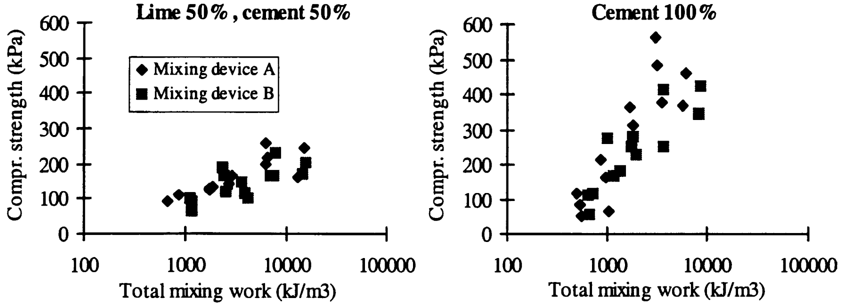
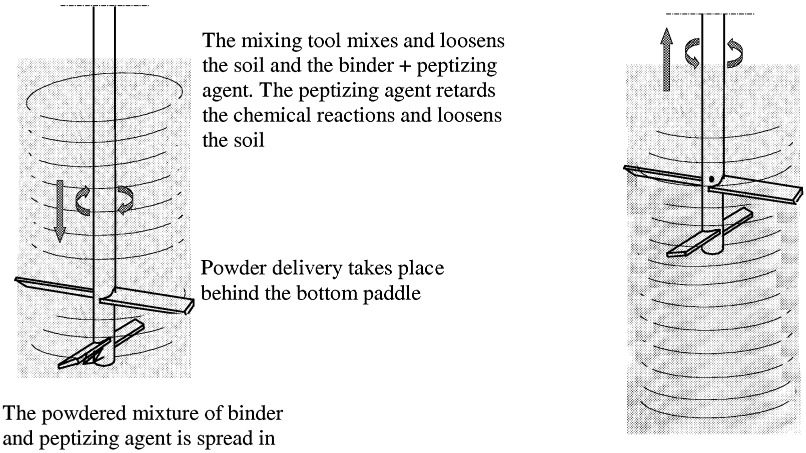


Fig 6.14 **Compressive strength as a function of mixing energy. Test specimens treated with lime-cement and cement. (Larsson et al. 1999)**

In the Scandinavian countries binder is almost exclusively used in dry form and is delivered to the soil as the mixing tool is withdrawn. The mixing energy could be increased by delivering the binder while the mixing tool is penetrating the soil. This would increase the mixing energy (cycles per column metre) at the cost of only a slight increase in the time for column manufacture. One reason why this technique is not used in Scandinavia is that it is difficult and energy-intensive to mix the soil and the binder once they have had time to react together. This problem is particularly acute in the case of lime, as the mixture very rapidly becomes granular. A way of overcoming the problem, not yet tested in Sweden, is to use a peptizing agent to change the rheological properties of the mixture. An in-principle design for such a mixing process is shown in Fig. 6.15. The peptizing agent could retard the chemical reactions, keeping the mixture loose and easily mixed. Dry peptizing agents exist which could be mixed with powdered binding agents. A further effect is that it could be considerably easier to evacuate the air that is injected into the soil when the mixture behaves like a liquid. The problem of evacuating air is discussed in section 6.7. Problems that have been much discussed are the uncertain quality of the base of columns, and whether the columns are supported on solid underlying soil. Injecting the binder while inserting the mixing tool would avoid the latter problem as the binder could be delivered from the base of the impeller.



The mixing tool mixes and loosens the soil and the binder + peptizing agent. The peptizing agent retards the chemical reactions and loosens the soil

Powder delivery takes place behind the bottom paddle

The powdered mixture of binder and peptizing agent is spread in the surrounding soil during insertion of the tool

The tool mixes and compacts the soil and the binder as it is withdrawn from the soil

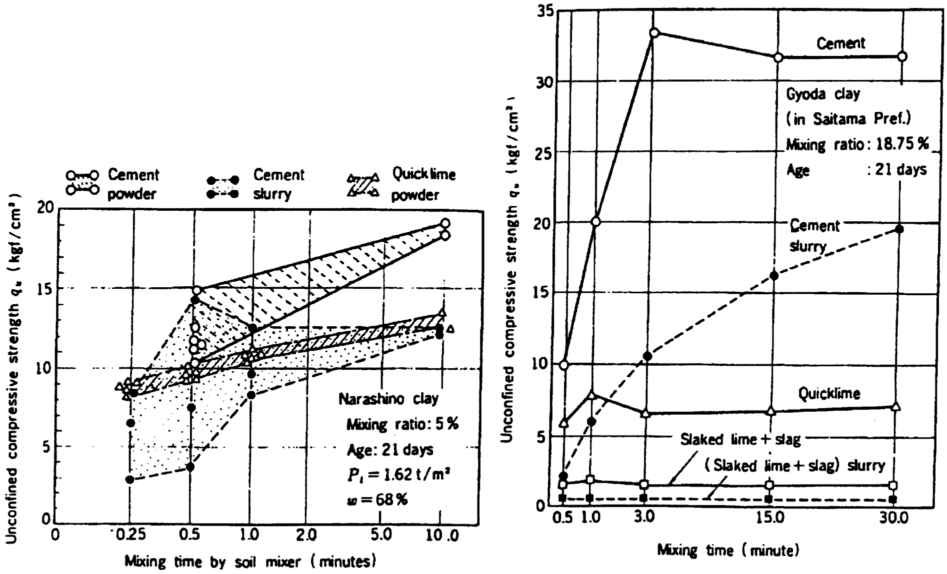
Fig. 6.15 **Principle of a mixing process in which binder and powdered peptizing agent are incorporated in the soil as the rotating tool is inserted into the soil.**

Type and quantity of binder

Walter (1998) and Larsson et al. (1999) presented a very simple laboratory device in which binder was mixed directly with soil samples (in standard 50×170 mm sample tubes) as shown in Fig. 6.13. Mixing binder with undisturbed soil permits the rheological properties during the mixing process to be investigated. The samples were mixed using two simple mixing tool geometries. The total mixing energy was evaluated by varying the retrieval rate of the mixing tool and measuring the torque during mixing. The results showed that in the order of two times more energy was consumed when the binder consisted of a lime-cement mixture (powder) than when it consisted of cement alone. Since mixture quality depends strongly on the mixing energy when the binder consists of cement, the implication is that mixing tools can and should be used which are better able to transfer energy to the mixture.

Chida (1982) also concluded that the type of binder has an effect on the mixing process and its outcome. Chida studied the effect of the type of binder, powder or slurry, on the strength of laboratory-prepared specimens. The results showed that when powdered cement was used as binder, the strength increased as a function of the mixing time during preparation of the specimens. With cement binder the compressive strength increased up to mixing times of around 3 minutes. With longer mixing times the compressive strength remained relatively constant, Fig. 6.16b. The results in Fig. 6.16a showed that using cement powder and cement slurry, the dispersion of the results was greater for short mixing times. The compressive strength is less dependent on mixing time when quicklime is used as binder, a finding also reported by Larsson et al. (1999).

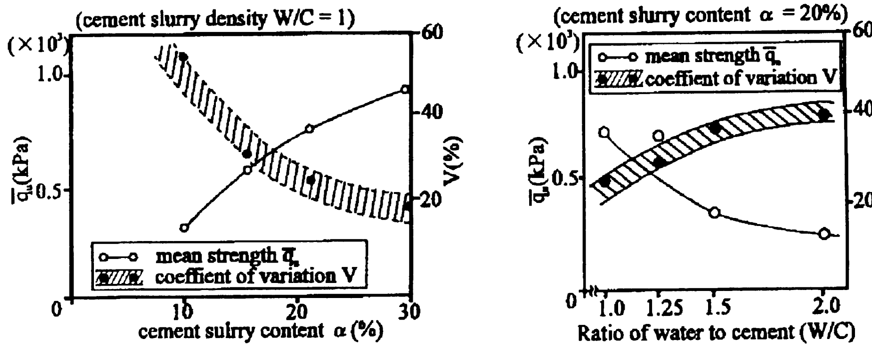
There is no question that the quantity of binder affects the strength of stabilized soil, however it can also affect the distribution of the binder and the dispersion of the strength values. Asano et al. (1996) studied the compressive strength and coefficient of variation while varying binder content for three types of binder. The results showed that when using a cement slurry, the coefficient of variation fell from ~40 % to ~20 % when the binder quantity was doubled. Matsuo et al. (1996) found a similar drop in the coefficient of variation with a doubling of the binder (cement slurry) content, Fig. 6.17a. However, their results suggest that the effect on the dispersion is greatest at low binder contents. Matsuo et al. (1996) also report results of a study showing that the coefficient of variation increases with the water:cement ratio, suggesting that a greater quantity of mixing water impairs the mixing efficiency, Fig. 6.17b. The effect of a greater quantity of mixing water on the mixing process depends on the initial rheological properties of the soil. When water is mixed with a soft soil with a high water content, the soil breaks up into lumps which will be entrained by the mixture while undergoing relatively little mixing themselves.



a) (Chida 1982)

b) (Chida 1982)

Fig. 6.16 Relation between compressive strength and mixing time with different binders.



a)

b)

Fig. 6.17 Change in strength and coefficient of variation of stabilized soil as: a) the binder quantity is varied; b) the water:cement ratio in the binder is varied (Nishibayashi et al. 1988, Matsuo et al. 1996).

Mixing tool design

No fundamental scientific studies have been published on the geometry of the mixing tool and its effect on the mixing process in the context of deep mixing. The few studies on tool design that have been reported are somewhat of a "sales" character, often presented by private companies at conferences or in periodicals specializing in equipment.

Dong et al. (1996) studied the effect of tool geometry, mixing time and rotation speed in a series of laboratory tests. Columns of diameter 400 mm and height 1000 mm were installed in a clayey sand of compressive strength ~29 kPa. The binder was a cement slurry. Two different types of mixing tool were used: type A, with two levels of paddles, and type B, with one paddle and a frame-like blade configuration rotating in opposite directions. Fig. 6.18 shows the 7-day compressive strength as a function of the retrieval rate for each tool. The results show that the retrieval rate or number of cycles of the mixing tool do have an effect on the strength and that tool B is probably more efficient than tool A. The authors also write that the degree of mixedness, based on visual observations, is better at higher rotation speeds. Unfortunately it is difficult to separate the rotation speed from the number of mixing cycles, since lower speeds were used with large retrieval rates and higher speeds with small retrieval rates.

Yoshizawa et al. (1997) reported a number of studies in which the effect of mixing tool geometry was investigated. Fig. 6.19 shows a comparison of the achieved compressive strength when a tool has one or four shafts. An example of a tool with multiple shafts appears in Fig. 6.36. The results show that smaller dispersion and higher strength are achieved with four shafts than with a single shaft. The reason for this, according to the authors, is that neighbouring shafts rotate in opposite directions, producing interacting mixing effects in the overlap. The improvement in mixing efficiency may be explained by the kneading action between the blades mounted on different shafts.

Yoshizawa et al. (1997) further report results from a series of tests comparing two different configurations of six blades on a dual-shaft mixing tool, Fig. 6.20. The tool labelled "H" has six horizontal paddles. In the tool labelled "0 – 1" the two middle paddles are replaced with two stirrups (termed Oval DM

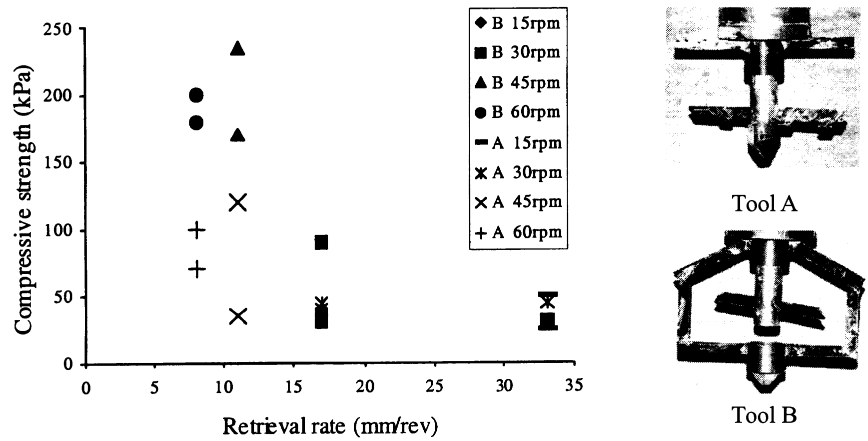


Fig. 6.18 **Relation between mixing tool retrieval rate and compressive strength (after Dong et al. 1996, modified)**

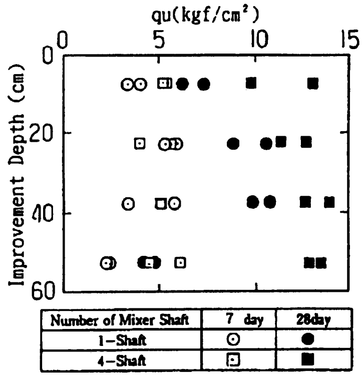


Fig. 6.19 Comparison of compressive strengths obtained with a tool having one or four shafts (Yoshizawa et al. 1997 after Nishibayashi et al. 1985)

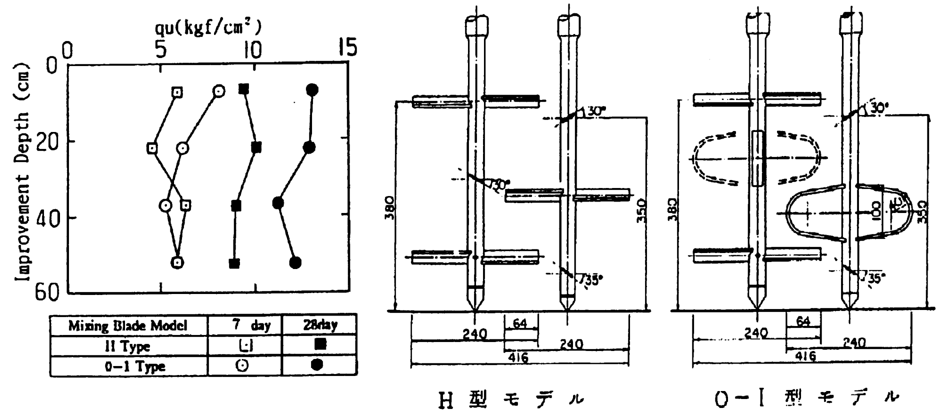


Fig. 6.20 Comparison of compressive strengths obtained with two different designs of a mixing tool (Nishibayashi et al. 1985, Yoshizawa et al. 1997)

according to Nishibayashi et al. 1985). The stirrups shear the earth in different directions (compare with Fig. 2.5, Chapter 2.5). The authors write that the stirrups are particularly effective in highly viscous (plastic) soils. However, it must be noted that the replacement of blades with stirrups entailed fitting the mixing tool in this study with more blades (compared to the H-tool).

Al-Tabbaa & Evans (1999) and Al-Tabbaa et al. (1999) compared three types of mixing tool in a series of laboratory tests and field trials. However, no quantitative comparison of the tools was made, the comparison being based on visual observation of the mixing results. The three tools studied in the laboratory are shown in Fig. 6.21. Tool 2 is a simplified version of a number of commercially available tools. Tool 3 is similar to Tool 2 but has fewer blades and has cutting teeth at the bottom. The tools were of diameter 6 – 9 cm. Tests were carried out with both water-based and powdered binders. The results indicated that the tools achieved equally good results in pure sand. In sandy clay and cohesive material Tool 2 was significantly more effective than Tool 1. Better mixing results were also obtained when the soil was premixed before binder was added.

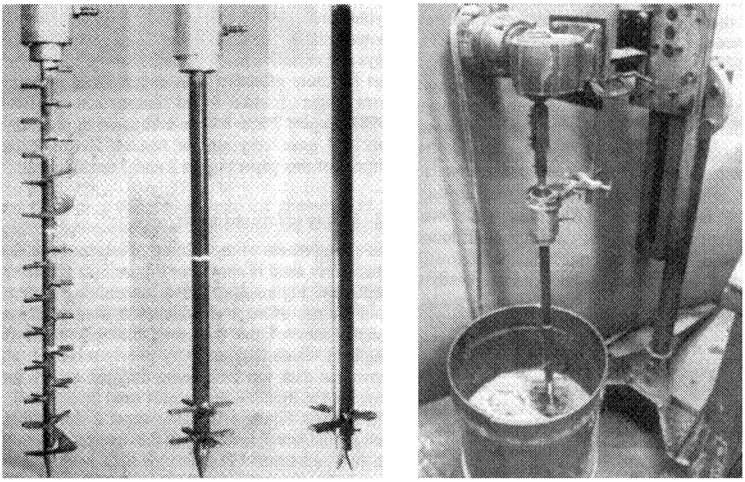


Fig. 6.21 Three mixing tools investigated in the laboratory. (Al-Tabbaa et al. 1999)

Aalto & Perkiö (2000) show a test- procedure and arrangement for a project concerning laboratory manufactured dry deep mixing columns by different mixing tools. Seven different mixing tools were compared according to Fig. 6.22. Aalto (2001) concluded that stronger and more uniform columns are made by the "cone type mixing tool". During manufacturing the columns made by the "pot type mixing tool" tended to lift up the soil mass. Furthermore, Aalto (2001) studied the influence of the consolidation pressure during the curing period. The test showed that the mixing work has an influence on the strength when the columns are loaded, Fig 6.22. The mixing work had a lesser influence on unloaded columns. The laboratory investigation is followed up by extensive field tests, presented by Aalto (2003). One important conclusion from the field tests is that the geometry of the mixing tool can have a considerable influence on the column strength.

Abe et al. (1997) compared the difference between two types of mixing tools; open-type blade and horizontal-type blades. The results showed that the in-situ strength obtained by the open-blade mixing tool is larger in the Humic soil layer according to Fig. 6.23. No discussion concerning causes is however metioned in the English reviews by Nozu (1998) and CDIT (2002).

In model experiments it is important to study the impact of scale effects, such as small vertical and horizontal stresses in the mixture. There is a risk of the mixture clinging to the rotating mixing tool during withdrawal. The mixture may also clump together between the blades, particularly when lime is used as a binder. Such effects were not investigated or remarked upon in the studies reported above.

Workers in agricultural research have studied the behaviour of discs, e.g. harrows, in the soil. The principle is to produce maximum movement in the soil with the least possible expenditure of energy, i.e. the same principle as in mixing soft soils with binders. Ali Al-Ghazal (1989) studied the effect of different angles, diameters, depths and spacings of different circular discs. Simple models of interaction between soil and discs were developed based on the Mohr-Coulomb failure criterion. The concept of specific resistance (= force/area) was used to rate the efficiency of the discs. The effects of different factors were studied in large-scale model tests, and the results showed that increases in the factors angle, diameter, depth and spacing of the circular discs caused an increase in the area of soil disturbance and a decrease in the specific resistance.

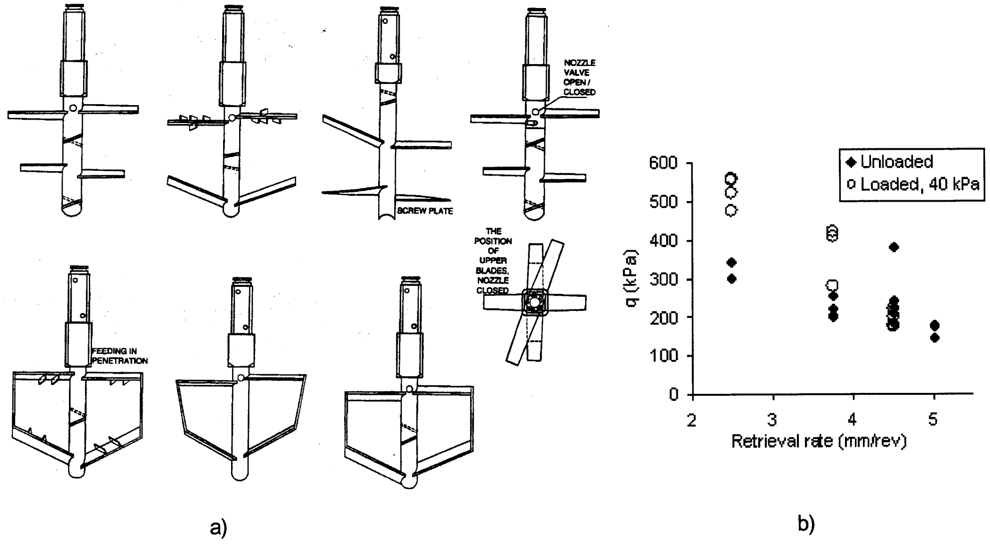


Fig. 6.22 Seven mixing tools used in laboratory tests (Aalto 2001). b) Unconfined compression strength vs. retrieval rate (after Aalto 2001, modified)

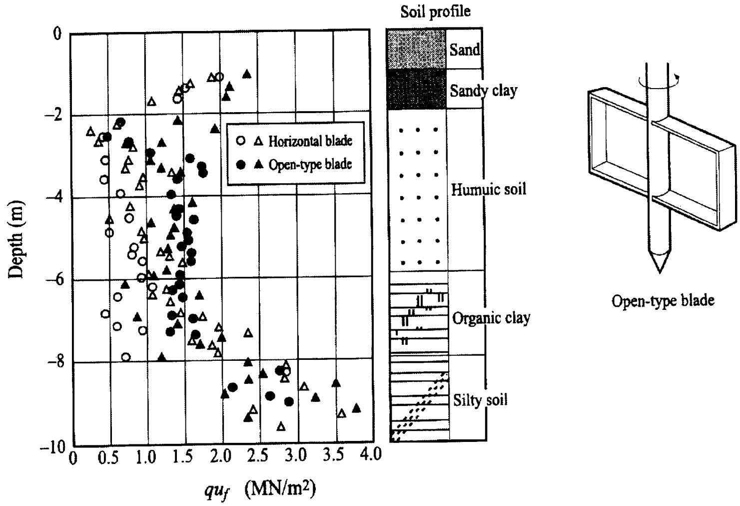


Fig. 6.23 Compression strength on samples taken from columns manufactured by two types of mixing tools (Nozu 1998 and CDIT 2002 after Abe et al. 1997)

Rheological properties of the soil

The complex rheological properties of soft soils are discussed in Chapter 5. The mixing of fine soils with binders is particularly difficult when the soil is extremely cohesive and sticky at moderate to high water contents. The type of soil and its rheological behaviour have a considerable impact on the efficiency of a mixing process. It is relatively easy, for example, and takes only limited effort to mix cement and dry sand to produce a mixture with small concentration variances. A considerably greater and more intensive mixing effort is necessary to mix cement with a cohesive clay. Unfortunately, no extensive investigations have been made into the effect of soil rheology on the mixing process in deep mixing.

Extensive studies of technical properties have been carried out in connection with shallow subgrade stabilization with lime and cement (reviewed by e.g. Sherwood 1993). The properties of deep-stabilized soft soils are similar to those obtained in surface-stabilized soils. The main difference between deep and surface stabilization is that most soils that are candidates for deep stabilization are water-saturated and therefore not compacted. The laboratory procedures for manufacturing stabilized soil are also very similar. For these reasons we shall also discuss experience of soil treatment with lime and cement for the purpose of surface stabilization.

In the late 1950 extensive studies were carried out at MIT (Massachusetts Institute of Technology, USA) on e.g. the effect of water content on the mixing process when mixing fine soils with lime or cement (Freitag et al. 1961). Laboratory studies showed that the water content was one of the most significant factors affecting both the power consumption and the time necessary to achieve a given degree of mixedness. The tests showed that for a given degree of mixedness, the most favourable water content in order to obtain the fastest possible mixing was around the plastic limit. However, it was around this same water content that the greatest mixing energy was required. Table 6.2 shows the effect of water content on a number of mixing characteristics. Note that it is easiest to mix a completely dry powder or a liquid. The tests also showed that the effect of the rotation speed of the mixing tool varied depending on the water content. At low water contents, below the plastic limit, the most effective mixing was at low rotation speeds. At high water contents the most effective mixing was obtained with high rotation speeds.

Freitag et al. (1961) also reported results of experiments with the use of additives to change the rheological properties of the soil. The tests showed that the energy consumption and efficiency could be significantly impacted by the treatment with dispersing or aggregating agents. When the water content of the soil was above the plastic limit it was found that aggregating agents were most effective for reducing the energy consumption and improving mixing efficiency. Dispersing agents did not increase efficiency or mixedness but did reduce the energy consumption in soils with high water contents.

Table 6.2 Effect of water content on mixing process parameters. (Freitag et al. 1961)

	Increasing water content →					
State	**Powder**	**Pellets and powder**	**Pellets**	**Plastic**	**Sticky**	**Liquid**
Energy consumption	Low	Low to moderate	Moderate	High	Moderate	Low
Homogenization rate	Rapid	Slow	Very slow	Rapid	Slow	Rapid
Energy efficiency	Very high	Favourable	Favourable to poor	Poor	Favourable to poor	High

When powdered quicklime, CaO, is used as binder the rheological properties change very rapidly once the lime comes into contact with the soil. In soft soils, the natural water content is often near the liquid limit. The incorporation of lime causes a rapid dewatering and the mixture becomes more plastic and difficult to work. If this rapid chemical reaction is not desirable, a peptizing agent may be used to retard and delay the reaction process. A possible application, as mentioned above, is when binding agent is delivered while the mixing tool is being inserted into the soil. However, no studies have been published which show whether peptizing is an effective method for changing the rheological properties of a mixture when using dry quicklime as binder.

Nishida et al. (1996) reported results illustratind the effect of the sensitivity of the soil, Fig. 6.10. The results showed that a higher degree of mixing may be expected in clays with high sensitivity.

It is difficult to measure and determine the rheological behaviour of soft soils in the partially remoulded state at high shear rates, as discussed in Chapter 5.3. In Japan the possibility has been investigated of using the mixing tool as a rheological measuring instrument during the mixing process (Hata et al. 1987, Aoi & Tsujii 1996). According to the authors, the method may be developed by e.g. measuring the energy input during the mixing process and relating it to soil properties.

Compaction energy

There has been discussion of how soon and how heavily the ground surface may be loaded after deep mixing. It may be important to impose the greatest possible consolidation stress at an early stage while the chemical reactions are at their most active. In Sweden normally no compaction is done apart from that brought about by the mixing tool. Since it is customary in Scandinavia to use air as the transport medium for a powdered binder, large amounts of air are injected into the soil. Unless the air is evacuated, the compacting capacity of the mixing tool may assume great importance for the mixing process and the strength gain. Even surface compaction may have a significant impact. The interfacial area between the binder and the soil is a measure of the mixture quality and the efficiency of molecular diffusion. The compaction energy may thus have an impact on the mixing process, since increased density reduces the distance between the binder particles and the soil particles. In Japan the binder is generally premixed to a slurry, with the result that compaction is of little consequence provided the soil to be stabilized is water-saturated.

Aalto & Perkiö (2000) and Aalto (2001) studied the influence of the consolidation stress during the curing period. Columns were manufactured by dry deep mixing in the laboratory using cement as binder. With reference to unconfined compression tests the results showed that the mixing work (retrieval rate) had a significant influence on the strength when the columns were loaded by 40 kPa, Fig. 6.22b. However, the mixing work had no influence on the strength when the columns were unloaded during the curing period. It must be mentioned that laboratory model columns are made by a low confining pressure that may have an influence on the strength properties. The same problem can appear at shallow depth for the full scale columns.

In shallow subgrade stabilization, compaction of the stabilized material is one of the most important operations (Assarsson 1972). It is well-known that the compaction energy and the type of compaction have an effect on the density and strength of non-saturated cohesive soils (e.g. Bell 1977). An important factor in compaction is the delay between the incorporation of the binder and the compaction operation ("aging" or "mellowing"). This delay may affect the compaction properties, producing a loss of strength in stabilized soil (e.g. Uppal & Bhasin 1979, Sweeney et al. 1988, Sivapullaiah et al. 1998a, Holt & Freer-Hewish 1998, 2000, Lindh 2000). Another used term is the "working period" that indicates the time from incorporation of the binder to compaction where a uniform stabilised material can be accheaved.

Sivapullaiah et al. (1998a) conclude from their own laboratory tests that the delay between binder incorporation and compaction has varying effects on strength depending on the binder (slaked lime) content. The longer the delay, the greater is the strength loss and the lower is the density attainable by compaction. With lower quantities of binder the delay has negligible effect on density and strength. With larger binder quantities, on the other hand, there is a considerable effect on the strength and compaction parameters, and therefore, according to Sivapullaiah et al. (1998b), a long delay between mixing and compaction should be avoided.

Lindh & Hjalmarsson (1975) also concluded from laboratory tests that a long delay impairs strength at high cement contents. The delay has a particularly large impact on cement-stabilized soil (Kézdi 1979). A study reported by Sivapullaiah et al. (1998b) showed that impact of delay is affected by the composition of the binder, making it difficult to draw general conclusions.

The time from incorporation of the binder to compaction, or the working time, should be about two hours for cement-stabilised soil according to Sherwood (1993). The working time for lime-stabilised soil is somewhat longer, as long as 72 hours according to British Lime Association (1990). The working period can however be increased by blending different binders (Lindh 2001, Lindh 2002). For deep mixing, the working times from a few hours to a few days, is a relatively short time. It is difficult to adjust the loading of the columns to such short periods. The compaction of the binder-soil mixture should therefore be made by the mixing tool and not by loads on the ground surface.

With a rotating tool equipped with paddles or similar arrangements, the effectiveness of compaction depends on the kneading capacity of the tool. It is important that the energy input from the mixing tool is directed axially downwards in the mixture. It is further important that no part of the tool tends to lift the material or cause it to catch in the tool and thus be pulled upwards as the tool is withdrawn.

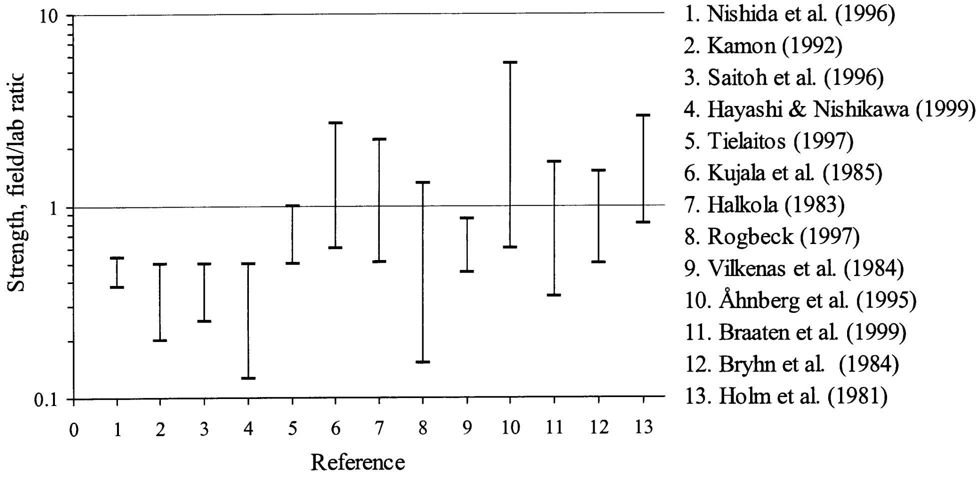


Fig. 6.24 **Relation of field results to results from laboratory-stabilized soils in a number of reported studies.**

6.5 LABORATORY PHILOSOPHY

Field studies of the mixing process are difficult and costly to perform. It is therefore appropriate for fundamental studies to be carried out in the laboratory environment using materials with controllable rheological properties and mixing tools with simple geometries. Such work may shed light on which phenomena are likely to be the most relevant for field trials. It should not aim to provide directly applicable data but to yield results that will suggest new approaches to the mechanism behind the real problem. To ensure that new findings are relevant, laboratory tests must keep in close contact with real-world problems. This will also ensure that problems are not over-simplified. Unfortunately, current laboratory methods for preparing test specimens tell us little about the mixing process. Some of the parameters reported in section 6.4 lie far outside the range of application of deep mixing. Examples are the laboratory preparation of specimens consisting of completely remolded soil and the mixing of specimens many times more than it is reasonable to do in the field. Such methods can teach us nothing about the soil's rheological properties, which are very important parameters of the mixing process. Current laboratory methods are fixated on the factors binder type and binder quantity. The primary purpose of laboratory tests is to tell us whether it is possible to stabilize a soil (Carlsten 1991).

It is an established opinion in the deep mixing industry that the mixing process cannot be simulated in the laboratory (e.g. Terashi 1997, Bruce et al. 1998a). The only variables that can be simulated are the type and quantity of binder. However, there is an aspiration to discover an empirical relation, based on accumulated experience, between the strength achieved in the laboratory and that achieved in the field. But such empirical relationships can only be found if the process parameters of the laboratory tests are within the range of application of the method. Since the factors affecting mixing as discussed in section 6.4 are not shown to be mutually independent, there is a serious risk that incorrect conclusions will be drawn if one or more of these parameters are kept constant far outside the application range.

Fig. 6.24 presents some of the reported relations between strength measured in the field or on samples taken from *in-situ* stabilized soils, and the measured strength of laboratory-prepared specimens. The purpose of presenting this data is to illustrate the difficulty of attempting to apply experience drawn from comparisons between lab and field. It is obviously difficult to apply such experience when one is comparing results of tests done by different methods or based on irreconcilable assumptions. The relation between field and lab strength measurements also varies with the number of measurements.

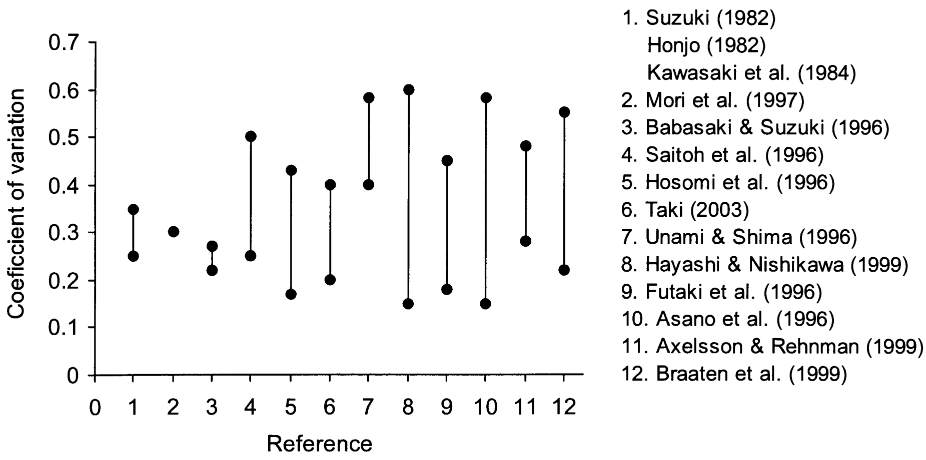


Fig. 6.25 **Coefficient of variation evaluated from compression tests in a number of reported studies.**

A comparison between results obtained in laboratory tests and results from field trials or from measurements on samples of in-situ stabilized soils is further complicated by the variation in the mixture quality, and hence the strength, of stabilized soils. In Japan compression tests are carried out on drill cores from stabilized soils as a means of quality control. Fig. 6.25 shows results from a number of reported studies in which the coefficient of variation of compression tests was evaluated. These results show that while the coefficient of variation is normally in the range 0.2 – 0.4, larger dispersions of results can be observed. According to Suzuki (1982), Honjo (1982) and Kawasaki et al. (1984), the dispersion in plan over column cross sections is of the same order. The wide variations in the coefficient of variation and in the relation between laboratory tests and field trials reported by Hayashi & Nishikawa (1999) is caused by the variations in the mixing time (number of mixing cycles) in their study.

It is unusual that the number of samples of stabilised soil extracted in a Swedish project is sufficient to permit evaluation of the coefficient of variation in e.g. compression tests. However, Axelsson & Rehnman (1999) presented a large number of results from lime-cement columns. Fig. 6.25 also presents the coefficient of variation from a large number of compression tests on specimens from lime-cement columns in Norway (Braaten et al. 1999). With column penetration tests, which test a large part of the cross-sectional area of a column *in-situ*, large variations can be obtained between different columns. Kujala et al. (1985) report standard deviations in the order of 15 – 60 % of the mean.

One purpose of today's standards for the laboratory preparation of specimens is that they should result in a best improvement effect in respect to the degree of mixing which should be considered as a sort of index for the soil in concern (Babasaki et al. 1997). The result is generally assessed on the basis of strength measurements. This maximum degree of mixedness is to be regarded as an index of the soil in question and is to be correlated against field data. However, a number of factors indicate that it is not possible to regard laboratory measurements as the best improvement effect. In section 6.4 we discussed a number of factors affecting the mixing process and its result. It should be beyond question that the mixing process is extremely complex and that the same factor may have different effects on it under different conditions. An example of this is the observation that different laboratories may return different results even when stabilizing the same soil with the same binder (Edstam & Carlsten 1999). There are often one or more parameters in which laboratories differ. Thus, having a standardized laboratory method is not the same thing as achieving best or optimum improvement effectiveness. For example, it is well known that the compaction work influence the mixiture. Aalto (2001) illustrates this influence in Fig. 6.22. Another factor that should be kept in mind is that a lengthy mixing procedure can totally alter the soil structure and in the worst case result in “over-mixing”. Pousette et al. (1999), reporting on laboratory mixing of specimens of peat, cement and slag, noted that long mixing times had a negative effect on stabilization, which was attributed to the breaking down of the peat fibres.

Temperature and water content during storage have a major effect on the properties of laboratory specimens. A major factor in the discrepancies between laboratory tests and field trials is the difference in temperature during hardening (Viatek 1997). Hence there is discussion of whether the *in- situ* temperature regime can be simulated in the laboratory, and Viatek (1997) present examples of temperature curves for different binders.

When quicklime is used as a binder the mixture dries out, and the sample may require wetting in order to allow the lime to hydrate and restore the natural water content (Brookes et al. 1997). The procedure for simulating seepage of water from the surrounding soil into the stabilized soil is relatively complex. Trials by Brookes et al. (1997) showed that the wetting of specimens over a long period resulted in softening of the stabilized soil, which is not characteristic of *in-situ* behaviour.

Al-Tabbaa & Ewans (1999) stated that laboratory-scale auger mixing should become an integral part of a treatability study since they observed similarities between the properties of laboratory-scale test and full-scale test. They studied a laboratory-scale modelling of stabilisation of a contaminated site by deep mixing and they concluded that the laboratory-scale test can simulate in situ conditions in a way which is not possible by manual mixing.

In a variety of other applications and sciences there has been a growing trend towards simulating, wherever possible, the processes that occur in the field. Four examples of such applications in the construction industry are:

1) Shallow subgrade lime stabilization. British Lime Association (1990) states that when manufacturing laboratory specimens it is important that the laboratory preparation does not differ significantly from field conditions;
2) Paving works (VTI 1999). Specimen preparation by the Marshall method is being increasingly abandoned because the properties of specimens produced by this method do not conform to those in the field;
3) Soil compaction (Venkatarama Reddy & Jagadish 1993, Kouassi et al. 2000). The laboratory compaction of soil samples by the Proctor method is increasingly criticized because the method does not resemble field compaction in terms of energy input and compaction mechanism;
4) Block stabilization (Hoikkala et al. 1997). In Finland a procedure has been developed for the laboratory mixing of peat samples which simulates the actual field loads.In Sweden, a similar laboratory procedure has been adopted (Axelsson et al. 2000).

The present review of the literature on laboratory tests indicates that efforts are being made to standardize laboratory mixing and testing, although the prevailing opinion is that laboratory simulation of mixing processes is not possible. There are also efforts directed at laboratory simulation of certain parameters of the mixing process. In the literature, however, one parameter is generally considered at a time. Nobody has yet attempted to simulate the whole mixing process.

Unless laboratory tests aspire to add to our knowledge of the mixing process in deep mixing, our understanding of the parameters affecting this process is likely to remain limited for a long time to come. This may well impede the further development of deep mixing methods.

6.6 MIXING TOOLS

Mixing tools in Scandinavia

Classification of existing tools

The most widely used mixing tool in Sweden at present is that referred to as the "standard tool", Fig. 6.26. A number of variations exist, but the differences in terms of the basic mixing mechanisms are slight. In its basic geometry the standard tool resembles impellers of the anchor agitator type, see Chapter 3. However, there are essential differences between them as a result of which their dominant mixing mechanisms differ. Mixing mechanisms are described in Chapter 2.

Anchor agitators are used for mixing high-viscosity liquids, pastes and plastic materials. They are less well suited for mixing viscoelastic materials in which forces producing movement rapidly die out due to elastic drag and shear resistance. In a mixture with these properties it can be difficult for an anchor agitator to produce movement in every part of the mixture. Anchor agitators are equipped with paddles which are generally vertical, round, or tilted at ~45° to the horizontal in order to force the largest possible volume of feed into movement around the blades (cf. Fig. 3.9).

The blades of the "standard tool" are generally tilted at a very small angle to the horizontal (~10°–20°). This means it is difficult for the tool to produce the tangential movements in the mixture which are the dominant flow pattern for paddles. The small angle of the blades to the horizontal rather places the

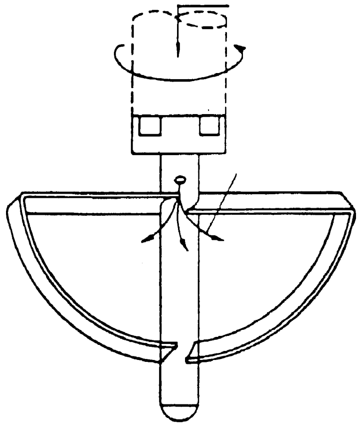


Fig. 6.26 The standard mixing tool. (SGF 2000)

tool in the propeller category (cf. Fig. 3.2). Propellers generate mainly axial flow, see Fig. 3.1. (They may be compared with ceiling fans, which even at low speeds generate axial flow in the room air; but a propeller operating in a liquid must run at high speed to produce sufficiently large movements.) On the basis of this classification the "standard tool" may be classed as being intermediate between a paddle and a propeller.

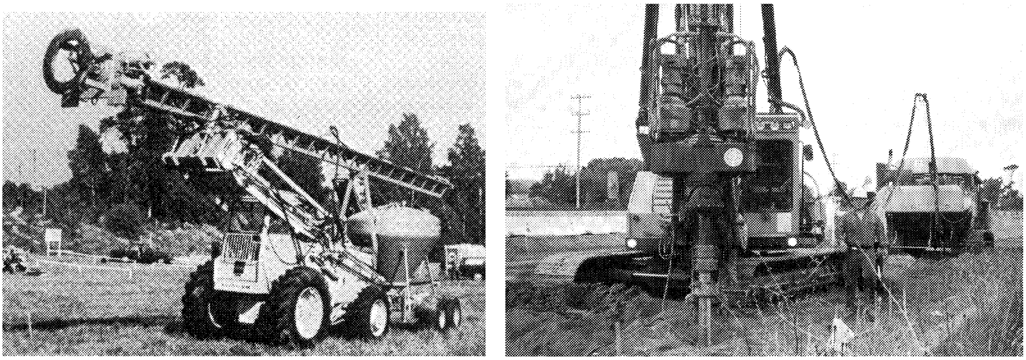
When mixing soft soils, no significant axial movement of the mixture is likely to occur with existing tools. The tangential and axial movements generated by the "standard tool" are probably limited to a very small volume close to the blades, as illustrated in Fig. 5.6. Dispersion of the lime and cement particles requires movement of the ingredients to occur so that the necessary shear forces may be produced, the materials deformed, agglomerates broken down, the interfacial area between the components increased, and the scale of segregation reduced. Without movements in the material the added components cannot be distributed in the mixture.

With each cut that the blades of the tool make through an mixture element, the thickness of the element is reduced, i.e. the mixing process takes place through the distributive mixing mechanism (cf. Fig. 2.9). Unfortunately the "standard tool" does not give the sliced elements much opportunity to redistribute themselves between successive slicing actions. It is also probable that the existing tool does not slice and remould the elements a sufficient number of times for the distributive mixing mechanism to be effective. Distributive mixing is generally unsuitable as the dominant mixing mechanism for the dispersion of solid particles in plastic and viscoelastic materials, where high shear stresses are necessary in order to break down agglomerates.

The dominant mixing mechanism with the "standard tool" is distributive mixing, plus laminar shearing within a very restricted volume close to the blades. For its primary purpose – dispersing lime and cement particles in the soil – we must unfortunately conclude that the "standard tool" is not a very efficient or appropriate mixing tool for all the applications in which deep mixing is used. Particularly in the case of very soft clays with a high water content, its limited capacity to generate movement in the mixture may give rise to problems.

Tool development in Scandinavia

Development of equipment for dry deep mixing in Sweden was begun in the early 1970s by Lindén-Alimak AB, and the first prototype may be seen in Fig. 6.27a. The method was adapted for the market by BPA Byggnadsproduktion AB (Boman & Broms 1975). During the early phase of development a variety of types of mixing tool were tried, and the tool shown in Fig. 6.28a was found to give the best results in



a) Lime column machine.
(Broms & Boman 1975a)

b) Lime column machine, Junttan.
(Stabilatören 1999)

Fig. 6.27 Machinery development from first prototype to today's machine type.

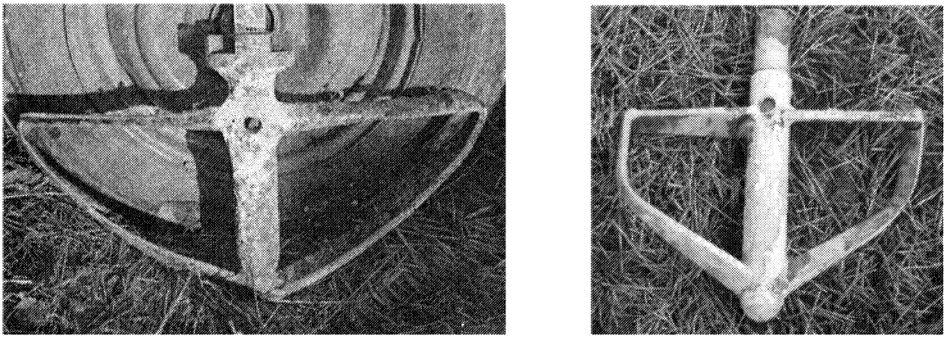
soft clay. In coarser and more solid soils an auger type tool gave better results. The aim in the early stages of development was a device of high production capacity. In the years 1975 – 1979 many types of mixing tool were tested (Wikström 1979). A tool with a number of tilted vanes (paddles) was trialled, but it was found that the clay stuck to the tool, impeding mixing. In the course of development the feed orifice was moved from below the top vane as in Fig. 6.28a to a position above the vane as in Fig. 6.26 and Fig 6.28b. The trials of the early tools are unfortunately unpublished and it is therefore not possible to review and comment on the results.

Since the initial development of mixing tools in the 1970s, most projects have been carried out with tools of the type in Figs. 6.26 and 6.29a. Slight variations of the "standard tool" appear in Figs. 6.28b-f. Further tool development has been very limited. On the machinery side, however, development has been dramatic, as Fig. 6.27 may illustrate. How does it come about that the mixing equipment and the *in-situ* mixing process have remained practically unchanged? The answer may be that there is a lack of basic knowledge of the mixing process and the fundamental mixing mechanisms. Why is this knowledge still lacking after nearly thirty years' experience?

Until the 1990s the main use of the method was for reducing settlement and increasing stability for relatively low embankments. From the late 1980s, however, it began to be applied to stabilize excavations, cuttings and increasingly high embankments. In response to increasing demands for control, columns began to be exposed for visual inspection and even whole columns were recovered. Some columns exhibited a binder distribution that was not acceptable to the client. An answer to the above question may thus be that problems with column quality did not appear on the agenda until the end of the 1980s.

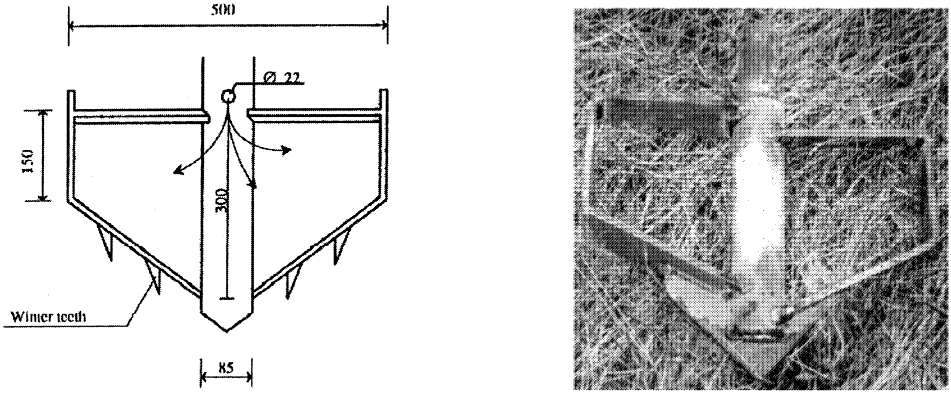
The development of mixing tools has been slow, and one reason for this may be that there is currently no incentive for contractors to develop new tools. Today's tendering procedures, with general contracts and conditions “recommending” a tool of the type in Fig. 6.26, make it economically unattractive for contractors to develop new tools. Another explanation may be that wear on the tools is severe and more complicated designs are prone to break down (Bredenberg 1999).

One problem is that improved column quality may make deep mixing more expensive. It is well-known today that mixing energy affects the quality and the strength gain of the column. It may be difficult to develop a tool that produces better results but does not require a higher energy input or longer mixing times. If the column quality normally achieved today is no longer accepted, a higher production cost may unfortunately be unavoidable due to longer mixing times and higher energy consumption.



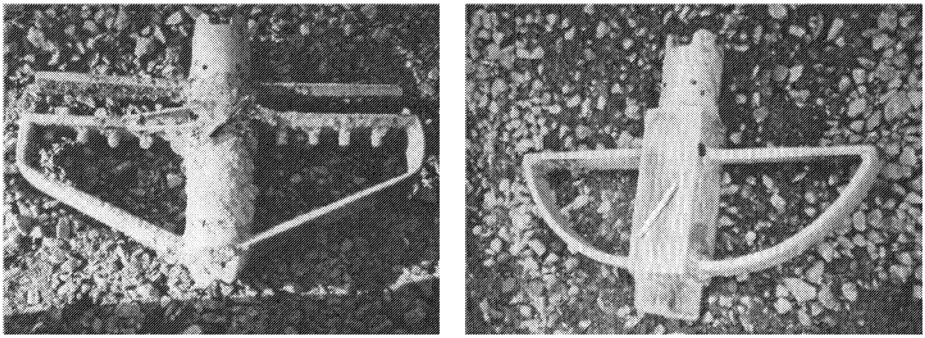
a) Mixing tool from early 1970s
(Boman & Broms 1975)

b) Mixing tool from late 1990s
(Photo: Morgan Axelsson)



c) Standard tool modified for winter conditions
(Rathmayer 1997)

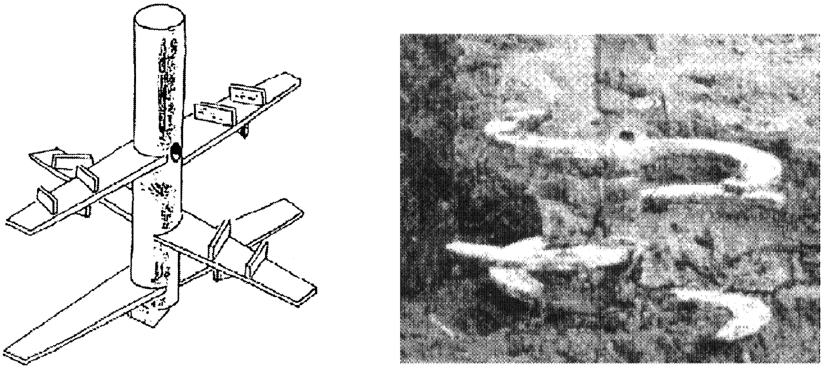
d) Standard tool, Hercules
(Johansson & Jons 1995)



e) Standard tool (EuroSoilStab 2002)

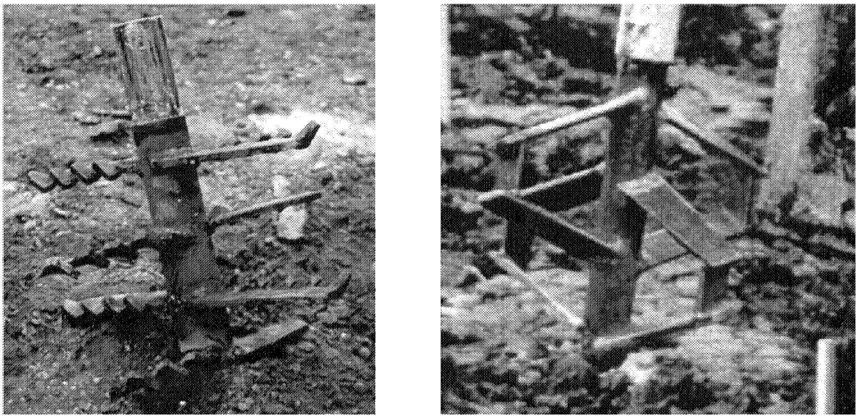
f) Standard tool (EuroSoilStab 2002)

Fig. 6.28 Some variations on the "standard tool."



a) "Pinnborr", LC-Markteknik. (Larsson 1999)

b) Modified KC mixing tool used for cell stabilization. (Jelisic 1999)



c) Tool developed by Hercules-Norén. (Johansson & Jons 1995)

d) Double-vaned tool. (Johansson & Jons 1995)

Fig. 6.29 Mixing tools that are used or have been tested in Scandinavia.

There is a lack of methods for assessing mixture quality. As discussed in Chapter 4, mixture quality is often assessed and compared on the basis of the finished product, sometimes using methods that have no direct relation to the performance of the mixing tool. Thus the difficulty of comparing evaluate. It is important to note, however, that the mixing tool and mixing process themselves are a rheological measuring instrument in deep mixing. By measuring the force applied to the system in the form of torque, it may be possible to study the rheological properties of the soil.

A number of attempts have in fact been made to develop new mixing tools. However, testing is generally very limited and the results are rarely reported. There is therefore a severe lack of experience in Scandinavia of the performance of different types of tool under different conditions.

Fig. 6.29a shows a mixing tool that has been used in many projects by Sweden's largest deep mixing contractor. However, it has not been shown that this tool differs in efficiency from the "standard tool". An examination of the shapes of the tools shows that they are unlikely to differ significantly, as both are characterized by paddles set at a very shallow angle to the horizontal.

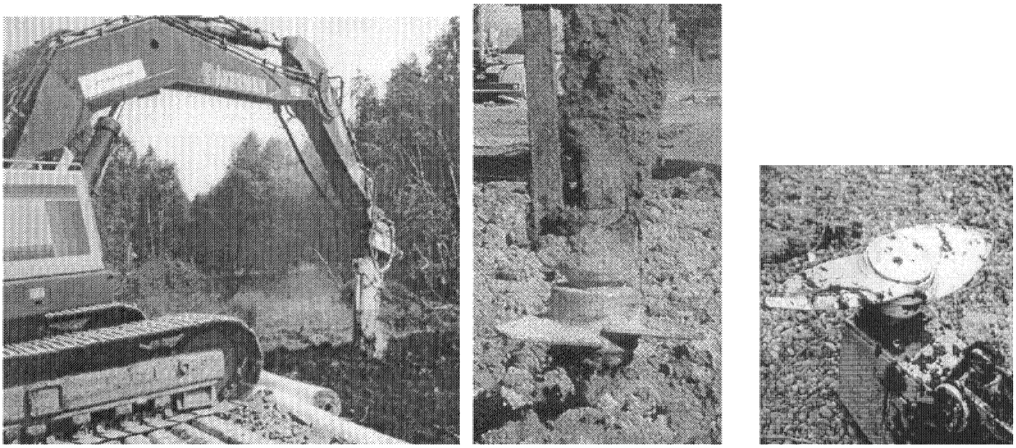
Fig. 6.29b shows a mixing tool that has been used for cell stabilization (Jelisic 1999, Rogbeck et al. 1999). It has curved blades, making the soil less likely to cling to the tool during mixing. This phenomenon can be particularly troublesome when stabilizing peat. However, the tool has a negligible angle to the horizontal, making it difficult to generate movements in the mixture. The same feature also impairs its compacting capacity. Still, it would be interesting to study the effectiveness of this tool with blades mounted at a A number of mixing tool designs were studied in the course of field trials reported in a thesis presented at Chalmers University of Technology, Sweden (Johansson & Jons 1995). Fig. 6.29c shows a tool in which some of the blades have been fitted with upward-pointing combs. The concept is that the mixture will be compressed between the combs and simultaneously pressed downwards and outwards away from the blades. Unfortunately the blades are not inclined to the horizontal, causing the tool to lift the mixture during mixing. Moreover, the combs on the blades are very closely spaced, which may cause mixture to get stuck between them. The result was, as Johansson & Jons observed, that large quantities of mixture clung to the tool as it was withdrawn, leaving large holes in the ground. Another consequence was that the remaining material in the column was poorly compacted.

Fig. 6.29d shows another tool studied by Johansson & Jons (1995). It had blades angled different ways, causing shearing of the mixture in various directions. The blades are rather closely spaced, however, which may result in material sticking between them.

A development of the Scandinavian dry deep mixing method is introduced by LCTechnology (2002), where some problems in connection to relatively dry and hard soils are overcome by adding water separately during insertion of the mixing tool. The soil profile can thereby obtain consistent water content. The added water can also act as a lubricant for the mixing tool during penetration.

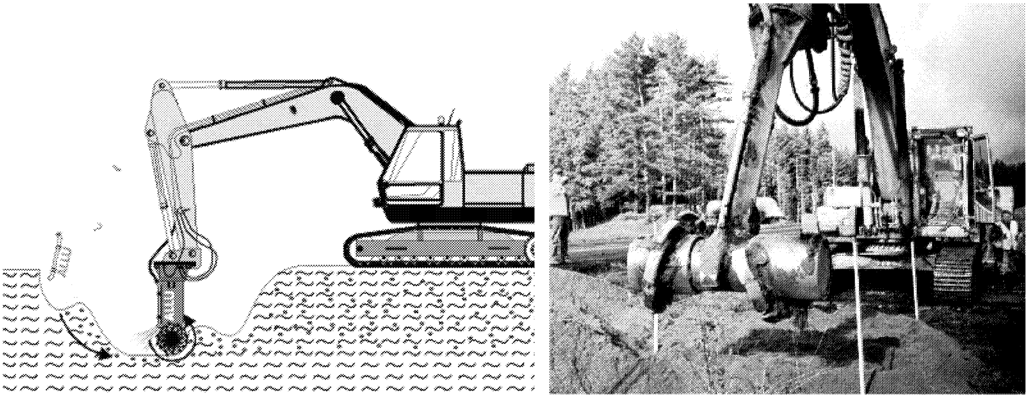
When the soil conditions are extremely bad, e.g. peat or gyttja, the whole soil volyme might be stabilised. In Finland a technique called mass stabilisation was developet in the early 1990s (Axelsson & Säfström 1996, Hoikkala et al. 1996). The dispersion of binders is carried out by a mixing tool mounted on an excavator according to Fig. 6.30. This equipment makes the process simple and flexible. The soil is only stabilised to 5 m depth by this technique. There is no automatic control over the mixing system since the mixing work is controlled totally by the driver. The blades on the mixing tool shown in Fig. 6.30 have been designed as propellers rather than paddles. This technique and equipment is refered as Mass stabilisation TYPE A according to EuroSoilStab (2002). According to the literature reviwew preseted by Jelisic (1999) the stabilised soil can be very heterogeneous.

Fig. 6.31 shows a developed promising technique for mass stabilisation using a large rotary cultivator (a mill tool). This technique is refered as Mass stabilisation TYPE B according to EuroSoilStab (2002) and has been used since 2001. The drum rotates by approximately 200 rpm and the soil is disaggregated befor the binder is added. This large rotary cultivator puts a relatively large volyme in motion during mixing. The maximum depth of treatment presently is 5m. However, there are no published records of the mixing quality achieved by this equipment.



a) b) c)

Fig. 6.30 Mass stabilisation TYPE A; a) equipment for mass stabilisation mounted on an excavator (Hoikkala et al. 1996); b) and c) mixing tools (Axelsson & Säfström 1996, EuroSoilStab 2002) .



a) b)

Fig. 6.31 Mass stabilisation TYPE B; a) Scematic scetch (EuroSoilStab 2002); b) the rotating drum/cutter mounted on an excavator (Niska Nyssönen, Road 32, Eksjö, 2002).

Mixing tools in Japan

Numerous Japanese firms have developed variations of deep mixing, resulting in a large number of mixing tools. Some of these are illustrated and commented upon briefly in this section. It should be noted that numerous patents exist on devices developed in Japan.

The first method to be developed in Japan, concurrently with its development in Sweden, was the "dry method", using quicklime in powdered form as binder. Subsequently Portland cement premixed with water was introduced. According to Saitoh et al. (1985) this development took place because injecting the binder into the soil in liquid form yielded a more uniform mixture with the soil and increased strength. The method is preferable in "more difficult conditions" because it makes the mechanical mixing of the soil easier (Bruce et al. 1998b). Deep mixing by the "wet method" has been extensively used in Japan, particularly in marine projects.

Fig. 6.32 shows mixing tools used in deep mixing by the "dry method", based on the principle that the binder is spread over the column cross section in the cavity formed behind the blades of the tool as it rotates in the soil. Faster rotation speeds increase the volume of the cavity and create a vacuum which facilitates the process when manufacturing large-diameter columns (Chida 1982). Further, according to Chida (1982), this process causes the injected air to move towards the outer parts of the cavity. The air is then evacuated from the column via the shaft of the mixing tool.

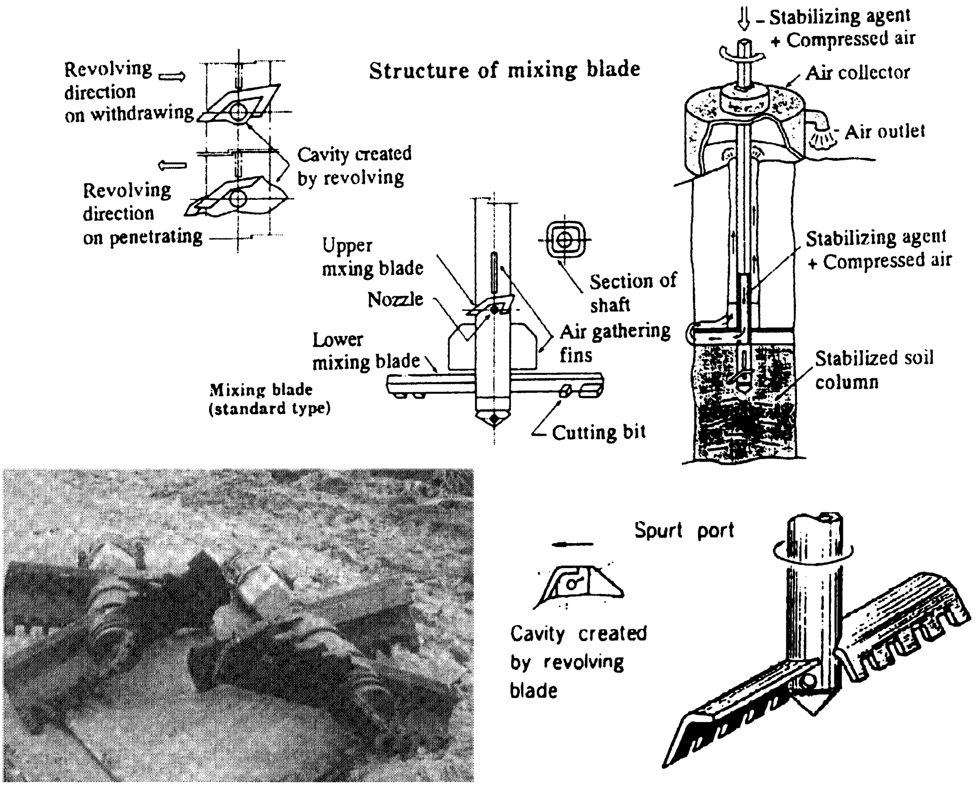


Fig. 6.32 **Mixing tools in which the binder is distributed in a cavity formed behind a paddle (Tateyama et al.1996, Porbaha et al. 1999c, Chida 1982)**

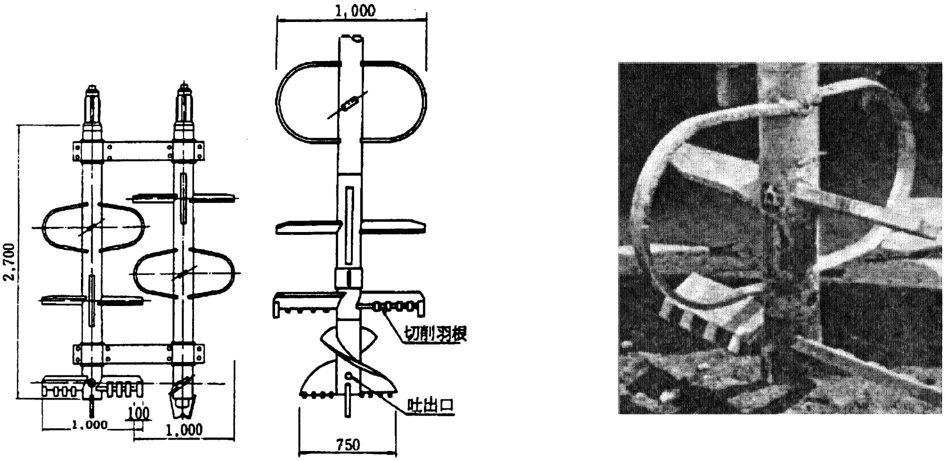


Fig. 6.33 The Oval-DM. (Nishibayashi et al. 1984)

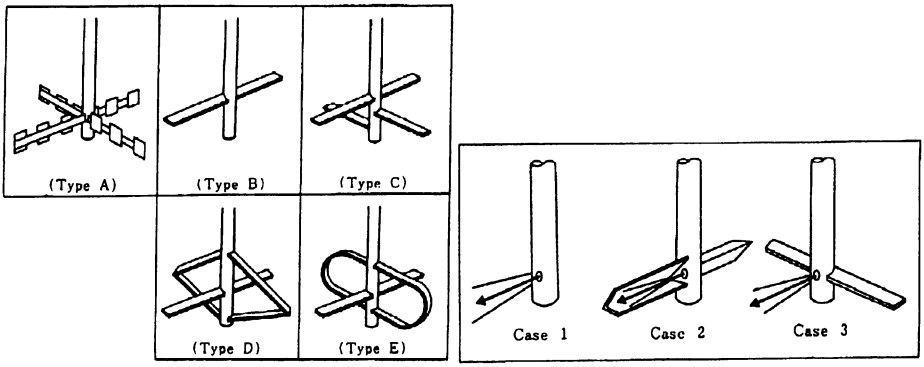


Fig. 6.34 Mixing tools and ways of spreading binder into the soil. (Nishibayashi et al. 1984)

Fig. 6.33 shows a tool that was trialled in the early 1980s (Nishibayashi et al. 1984). The tool and the method were known as "Oval-DM". The tool is fitted with combinations of screws, thick and thin paddles, teeth and stirrups. A variety of other basic designs of mixing tool and different ways of incorporating binders into the soil were tested at this time, see Fig. 6.34. One of these was the method of allowing the binder to spread over the cross section of the column in the cavity formed behind the paddle of a mixing tool.

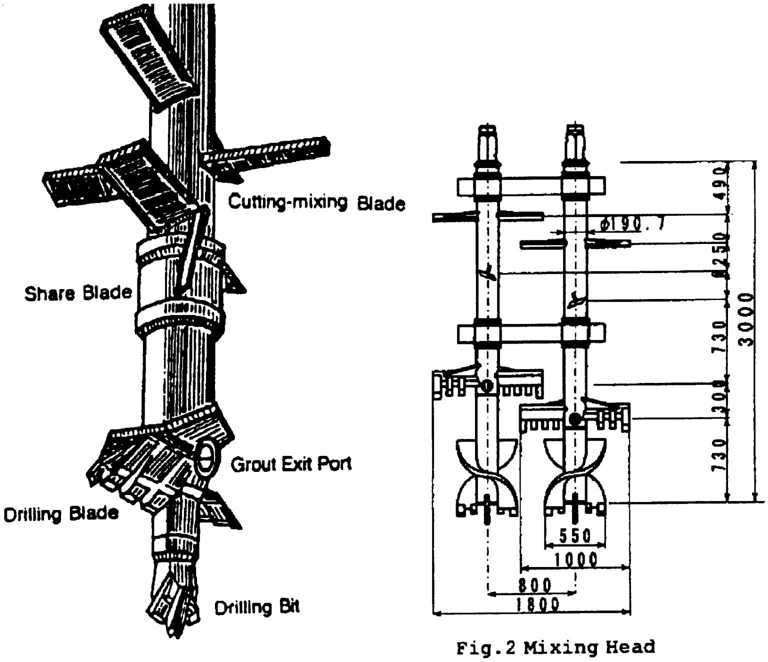


Fig.2 Mixing Head

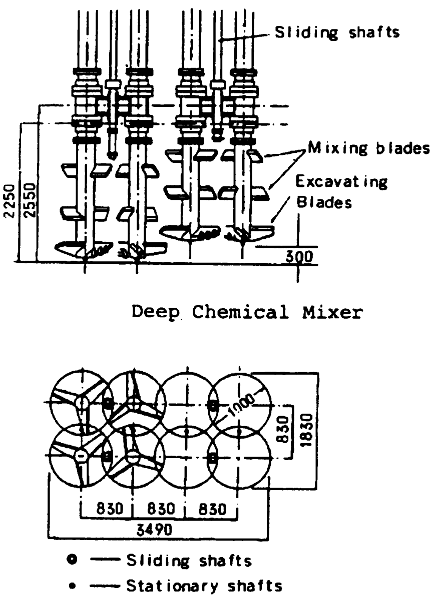
Fig. 6.35 Mixing tool for the "wet method". (Taki & Bell 1998, Yoshida 1996)

There are a variety of ways of injecting water-based binders into the soil. A common approach is to inject part of the binder as the mixing tool is penetrating the soil, e.g. from the tip of a screw or paddle. As the mixing tool penetrates, it disaggregates the soil and at the same time lifts it slightly in order to facilitate incorporation. The remainder of the binder is injected as the tool is withdrawn from the soil. Some typical tools are shown in Fig. 6.35.

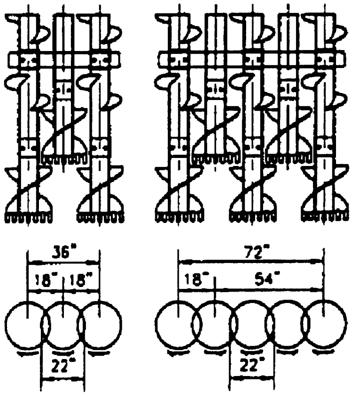
It is common in Japan to install a number columns simultaneously using multiple shafts and mixing tools. It is possible by this method to efficiently construct configurations such as blocks, lattices, walls etc. (e.g. Kawasaki et al. 1981, Nicholson et al. 1998). It is common to reinforce these columns with I-beams (Schaefer et al. 1997). Fig. 6.36 shows some examples of mixing tools used in combination.

Fig. 6.37a shows a mixing tool for manufacturing columns of diameters between 1.4 and 2.0 m. By providing the tool with an outer and an inner rod rotating in opposite directions it is possible to mix frictional materials. Fig. 6.37b shows a tool with an auger to compensate for the expansion of the soil that takes place when the binder is injected. This expansion can cause horizontal displacement of the ground.

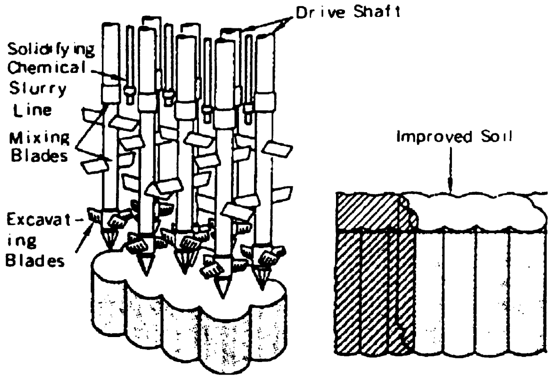
Fig. 6.38 shows the effect of fitting the mixing tool with "anti-rotation vanes" which prevent the materials being mixed from rotating along with the tool. These vanes do not rotate in the soil and thus provide resistance to the rotating blades as they pass. The mixing mechanisms with this tool are thus similar to those of the mixers shown in Fig. 3.9. The tool in Fig. 6.35 is also fitted with blades which do not rotate during mixing. These vanes are somewhat longer than the rotating blades and thus cut into the surrounding soil for support. However, the technique was presented in the early 1980s by e.g. Inoue & Hibino (1985) and Enami et al. (1986b), as shown in Fig. 6.38.

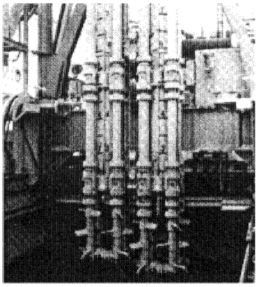


Kawasaki et al. (1981)



Taki & Yang (1990)





Kawasaki et al. (1984)

Kawasaki et al. (1981)

Fig. 6.36 Mixing tools used to manufacture a number of columns simultaneously.

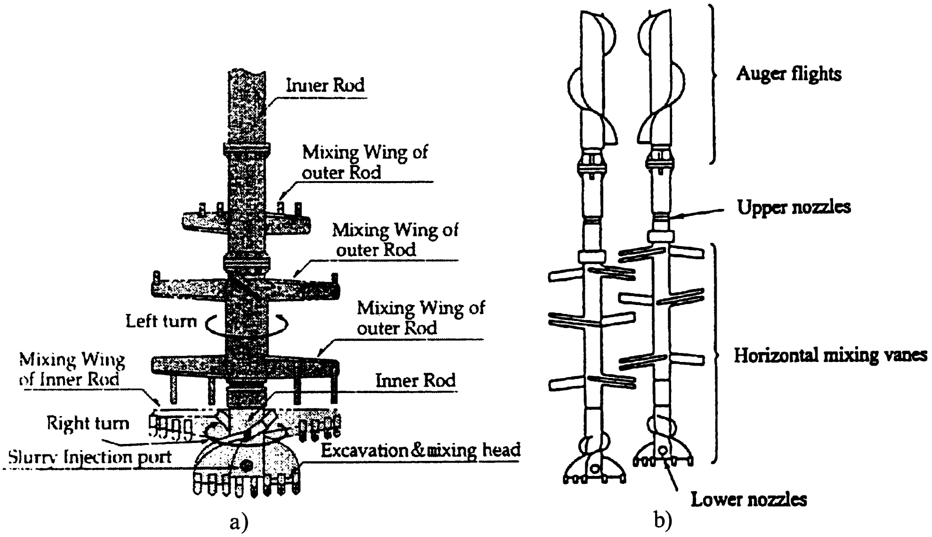


Fig. 6.37 a) Mixing tool for large column diameters in frictional soil. (Isobe 1996)
b) Mixing tool which compensates for expansion due to binder injection. (Hirai et al. 1996)

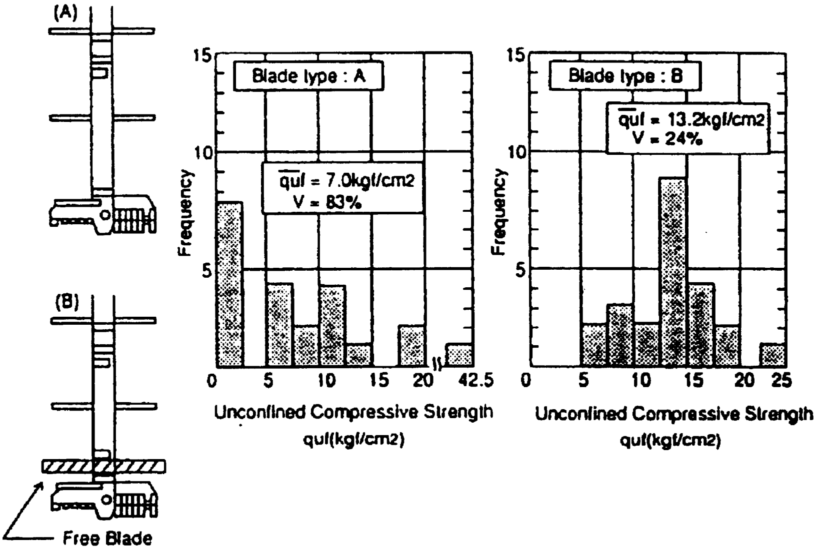


Fig. 6.38 Effect of "anti-rotation vanes". (Yoshizawa 1997 after Enami et al. 1986b)

In order to isolate waste desposal sites and to prevent the movement of toxide substances deep mixing methods can be used. It is common to create column walls, grids or blocks in the ground. A relatively newly developed soil mixing wall method is conducted with a chain-saw cutter device as shown in Fig. 6.39 (Kamon 2000). The advantage, compared to walls created by columns, is the secured continuity of the wall. By motion of the chain the slurry around the cutters forms eddies and turbulent mixing occurs.

In Japan it has also been a common practice to install rectangular columns. This technique was developed in the early 1980s (Khono 1984). Examples of equipment for the purpose appear in Fig. 6.40.

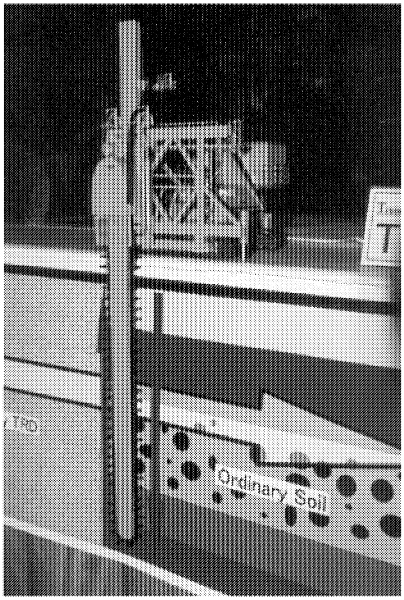


Fig. 6.39 Scematic of TRD method.

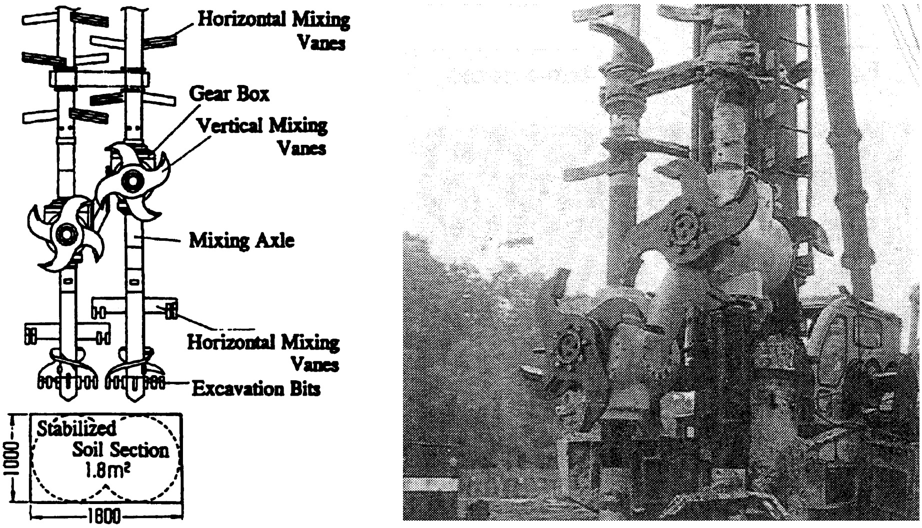
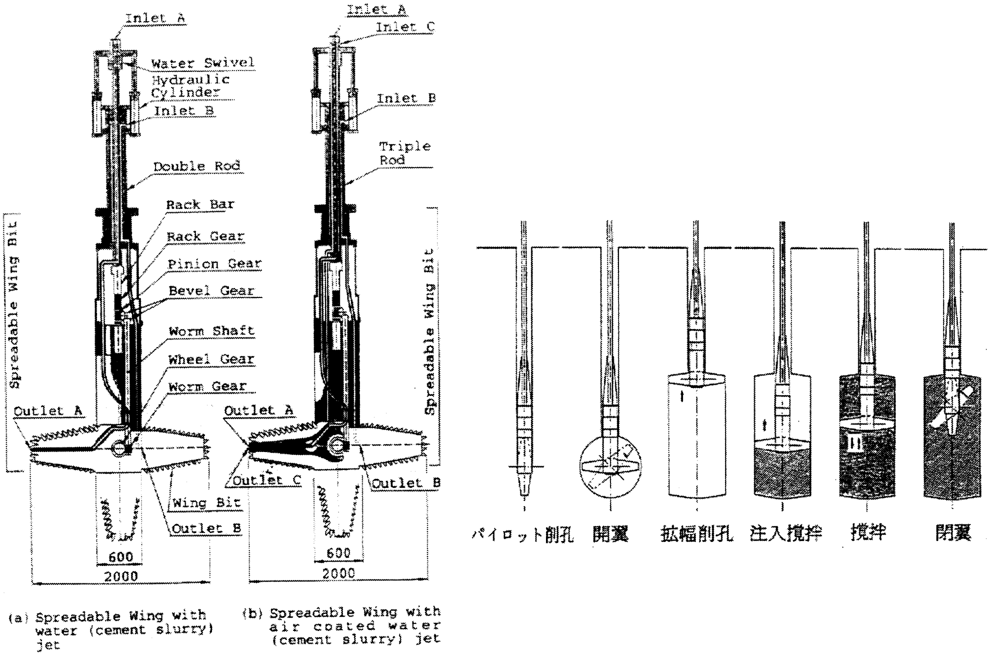


Fig. 6.40 Mixing equipment for rectangular columns. (Watanabe et al. 1996)

Figs 6.41–6.43 illustrate methods which are combinations of deep mixing using mechanical mixing and jet mixing. The main advantage of these methods is that they can produce large-diameter columns without large, bulky mixing equipment. The oldest of the methods is SWING, developed at the beginning of the 1980s (Kawasaki et al. 1996, Yang et al. 1998b, Ogawa 1990). Similar methods have subsequently been developed incorporated evolved forms of jet mixing (e.g. Miyoshi & Hirayama 1996, Mori et al. 1997, Ueki et al. 1996, Matsumoto et al. 1998).



(a) Spreadable Wing with water (cement slurry) jet

(b) Spreadable Wing with air coated water (cement slurry) jet

Fig. 6.41 Combination of deep mixing and jet mixing: the SWING method. (Kawasaki et al. 1996, Ogawa et al. 1990)

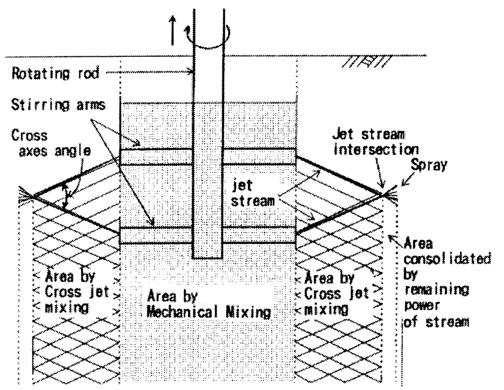


Fig. 1 Overview of cross jet mixing

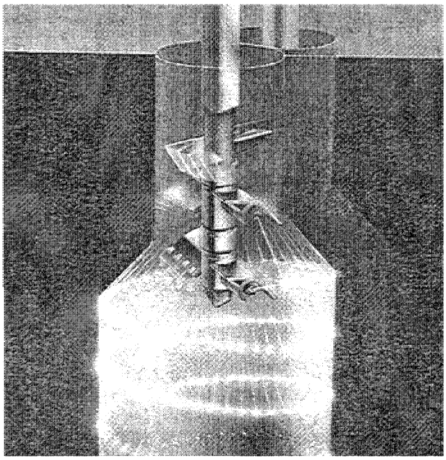


Fig. 6.42 Combination of deep mixing and jet mixing: JACSMAN or Cross-jet injection compound mixing DM method. (Miyoshi & Hirayama 1996, Matsumoto et al. 1998)

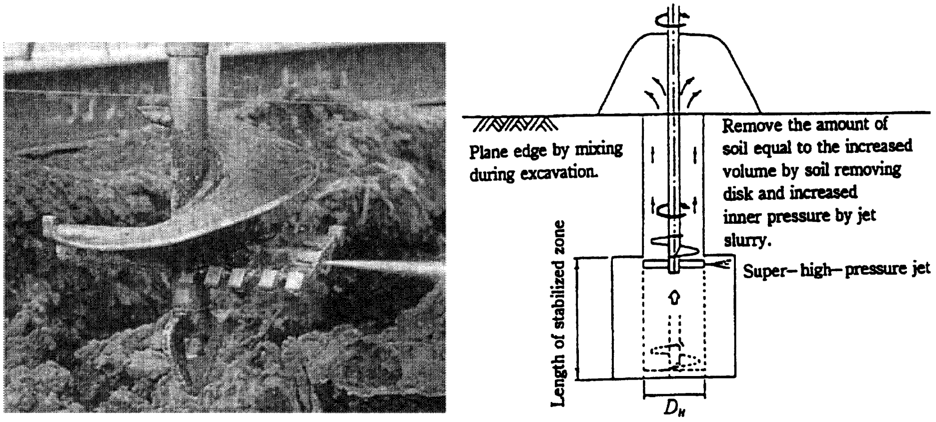
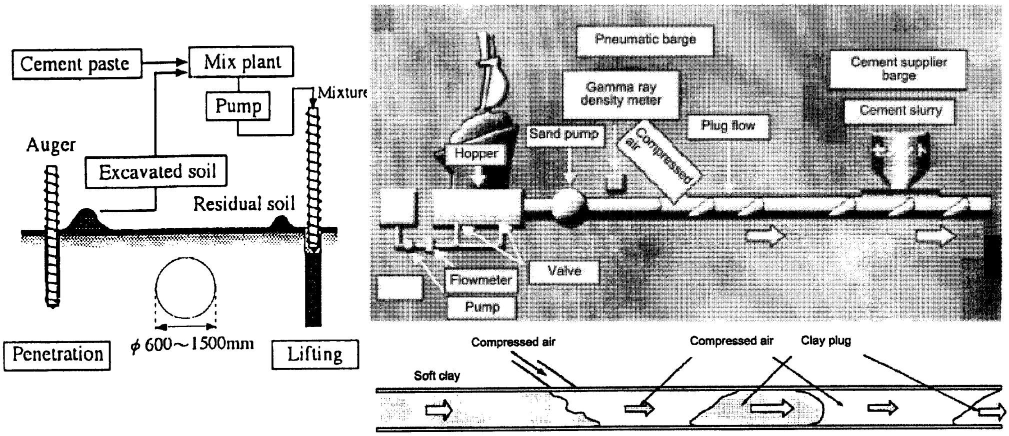


Fig. 6.43 Combination of deep mixing and jet mixing: the LDis-method. (Ueki et al. 1996)



a)

b)

Fig. 6.44 a) Deep mixing with factory mixing. (Mori et al. 1997)
b) Pneumatic flow mixing method. (Kitazume and satoh 2003)

Fig. 6.44a illustrates a relatively new method that has been trialled in Japan. A continuous auger is used to mix the soil and the binder. In an initial step soil is transported to the ground surface as the rotating helical mixer is inserted into the earth. The soil is mixed in a mixing plant with a water-based binder and then pumped back into the ground as the tool is withdrawn. This method yields a controllable product, comparable to concrete, whose strength and deformation properties can be varied. The displacement caused by the injection of binder *in-situ* is reduced.

The construction of man-made islands in Japan has results in a development of methods for the reclamation of dredged soils. In order to stabilise large quantities of dredged soil a pneumatic flow mixing method has been developed (Kitazume & Satoh 2003). The principal mixing equipment is a static mixer where the dredged soil is transported through pipe by means of compressed air, Fig. 6.44b (cf. Fig. 3.7). The soil-binder mixture forms separated mud-plugs in the pipe, and is mixed by turbulent flow generated in the plug. The properties in the stabilised soil are predictable and the control is relatively easy to perform. The mixing plants are, however, enormous and build for large projects and large quantities.

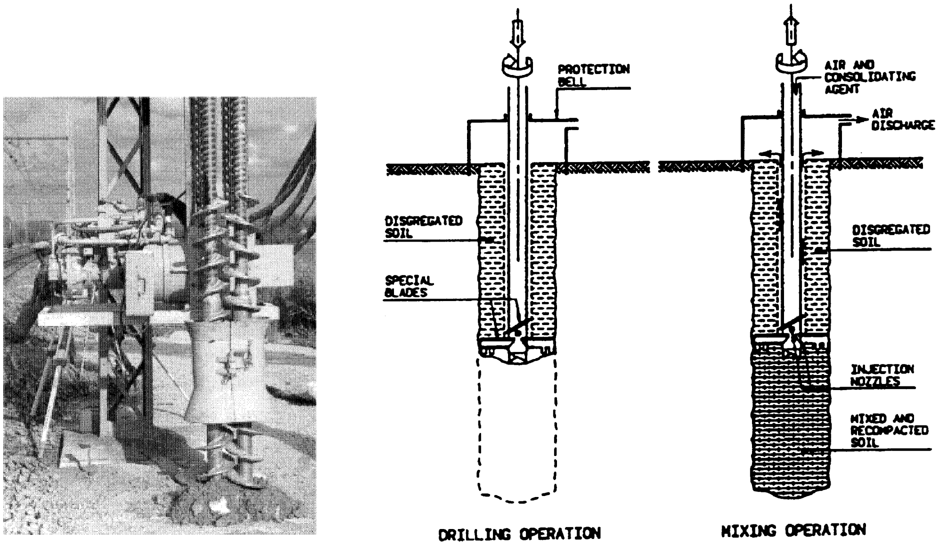
Other countries

Deep mixing soil equipment has been developed in other countries such as France, England and Italy (Harnan 1993; Harnan & Iagolnitzer 1994; Paviani & Pagotto 1991; Pagliacci & Pagotto 1994). Fig. 6.45 shows two such devices which have been used in Europe. The Colmix method, developed by Bachy in the late 1980s, involves mixing the soil with a water-based or dry binder by means of a helical tool. The binder is injected as the tool penetrates the soil. Mixing and compaction take place as the tool is withdrawn. The Trevimix method was developed in Italy in the early 1980s and use boath dry and wet binders.

Shallow soil mixing is a technology developed by Geo-Con in North America in the early 1990s to improve large mass of soils within ten meters of the surface (Broomhead & Jasperse 1992, Day & Ryan 1995). The process uses a single mixing tool 1 m to 4 m in diameter as shown in Fig. 6.47. Slurry grout is incorporated into the soil at the bottom of the mixing tool via three ports, located in the auger flights. Dry binder is used and distributed pneumatically if sludges or wet soils are stabilised. A common application for deep mixing in US is environmental cleanups, contain, stabilise or treat the soils to permit safe closture. Geo-Con also uses a deep mixing technique where multiple augers mix the soil and slurry to deeper applications. The technique is similar to the Colmix method.

Also in USA a combined technique between jet mixing and mechanical mixing is developet, GEOJET (Reavis & Freyaldenhoven 1994). The mixing tool is provided by two relatively broad paddles. When the mixing tool is rotated into the soil, cement slurry under high pressure is discharged via a number of nozzles placed along the blades. The combination of mechanical mixing and hydraulic mixing creates a liquefied mixture of soil, and cement.

A similar technique as shown in Fig. 6.39 is developed in Germany, the FMI method, Fig. 6.48 (Sarhan 1999). The mixing equipment is similar a power saw. A stabilised wall, 0.5-1.0 m wide, is created when the soil is mixed with a cement slurry.



a) b)

Fig. 6.45 **a) Colmix. (Bachy 1999)**
b) Trevimix. (Paviani and Pagotto 1991)

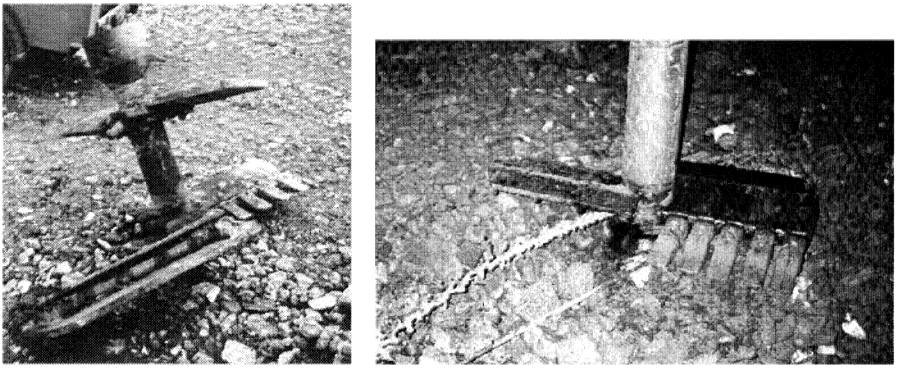


Fig. 6.46 Mixing tools developed in Europe for wet mixing. (CEN/TC 288 2002)

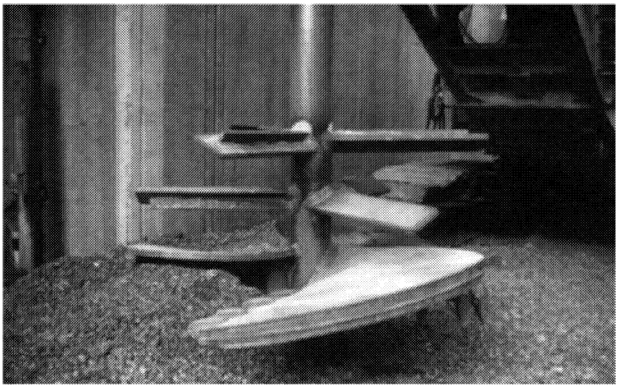


Fig. 6.47 Mixing tool for shallow soil mixing. (Day & Ryan 1995)

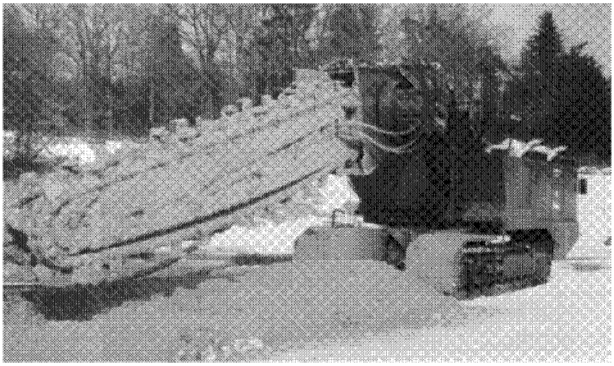


Fig. 6.48 Fräs-Misch-Injektionsmachine. (Sarhan 1999)

6.7 DISCUSSION OF SOME CHARACTERISTIC DEFECTS

Graininess

On visual inspection after exposure of the top of a column, a grainy, porous structure is often observable. This phenomenon is probably attributable to insufficient compaction. On incorporation of binder into the soil, the water content drops while the plastic limit increases, and the soil assumes a more granular structure. Lumps of material form showing a localized structural change on their surface. Unless the stabilized material is compacted within a relatively short time (a few days), it will have low density and low strength.

This phenomenon is particularly clear in dry surface clay but can also occur in the looser layers further down the column. A grainy, lumpy texture at this depth may be due to failure to evacuate all the air from the column. Once again the phenomenon is due to inadequate compaction.

Craters

Craters are a frequent phenomenon in dry deep mixing. They range in depth from a few tens of centimetres to a couple of metres. The phenomenon is most easily illustrated in model scale studies of the mixing process for column manufacturing (Larsson S.1999, Larsson & Broms 2000). Crater formation was clearly observed when manufacturing lime-cement columns of diameter 50 mm and length 500 mm in a shear box. The manufacturing process is shown in Fig. 6.49. A tube was driven into the soil, its lower end being sealed by means of a plug fitted to the end of a rod. As the tube was inserted it displaced soil, and slight surface heave took place corresponding to the volume of the tube. The rod was withdrawn from the tube, which was then filled with dry binder. The tube was withdrawn from the soil, leaving a pile of air and binder in its place. A rotating mixing tool of diameter 50 mm was inserted to the desired depth. The direction of rotation was reversed and the mixing tool withdrawn. The angled blades of the mixing tool compacted the soil and simultaneously dispersed the binder. During this process the air is extracted along with the mixer. When the air reaches the surface, a crater forms. Under field conditions the mixing tool may also pull the top layer of dry clay up with it, exacerbating the crater effect.

The depth of the crater depends primarily upon the amount of air injected, the rheological properties of the soil, and the compaction characteristics of the mixing tool. According to one hypothesis, when the soil is very loose and behaves like a liquid, the air is easier to evacuate and hence a deeper crater forms. When the soil is stiffer, the compaction characteristics of the mixing tool have a major effect on the amount of air evacuated with the tool. If these characteristics are poor, much of the injected air will be left in the column and hence the crater will be shallow, while the column may be porous and grainy in character.

Tapered or tubular columns

Uneven spreading can result in an accumulation of binder around the column periphery or around its centre, Fig. 6.50. This may be the result of delivering the binder into the soil by means of a jet. The upper paddle on the mixing tool passes through the soil and creates a cavity where the binder can be spread over the column cross-section. The spreading of binder can be uneven since the binder flow is not necessarily even over the section. A high air pressure can contribute to an uneven spreading and may furthermore cause pneumatic fracturing of the clay. Under unfavourable conditions the high air pressure can fracture the soil and lift the soil mass above the mixing tool. This process can result in large variances in binder concentration across the column cross section. The relatively short mixing time is then insufficient for the tool to disperse and distribute the binder over the cross section. For similar reasons, binder may concentrate in the central part of the column. Tapered columns can occur when the paddle on the mixing tool is unable to form the requisite cavity and the jet is unable to spread the binder over the whole column cross section. The problem is more severe at depth, since the confined in-situ pressure is high and the

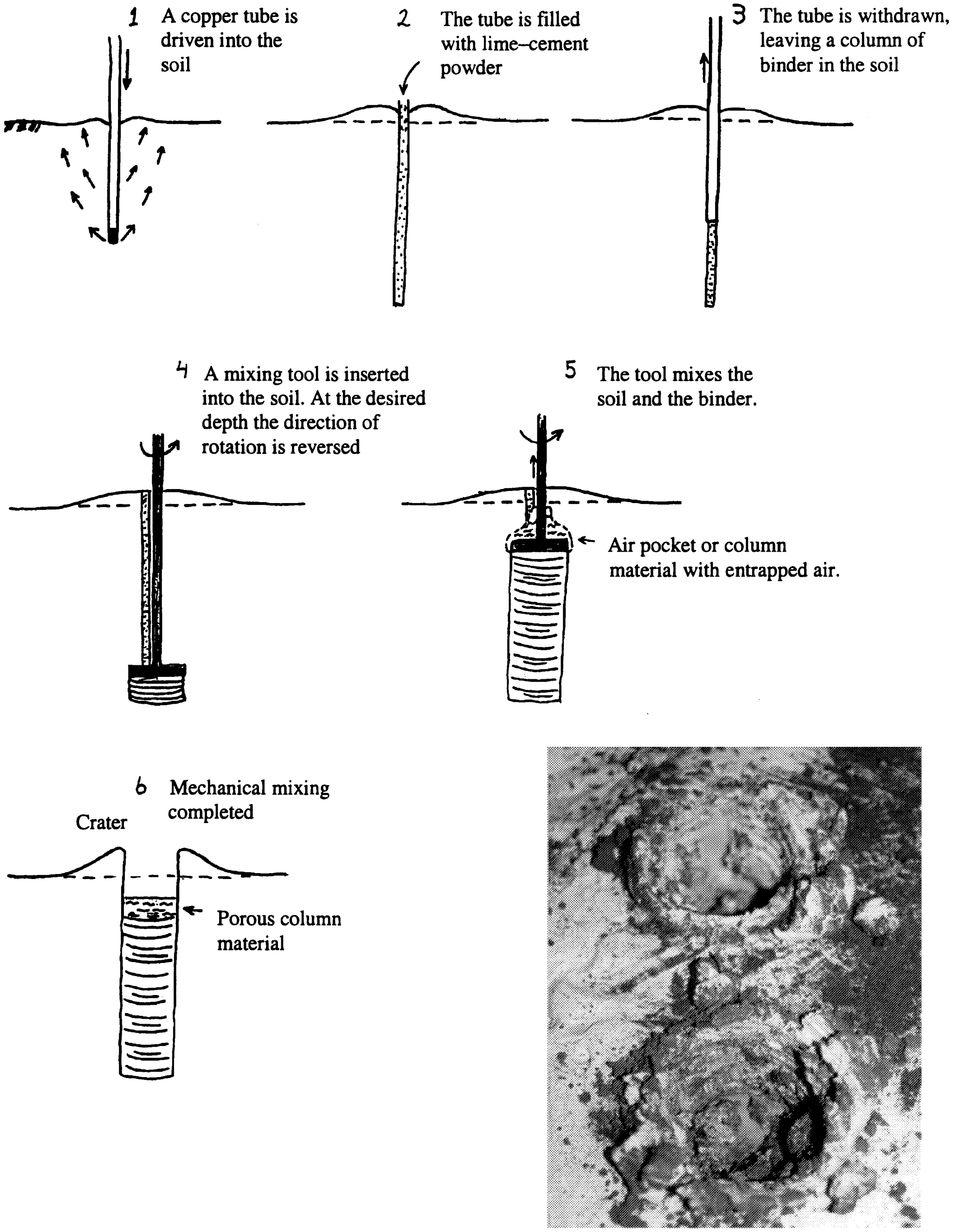


Fig. 6.49 Crater formation in model-scale column manufacture.

strength properties of the soil often improve with depth, i.e. the rheological properties of the soil change and its yield point increases at higher pressures. Greater input of energy may thus be required to form a kavity and for adequate disaggregation of the soil. Mixing tools of existing designs do not generate the movements necessary to distribute the components of the mixture throughout the volume being mixed. The short mixing time may be another reason for the poor distribution.

Short mixing times are obviously desirable in any type of mixing process. In many applications, however, satisfactory results cannot be achieved with short mixing times because of limitations of the equipment, usually lack of power.

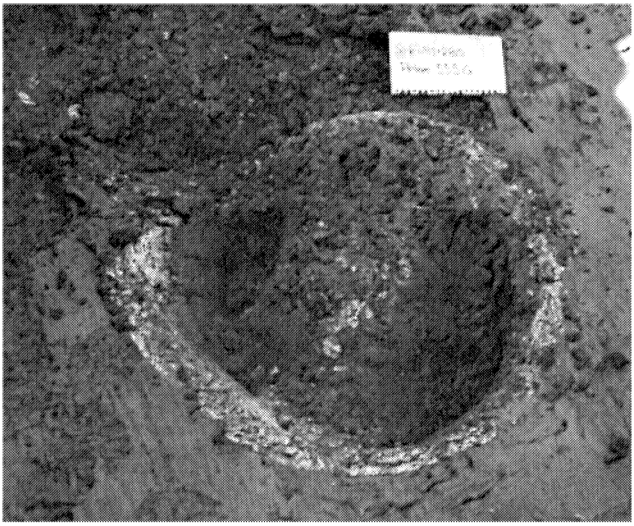


Fig. 6.41 Example of concentration of binder around the column periphery. (Axelsson & Larsson 1994)

7. Assessment of mixture quality: Field test in Arboga

1 INTRODUCTION

Deep mixing by means of lime-cement columns is very extensively used in Swedish infrastructure construction. Newer and bolder applications, such as slope stabilization and the stabilization of high embankments, impose ever increasing demands on the quality of columns, in particular the dispersion of the binder, in order to secure predictable and verifiable properties. The functions of deep mixing, differing with the application, entail different requirements on column properties. Thus the demand for uniform distribution of binder in the columns may vary depending on the requirements of the final product. New applications may demand better mixture quality and better control of the state of the mixture. Both clients and contractors need methods for assessing mixture quality.

No standard procedure exists today for the verification and assessment of mixture quality in respect of the dispersion of binder through the column volume. Routine checks such as column penetration tests, which are done to assess column strength and continuity, are not normally suitable for assessing mixture quality, since the strength parameters of a stabilized soil depend on other factors besides the efficiency of the mixing process.

In Chapter 4 we discussed statistical models and a range of mixing indices for the quantitative assessment of the quality of various types of mixture. The experience and the methods referred to there are mainly drawn from the process industries. In the context of deep mixing, mixing indices and statistical models have only been used in a few Japanese studies. Muro et al. (1987a,b) used a mixing index to assess the degree of mixedness of laboratory-prepared specimens. The degree of mixedness was used as a quantitative estimate of the effect of mixing process parameters such as the mixing time (number of mixing cycles) and rotation speed (see Chapter 6, Figs 6.7-6.9). Nishida et al. (1996) also used a mixing index to assess the degree of mixedness of laboratory-prepared specimens. The degree of mixedness was used to investigate the effect of mixing time and soil sensitivity on mixture quality (see Chapter 6, Fig. 6.10).

In order to assess mixture quality as a function of the mixing time of stabilized soil in the laboratory, Omine et al. (1998) measured colour variations in the stabilized material and defined an improvement rate as the ratio of improved area to total area. This measure of the improvement rate was used to validate a proposed model for predicting stress-strain relationships in mixtures of different materials.

In quality control of the strength properties of stabilized soil, statistical analyses are increasingly utilized for the evaluation of results. A quality index, expressed as the coefficient of variation, was used by Porbaha et al. (1999) to evaluate the results of CPT probes in a cement-stabilized soil (stabilized fill). In their study the quality index is proposed to form the basis for the quality control of stabilized soil. A statistical model from Finland uses the mean and the standard deviation to evaluate the results of column probes (Halkola 1999). The evaluation is done on strength parameters.

In a number of Swedish studies workers have attempted to assess mixture quality on the basis of subjective visual inspection. Such studies have been reported by e.g. Larsson & Axelsson (1994), Johansson & Jons (1995) and Holm et al. (1999).

However, no comprehensive studies of mixture quality with respect to binder dispersion have appeared in which direct measurements of binder content have been done. The aim of the present study is to investigate the dispersion of binder in lime-cement columns by measuring binder concentrations in samples taken from *in-situ* production columns. Samples were taken from different columns, at different depths, and from different parts of the column cross section in order to study the effects of these parameters. Samples were also taken of different sizes in order to study the effect of sample size.

Another aim of the present study is to investigate whether statistical analyses and mixing indices can be used for assessing the mixture quality of lime-cement columns. However, the study does not attempt to pre-empt judgements of how good the mixture quality needs to be in order for the columns in a structure to meet specifications of e.g. strength and deformation parameters. The interaction between the mixture quality and the mechanical system is discussed in Chapter 10.

Binder content is expressed as calcium oxide content, and it is assumed that all the calcium ions come from the lime and the cement in the binder. In addition to the chemical analyses and measurements of calcium oxide content, the water content, pH and electrical conductivity of selected samples was measured.

7.2 METHODS AND MATERIALS

Sampling site and sample columns

In the course of the research project "Production control methods in deep mixing with lime-cement columns" a number of test columns were installed (Axelsson & Rehnman 1999). These were used to study various methods of control, primarily by means of column penetration tests. For purposes of sampling and visual inspection, a number of whole columns were recovered by means of a split sampling tube, Fig. 7.3. The recovery method and the full extent of the field trials are reported by Axelsson & Rehnman (1999). Their field investigation and the present study were coordinated in conjunction with the recovery of the whole columns.

The test site is located just outside the town of Arboga near the Arboga – Örebro E18 highway project. The soil on the site consists of a very soft clay to a depth of 8 metres. Table 7.1 and Fig. 7.1 show analysis results from soil samples taken from the test site. Plan over the test site can be found in Axelsson (2001).

Table 7.1 Some geotechnical properties of the test soils.

Depth	Soil type	Density (t/m^3)	Liquid limit[a] (%)	Plasticity index (%)	Sensitivity[a] (-)	Undrained shear strength[a] (kPa)	Rapidity[b]
2.0	Brown-grey clay (some dry surface clay)	1.49	102.8	62	7	35.5	3-4
3.0	Grey clay	1.49	84.2	54	15	22.5	
4.0	Grey sulphide clay	1.49	65.9	35	25	14.0	5
5.0	Grey sulphide clay	1.53	60.7		32	13.7	6
6.0	Grey clay	1.56	56.6	30	36	14.3	6
7.0	Grey varved clay	1.49	79.6	52	19	9.0	

[a] By cone test to Swedish Standard.

[b] Defined by Söderblom (1974).

Table 7.2 Test column installation data.

Parameter	Nominal value
Column diameter	ϕ600 and ϕ800 mm
Column length	6–8 m
Binder: type, ratio	Lime/cement 50/50
Binder quantity	82 kg/m^3 (23kg/m, ϕ600 mm column)
Mixing tool	Pinnborr
Rotation speed	180 rev/min
Retrieval rate	20 mm/rev

The test columns were manufactured in the same way as the production columns in the highway project. Installation data appear in Table 7.2.

During the manufacturing process the quantity of binder and the rotation speed of the mixing tool were recorded. The retrieval rate of the mixing tool on the type of machine used is a fixed parameter, i.e. it cannot be varied while manufacturing a column. The plot from the machine showed very small variations in the nominal values of the binder quantity injected and the rotation speed.

The mixing tool used is referred to as the Pinnborr, see Fig. 6.24a. The tool has six paddles arranged in three tiers.

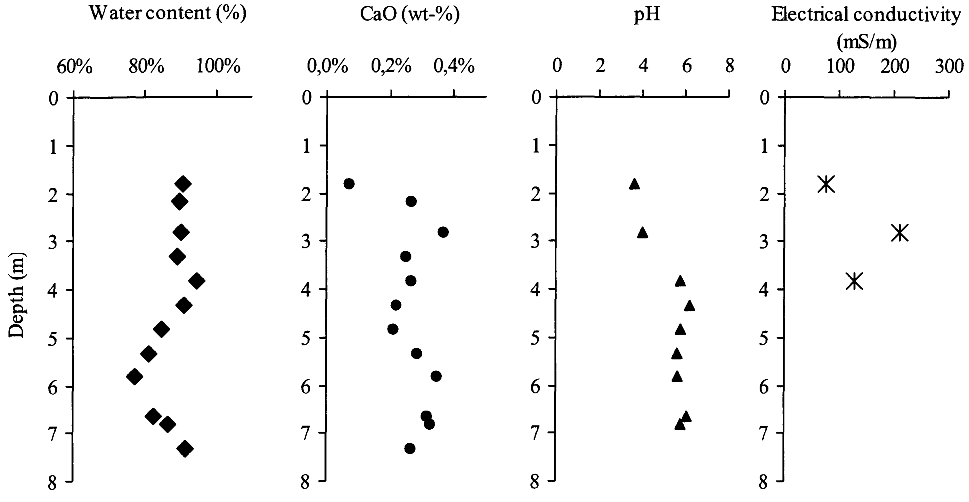


Fig. 7.1 **Results of laboratory analyses of soil samples from test site, Arboga.**

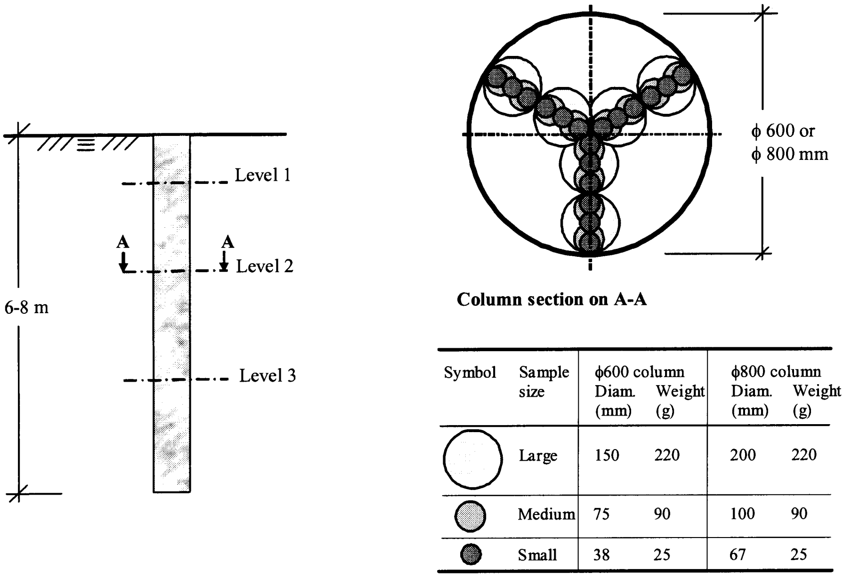
Sampling procedure

Samples were taken from a number of columns in three sections at three different levels, see Figs 7.2 and 7.3. Samples from four columns are analysed and reported in the present study. Two of the columns were of diameter 600 mm (columns 16 and 26) and two of diameter 800 mm (columns 43 and 53). The samples were not taken according to a randomized pattern but on the pattern illustrated in Fig. 7.2. This pattern was chosen in order to be able to demonstrate the radial dispersion of binder from the centre to the periphery of the column. Mixing tools used in Sweden today have the outlet hole for the binder in the Kelly rod, i.e. the binder is blown from the centre of the column towards its periphery. Based on this method of incorporating and spreading the binder, the hypothesis was framed that the initial stage of the dispersion process as shown in Fig. 6.1 is the stage having the greatest impact on the quality of a column.

Samples were taken in three sizes, referred to as the small, medium and large scale, in order to investigate the effect of sample size on the evaluated mixture quality. As discussed in Chapter 4, the scale of scrutiny has a major impact on the evaluation of column quality. Further, the samples were taken on three radii from the column centre, on bearings 0°, 120° and 240°, in order to study the dispersion of the binder over the cross section. This sampling method results essentially in a two-dimensional scrutiny of mixture quality at three levels in each column.

Laboratory analyses

At the laboratory the water content and binder quantity of all 432 samples were determined. Water content was measured by the method of Swedish Standard SS 02 71 16. The dry samples were then ground in a mill to a powder. A 0.5 g quantity of each powdered, homogenized sample was dissolved in 50% hydrochloric acid. The soil was removed by filtration and the solution diluted 1000 times. The diluted solution was then analysed for calcium ion concentration, Ca^{2+}, by OES-ICP (optical emission spectroscopy in inductive coupled plasma). The Ca2+ content (wt-%) is the dry weight concentration of calcium ions in the dry sample, expressed as a percentage. The equivalent calcium oxide (CaO) content is



Column section on A-A

Symbol	Sample size	ϕ600 column Diam. (mm)	ϕ600 column Weight (g)	ϕ800 column Diam. (mm)	ϕ800 column Weight (g)
○	Large	150	220	200	220
◉	Medium	75	90	100	90
●	Small	38	25	67	25

Fig. 7.2 Sampling procedure.

Fig. 7.3 Sample collection in the field. (Photo: Morgan Axelsson)

obtained by multiplying the Ca^{2+} content by the molar mass of CaO divided by the molar mass of Ca. However, the analytic method does not show whether the calcium ions come from the added lime or cement. The nominal binder quantity, 82 kg/m^3, corresponds roughly to a CaO content of 7 % (CaO content calculated from binder quantity according to Tränk & Johnson 1997). The CaO content of the unstabilized soil is low, 0.1 – 0.4 %, and is therefore ignored in evaluating the binder dispersion in the columns. All the CaO is thus assumed to come from the binder.

A number of triple tests were carried out in order to verify the reproducibility of sample preparation and of the analytic method. The results showed that the CaO content is evaluated to an accuracy of ± 0.2 % in this study. This error interval applies to samples having a relatively high CaO content, > 5 %.

For 40 samples from the four columns, pH and electrical conductivity were determined in accordance with Swedish Standard SS-ISO 10 390 and SS-ISO 11 265 respectively. All of these determinations were made on samples of the medium size.

A number of double tests of the pH analysis showed that pH could be determined to an accuracy of one decimal place. A large number of pH measurements were made at various times after agitation. This study too showed that pH could be determined to an accuracy of one decimal place. Calibration was done using buffer solutions of pH = 7 and pH = 10, which may result in lower accuracy for samples with low pH. The samples were dried at 105 °C, which is considerably higher than the maximum temperature of 40 °C specified in the standard.

A number of triple tests showed that the variation in the determination of electrical conductivity was somewhat greater than specified in the standard, ~15 % as against < 10 %. Investigation of the cause of this showed that the conductivity was reduced by contact with the air during filtration. However, the Swedish Standard does not mention this.

Statistical analysis

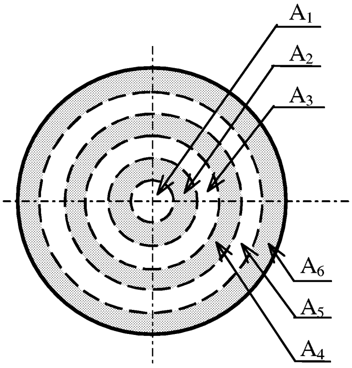
Based on the results of the chemical analyses and the evaluation of the CaO content of the samples, a number of statistical analyses were carried out to provide a quantitative assessment of mixture quality in the four test columns.

The sampling procedure of Fig. 7.2 has the effect that the inner parts of the columns are over-represented and the outer parts under-represented. Since sampling was not done according to a random test procedure, a method was adopted for weighting the samples according to their position. The mean and the variance for each series of samples taken from the column cross sections were evaluated as

$$\bar{a} = \frac{\sum_{j=1}^{3} \sum_{i=1}^{n_s} (a_{ij} \times \alpha_i)}{3 \times \sum_{i=1}^{n_s} \alpha_i} \tag{7.1}$$

$$\sigma^2 = \frac{\sum_{j=1}^{3} \sum_{i=1}^{n_s} ((a_{ij} - \bar{a})^2 \times \alpha_i)}{3 \times \sum_{i=1}^{n_s} \alpha_i - 1} \tag{7.2}$$

where *a* is the measured calcium oxide content of each sample. The samples are numbered outwards from the column centre from i = 1 till i = n_s, where n_s = 6 for the large scale, n_s = 4 for the medium scale and n_s = 2 for the small scale. The samples were taken on three radii numbered from j = 1 to j = 3. The concentration aij is assumed to be valid for the entire area $A_i/3$ according to Fig. 7.4. The coefficient a represents the area quotients represented by the samples according to Fig. 7.4.



Column section

Area quotient, $\alpha_i = A_i/A_1$

i	α_i
1	1
2	3
3	5
4	7
5	9
6	11

Fig. 7.4 Area relations between sampling positions.

The coefficient of variation was then calculated as the standard deviation divided by the mean.
Two mixing indices were evaluated in the study, those defined by Miles (1962), equation 4.12, and by Rose & Robinson (1965), equation 4.13:

$$M^1 = 1 - \frac{\sigma^2}{\sigma_0^2} \qquad \text{and} \qquad M^2 = 1 - \frac{\sigma}{\sigma_0}$$

where the variance σ^2 is evaluated according to equation 7.2 above and the variance for a completely segregated mixture σ_0^2 is evaluated according to Lacey (1943), equation 4.7:

$$\sigma_0^2 = \bar{a}(1-\bar{a})$$

7.3 RESULTS

CaO content and statistical analysis

The results of the chemical analyses and the evaluation of CaO content are reported in Figs 7.5–7.8. The results of the statistical evaluation are presented in Tables 7.3–7.6.

The CaO contents and the statistical analyses are reported for each column separately, i.e. the first page shows the results for column 16, the second page those for column 26, etc.

pH and electrical conductivity

Fig. 7.9 shows the results of the determination of CaO content, pH and electrical conductivity for 40 samples. The results are shown as relations between CaO, pH and electrical conductivity.

Water content

Fig. 7.10 shows the relation between calcium oxide content and water content determined from samples taken from the four test columns.

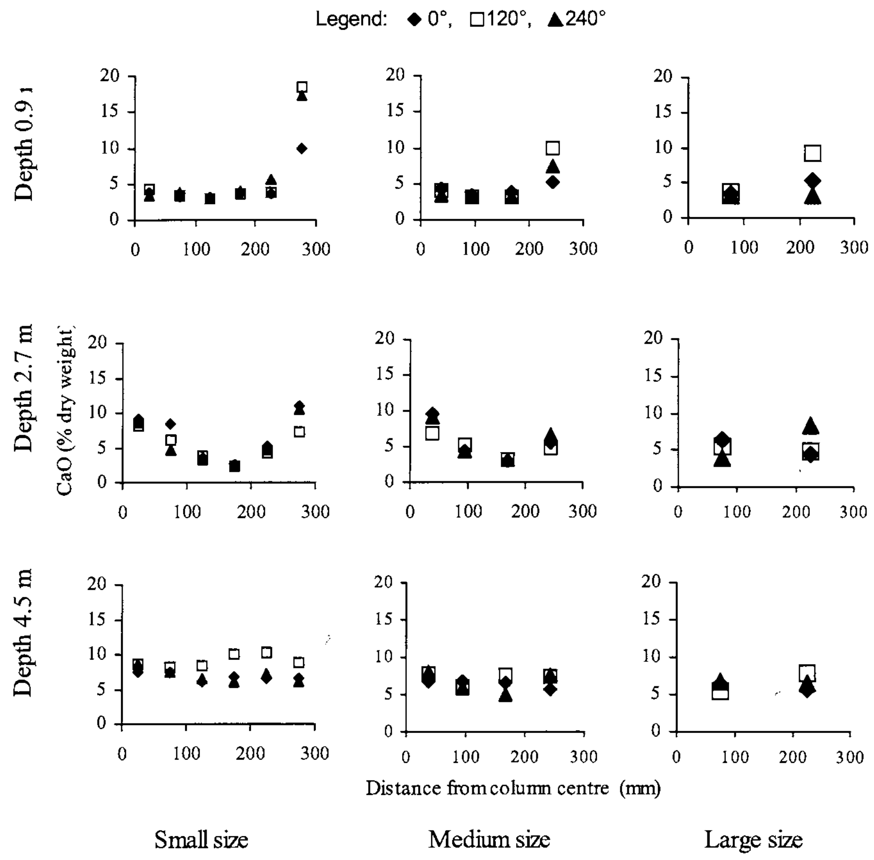


Fig. 7.5 **Results of chemical analysis of samples from column 16.**

Table 7.3 **Statistical analysis for column 16.**

Column	Sample size	Depth (m)	Mean (wt-%)	Variance	Coeff. of variation (-)	M[1] (-)	M[2] (-)
16	Small	-0.9	7.28	32.5	0.78	0.952	0.781
		-2.7	5.80	9.03	0.52	0.983	0.871
		-4.5	7.46	1.94	0.19	0.997	0.947
	Medium	-0.9	5.17	5.89	0.47	0.988	0.890
		-2.7	4.80	2.45	0.33	0.995	0.927
		-4.5	6.64	0.88	0.14	0.999	0.962
	Large	-0.9	5.32	6.30	0.47	0.988	0.888
		-2.7	5.73	3.05	0.31	0.994	0.925
		-4.5	6.48	0.84	0.14	0.999	0.963

[1] Mixing index defined by equation 4.12

[2] Mixing index defined by equation 4.13

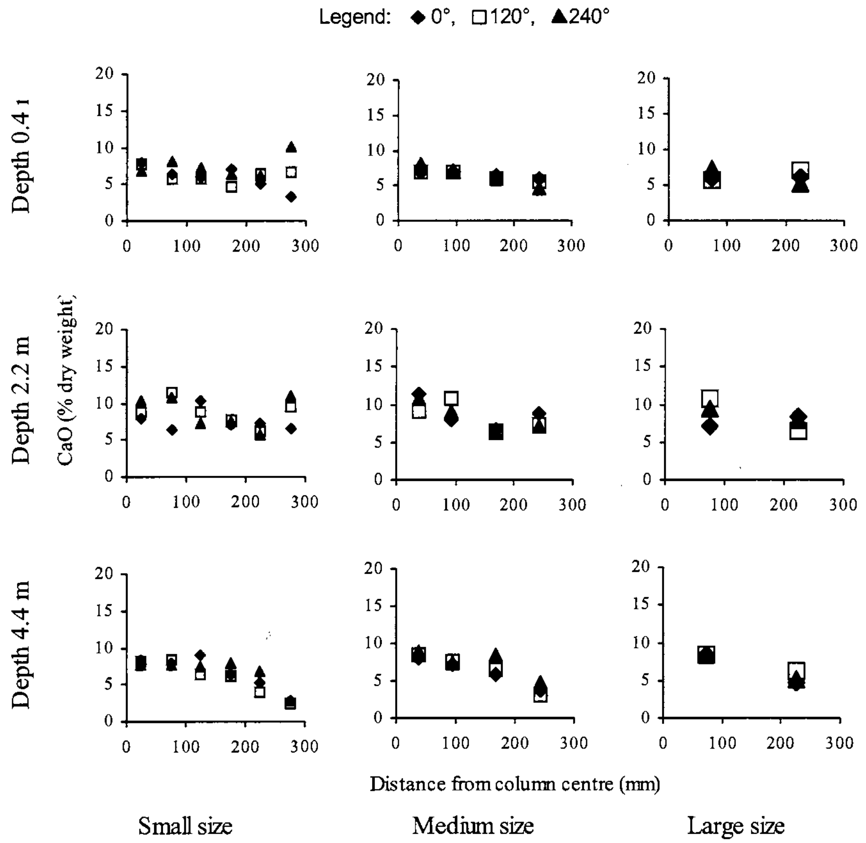


Fig. 7.6 **Results of chemical analysis of samples from column 26.**

Table 7.4 **Statistical analysis for column 26.**

Column	Sample size	Depth (m)	Mean (wt-%)	Variance	Coeff. of variation (-)	M[1] (-)	M[2] (-)
26	Small	-0.4	6.33	3.02	0.27	0.995	0.929
		-2.4	8.03	3.18	0.22	0.996	0.934
		-4.4	5.43	4.70	0.40	0.991	0.904
	Medium	-0.4	6.06	0.64	0.13	0.999	0.966
		-2.4	7.78	1.91	0.18	0.997	0.948
		-4.4	5.78	3.63	0.33	0.993	0.918
	Large	-0.4	6.16	0.52	0.12	0.999	0.970
		-2.4	8.05	1.64	0.16	0.998	0.953
		-4.4	6.15	2.18	0.24	0.996	0.939

[1] Mixing index defined by equation 4.12

[2] Mixing index defined by equation 4.13

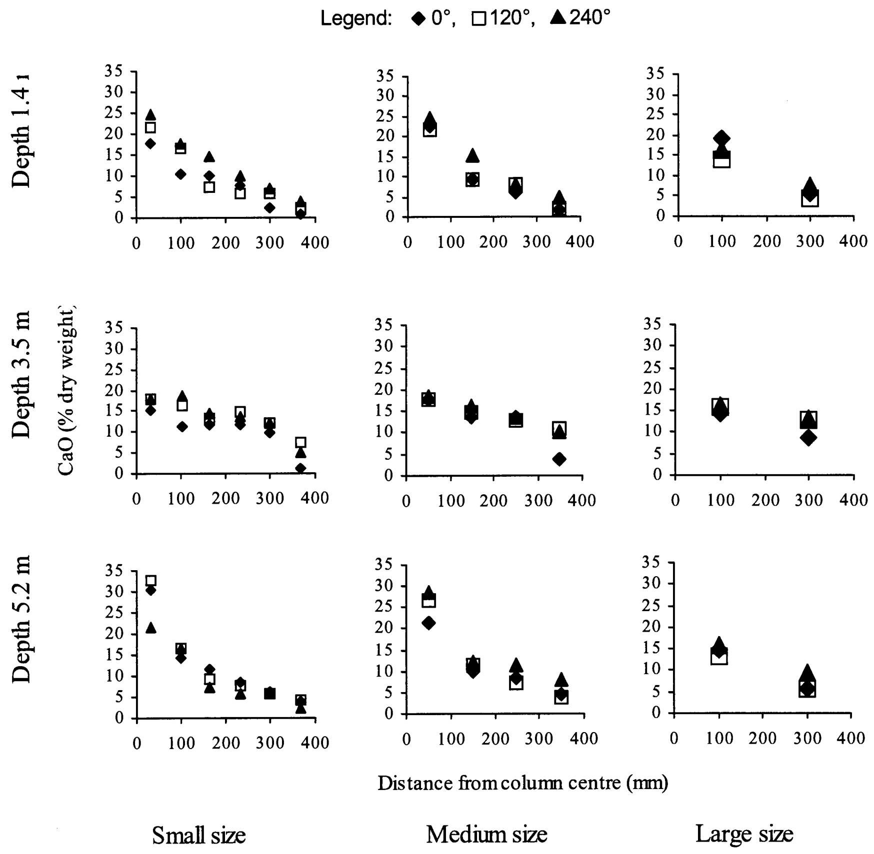


Fig. 7.7 **Results of chemical analysis of samples from column 43.**

Table 7.5 **Statistical analysis for column 43.**

Column	Sample size	Depth (m)	Mean (wt-%)	Variance	Coeff. of variation (-)	M[1] (-)	M[2] (-)
43	Small	-1.4	6.79	24.89	0.73	0.961	0.802
		-3.5	10.39	20.16	0.43	0.978	0.853
		-5.2	7.28	25.66	0.69	0.962	0.805
	Medium	-1.4	7.11	30.48	0.78	0.954	0.785
		-3.5	11.67	15.17	0.33	0.985	0.879
		-5.2	8.92	27.30	0.59	0.966	0.817
	Large	-1.4	8.49	25.48	0.59	0.967	0.819
		-3.5	12.44	7.07	0.21	0.994	0.919
		-5.2	8.82	14.74	0.44	0.982	0.865

[1] Mixing index defined by equation 4.12

[2] Mixing index defined by equation 4.13

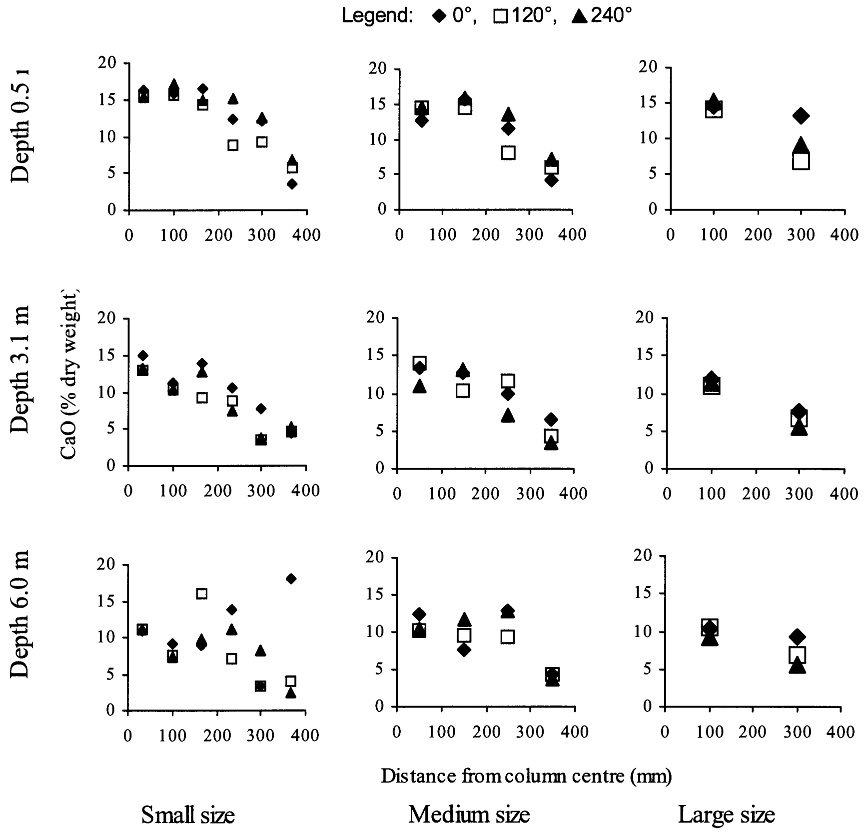


Fig. 7.8 Results of chemical analysis of samples from column 53.

Table 7.6 Statistical analysis for column 53.

Column	Sample size	Depth (m)	Mean (wt-%)	Variance	Coeff. of variation (-)	M[1] (-)	M[2] (-)
53	Small	-0.5	10.70	17.82	0.39	0.981	0.863
		-3.1	7.36	10.71	0.44	0.984	0.875
		-6.0	8.39	24.55	0.59	0.968	0.821
	Medium	-0.5	9.70	17.23	0.43	0.980	0.860
		-3.1	8.11	12.48	0.44	0.983	0.871
		-6.0	7.95	13.70	0.47	0.981	0.863
	Large	-0.5	10.91	10.64	0.30	0.989	0.895
		-3.1	7.80	5.29	0.29	0.993	0.914
		-6.0	7.93	3.50	0.24	0.995	0.931

[1] Mixing index defined by equation 4.12

[2] Mixing index defined by equation 4.13

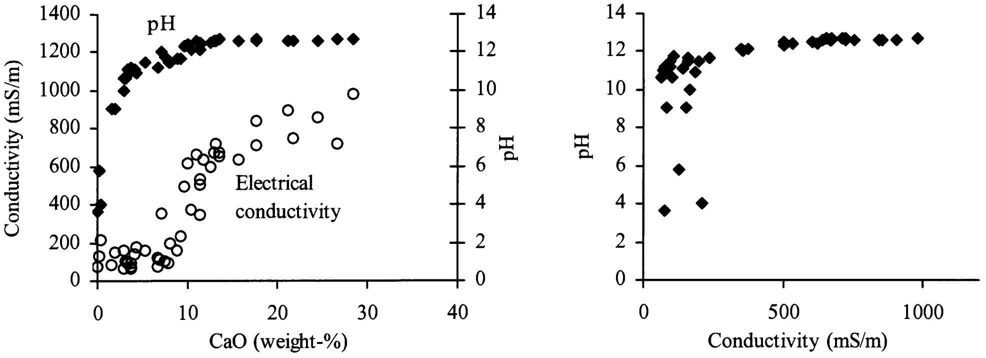


Fig. 7.9 Relations between CaO, pH and electrical conductivity

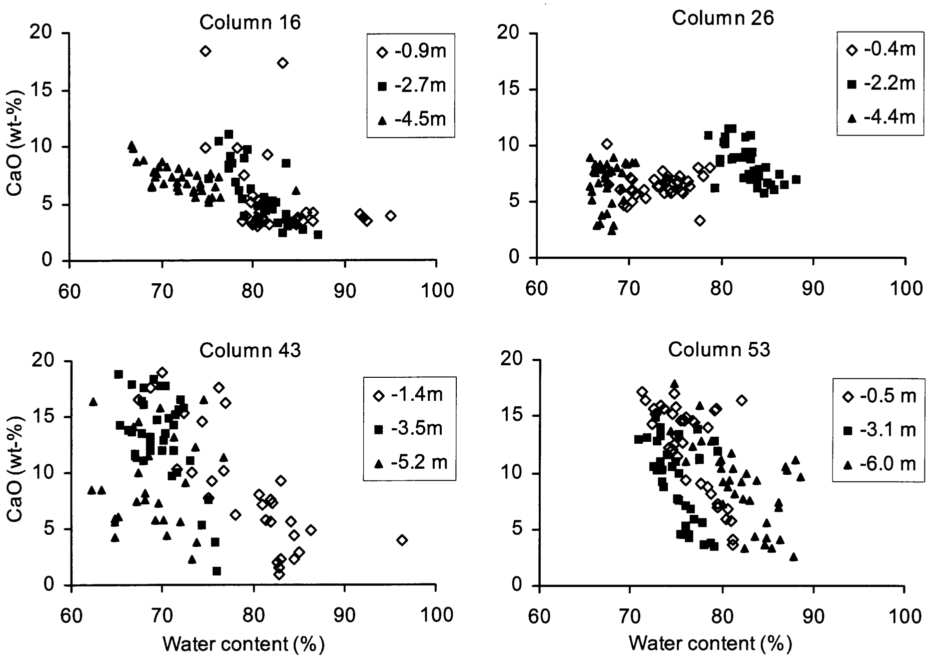


Fig. 7.10 Relation between CaO content and water content.

7.4 DISCUSSION

CaO content and statistical analysis

As mentioned in the introduction to this chapter, it has not been the practice to use statistical expressions or mixing indices for the quantitative assessment of mixture quality in lime-cement columns. In Swedish practice (SGF 2000) there are no methods for assessing mixing quality. Far too often, subjective methods are used to assess the dispersion of the binder in columns. An example is visual inspection, where there is a risk of incorrect evaluation. As discussed in Chapter 5, Mixture Quality, it is common to judge a mixing process by properties of the final product. There is a risk attached to assessing a mixing process on the basis of e.g. column penetration tests of lime columns, since strength properties are related to other parameters besides the efficiency of the mechanical mixing. An assessment of mixture quality must distinguish between the distribution of binder and a particular property of the stabilized soil. If it is the mixture quality or the distribution of binder that is to be assessed, measurements of the quantity of binder should be performed.

Figs 7.5–7.8 show the results of chemical analysis of the CaO content of samples taken from the four test columns. A number of comments need to be made on the results.

The samples were taken on three angularly separated radii, and the results show that the dispersion of binder is relatively similar on all three radii in the sections studied. An exception is e.g. column 53, level 6.0 m, where the dispersion patterns in the three directions differ. However, the results do show that the dispersion of binder is radial in character, i.e. the process of incorporation and distribution by means of an air jet has a major impact on the character of the binder dispersion.

The binder dispersion varies between the column sections, most clearly in columns 16 and 26. In column 16, for example, there is a heavy concentration of binder in the outer regions of the column down to about the 3 metre level. There was a clearly visible ring of harder material all the way around the column periphery. At level 4.5 m the binder is evenly dispersed over the entire cross section. In column 26 there is even dispersion of binder down to a depth of about 4 metres. At level 4.4 m the binder concentration is very low in the outer parts of the column. Consequently it is difficult to draw conclusions about the distribution of binder from a few samples taken from a few columns and levels, since the binder dispersion can vary with depth.

Tables 7.3–7.6 show the results of the statistical analysis, which is an attempt to quantify the results of the chemical analysis presented in Figs 7.5–7.8. The statistical analysis will now be discussed.

As mentioned in Chapter 4, the mixing index defined by equation 7.3 is relatively insensitive to mixture quality. This index may therefore be inappropriate to use, as the results of the present investigation confirm. The mixing index defined by equation 4.12 is more sensitive to different binder distributions and can be used as a quantitative rating of mixture quality. The difference between the mixing index defined by equation 4.13 and the coefficient of variation is that the mixing index takes into account the mixing that can be achieved according to equation 4.11. The relation between coefficient of variation and the mixing index defined by equation 4.13 is illustrated in Fig. 7.11.

Fig. 7.12 shows the relation between coefficient of variation and sample size. The results show that the sample size has significant impact when the mixture quality is poor and less impact when the mixture quality is good. Thus in order to avoid overestimating or underestimating the mixture quality, the "scale of scrutiny" must first be defined, after which an appropriate sample size can be established (see Chapter 4.3).

The different sample sizes display generally similar binder dispersion pattern, even though the magnitude of the mixing index varies with the different sample sizes. There are a number of exceptions, however, where a larger sample does not indicate the mean of a smaller sample. An example is column 43, level 5.2, radius 240°, Fig. 7.7, where the small scale shows a considerably smaller quantity of binder than do the medium and large scales. One cause of this is that the small samples are not sub-samples of the medium samples, nor are the medium samples sub-samples of the large samples. Moreover, the samples differ in their tangential extension, which may have an effect on the results.

The mean values for the different sample sizes vary. The differences lie within the range 0.25 –2.1 wt-% CaO. The largest differences are found in the sections where the binder dispersion was poor. This shows that there are major uncertainties in the evaluation of the mean and the coefficient of variation when column quality is poor.

Because the sampling procedure was not based on a random selection procedure of sampling points and because the number of samples in each series was small, it is difficult to estimate a confidence interval for the means, variances and coefficients of variation. As equation 4.16 shows, the measured concentration variance of the results depends on the sampling method and the analytic method. In the present study the variance due to the analytic method and to sample purity may be assumed to be small. However, the variance due to the sampling method is difficult to evaluate quantitatively. The mean may vary between the sample sizes even when the mixing quality is relatively good, indicating that the sampling method has some influence. The statistical analyses reported in Tables 7.3–7.6 must thus be regarded as rough estimates of the mixture quality of the columns.

Our current knowledge of binder dispersion in lime-cement columns is very limited and consequently it is difficult to draw conclusions from a small number of samples. Thus there is a need for greater knowledge of the character of binder dispersion. In general, a poor quality mixture will not be normally distributed. As the mixture quality improves the distribution approaches a normal distribution (Harnby 1992). This makes it difficult to compare poor quality mixtures. Given greater knowledge, it may be possible to use statistical analysis to assess mixture quality and thus provide a tool for the development of the mixing process.

Measurements of mixing quality can facilitate and improve our understanding of the mixing process. Its experimental determination is a major problem, however, since the collection of samples from columns and their chemical analysis is difficult and costly. Extensive sampling should therefore be carried out in conjunction with major construction or R&D projects in which whole columns are recovered. The sampling method should be based on random selection, e.g. the method presented by Harnby (1972). Determining the nature of binder dispersion will make it possible to use statistical methods for rating mixture quality. Given greater knowledge, it may be possible to rate mixture quality from a small number of samples. Lacking this knowledge, the present situation will continue in which we cannot assess mixture quality from a few samples. The present study shows that there is a major risk that a small number of samples will not be representative of the binder dispersion in the columns.

pH, electrical conductivity and water content

Fig. 7.9 shows the relation between pH, electrical conductivity and CaO content based on analyses of 40 samples. The results show that pH increases very rapidly even at low contents of lime and cement. In the CaO content range from 0 % to 15 % the pH increases very rapidly to pH ~11.5 at a CaO content around 4 %. At a nominal binder content of 7 % the pH is >12. These results make it doubtful whether pH can be used to assess column quality with reference to binder dispersion.

For electrical conductivity the picture is reversed. Conductivity is relatively constant in the range 50 – 200 mS/m up to a CaO content of 7 %. It then increases very rapidly to 600 – 700 mS/m at CaO content 12 %. For CaO contents between 12 % and 25 % there is a moderate increase of conductivity to 700-

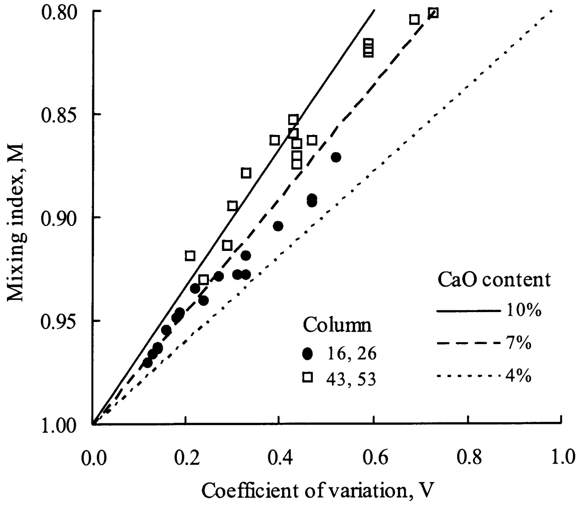
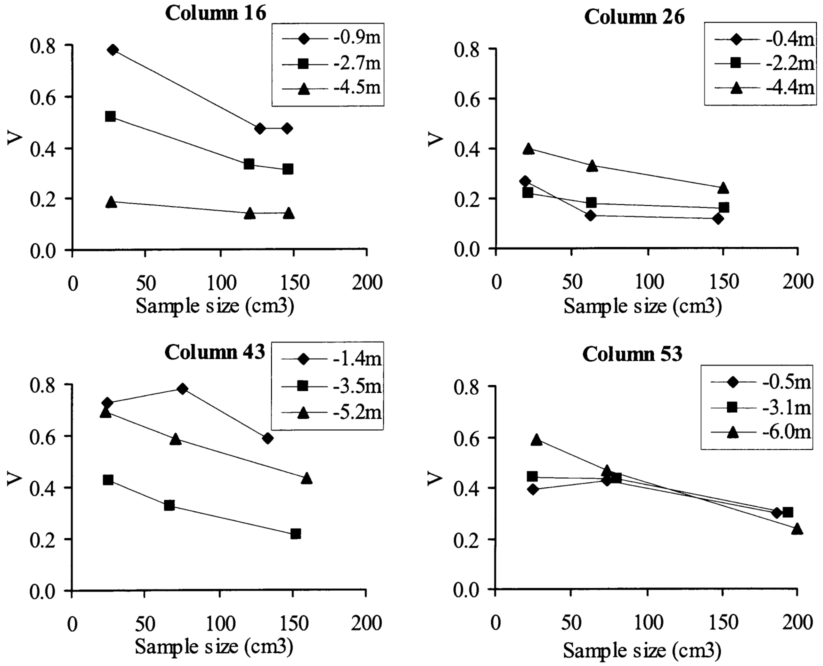


Fig. 7.11 Relation between coefficient of variation and mixing index defined by equation 4.13.



Fig, 7.12 Relation between coefficient of variation with respect to the CaO-content and sample size.

1000 mS/m. Again it is doubtful whether it is appropriate to use electrical conductivity for assessing column quality with reference to binder dispersion.

The results of the analysis and evaluation of the water content of the samples show that the dispersion of the results in relation to the CaO content is very large, Fig. 7.10. Causes of the large dispersion include edge effects, differing degrees of compaction, the sampling method and the analytic method. A hole had been drilled down the centre of all four columns studied, permitting the free flow of water through the column centre. Differences in hydraulic gradient across the column sections result in water flows, with differing effects on the samples depending on the part of the section from which they were taken. A high CaO content does not necessarily mean that the water content will fall, since the degree of compaction may vary. An accumulation of binder may be very porous, with a high water content, due to poor compaction or poor consolidation. The sampling and analytic methods can also affect the results. The analysis was carried out over a relatively long period of time.

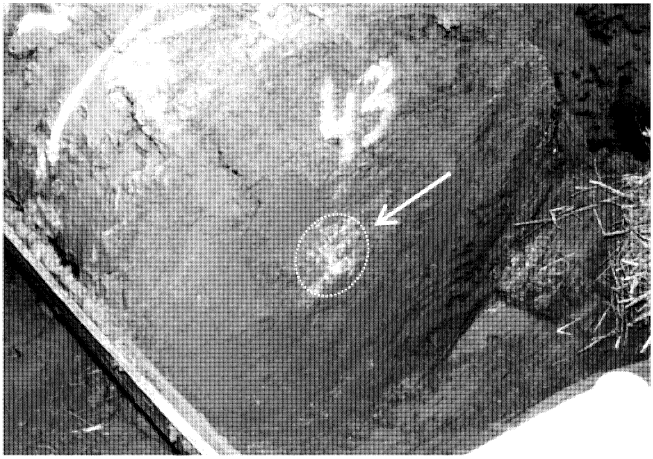


Fig. 7.13 Photograph of Column 43, depth 5.2 m. There is a high binder content at the centre of the column.

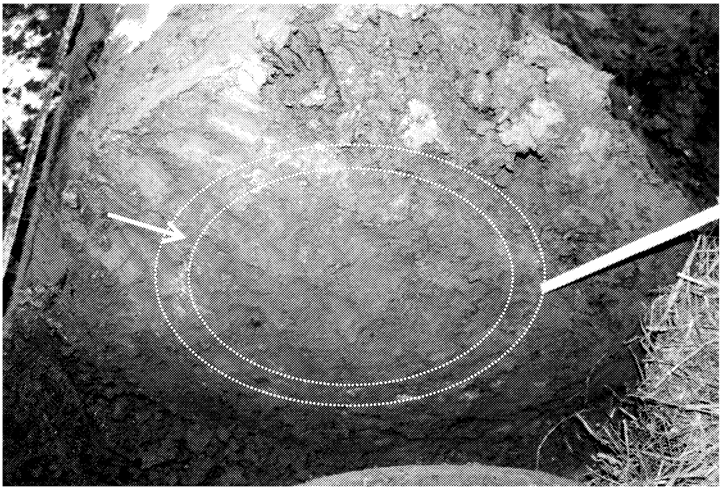


Fig. 7.14 Fig. 13. Photograph of Column 53, depth 6.0 m. There is a high binder content in a ring located 0.15 - 0.25 m from the centre of the column.

Fig. 7.15 **Photograph of Column 16, depth 0.9 m. There is a high binder content in a white ring around the periphery of the column.**

Visual examination

The assessment of the mixing quality by sampling and chemical analysis is relatively expensive and time-consuming. It is therefore tempting to assess the binder distribution by visual examination. Here, it is common to observe differences in colour, especially when using lime as binder.

Each column cross-section where samples were taken was examined visually. Fig. 7.13 shows the cross-section of Column 43 at a depth of 5.2 m. The cross-section was grey with a sharp white, grainy area at the centre of the column. This brittle grainy area consisted of clumps and agglomerates of unmixed lime and cement with trapped air. The chemical analysis indicated a high CaO content, 20 - 35%, near the centre of the column (Fig. 7.7). The binder content decreased gradually toward the periphery, where the CaO content was only 5%. The colour did not vary when the CaO content was 2 - 15%.

The cross-section of Column 53 at 6.0 m depth is shown in Fig. 7.14. Also this section has a sharp white, grainy area approximately 0.15 - 0.25 m from the centre of the column. The chemical analysis indicated a high CaO content, 10 - 17% as shown in Fig 7.8. A number of clumps with trapped air were observed in this region.

Fig. 7.15 shows the cross-section of Column 16 at a depth of 0.9 m. The cross-section was light brown with a sharp white ring around the periphery. The chemical analysis indicated a CaO content of 10 - 20%. This white ring was harder than the rest of the cross-section. There were no large clumps with trapped air.

The binder content analysis and the visual examination indicated a relationship between the white parts of the column's cross-section and a high binder content. It was not possible to perform visual detection of differences when the binder content was less than 10%. Low and normal contents, i.e. <10%, seem impossible to detect in this way. All the white parts observed had high binder contents, according to the chemical analysis. Visual examination is therefore of limited value for assessment of the binder distribution over the cross-section.

7.5 CONCLUSIONS

This chapter discusses the concept of mixing quality with respect to the binder distribution, and the use of mixing indices, as a quantitative assessment. The possibility of using mixing indices with the lime-cement column method is taken up. Statistical analysis was performed on a number of samples taken from four lime-cement columns at Arboga, Sweden.

The most important conclusions of the present study are:

- The difference in binder contents is relatively large over the cross-section and the character of the dispersion of the binder varies between the columns in the study.
- Sample size has a significant influence on the evaluated mixture quality when the mixing quality is poor. It has a smaller effect when the mixture quality is good. Thus in order to avoid overestimating or underestimating the mixture quality, the "scale of scrutiny" must first be defined, after which an appropriate sample size can be established.
- The pattern of binder dispersion in the columns is of a radial character, implying that the incorporation and distribution process using compressed air has a major impact on mixture quality.
- Since the sampling and chemical analysis of samples is difficult and costly, extensive sampling by a random selection method should be carried out in conjunction with major construction and R&D projects in which whole columns are recovered. A greater knowledge of binder dispersion in lime-cement columns is essential in order for reliable estimates of column quality to be made on the basis of small numbers of samples taken for production control.

8. Uniformity of lime-cement columns; Field test in Håby

8.1 INTRODUCTION

Introduced into practice in the mid 1970s, applications of the Swedish lime-column method increased significantly at the end of the 1980s in connection with a large investment program for infrastructure projects in Sweden. This increased usage led to new binders and more powerful machinery, which allowed for longer and larger diameter columns with higher capacities. Despite this development, the mixing process and the mixing tools are still principally the same as in the original 1970s process.

A large number of general reviews have been presented during the years, primarily in connection to conferences, e.g. in Tokyo, Stockholm and Helsinki (Yonekura, Terashi & Shibazaki, 1996; Bredenberg, Holm & Broms, 1999; Rathmayer, 2000). Deep mixing methods have received a great deal of attention the last ten years. However, few publications are concerned with the mixing process, mixing mechanisms and installation techniques. Tests concerned with the mixing process tend to be fragmentary and it is difficult to draw general conclusions from these tests. Yoshizawa et al. (1997) and Porbaha et al. (2001) have summarised Japanese experiences. The mixing process and Swedish experiences have been reviewed by Bredenberg (1999) and Larsson (1999, 2000).

There are no simple methodologies available to assess the influence of different factors affecting the mixing process. Contractors need a simple method for development of machinery and mixing tools. Clients, consultants, suppliers, and researchers also need simple test methods for the purpose of studying the influence of soil/binder properties and for development of new binders.

The paper deals with a simple field test for the study of several influential factors in the mixing process of lime-cement columns. As a background introduction, the mixing process of column installation, factors influencing the process and a short review of studies related to the mixing process for deep mixing are presented. The application of the proposed test method is demonstrated by a field study where the influence of several parameters in the installation process has been investigated by statistical multifactor experiments. The study includes the influence of the shape of the mixing tool, retrieval rate, rotation speed, diameter of the binder outlet and the binder air tank pressure. The results from a large number of hand-operated penetrometer tests on excavated column sections in test pits are treated with a number of statistical analyses supplemented by visual examinations.

8.2 INFLUENCING FACTORS

As for all materials, the properties in stabilised soil depend on its microstructure. The microstructure is determined by the composition, the conditions during the curing period, and the mixing process. The mixing process in deep mixing is complex, and consists of many phases; several factors influence the process and the results (Fig. 6.1). The knowledge of the influencing factors and their interaction is limited, mainly to the difficulty to perform qualitative field studies and the high costs.

There are a number of requirements with reference to the test methodology and the factors to be considered:

A. Several factors in the installation process should be studied simultaneously, such as;
  a) the geometry of the mixing tool;
  b) the retrieval rate;
  c) the rotation speed;
  d) the feed pressure and the amount of air;
  e) the machine type and the driver;
  f) the *in-situ* stress situation at the time of the installation.

B. Other influencing factors in the mixing process such as;
  a) the rheological properties of the unstabilised soil and the mixture;
  b) the type of binder and amount;
  c) the *in-situ* stress situation during the curing period.

C. The trials should be performed by different test methods.

D. The mixing quality should be assessed by statistical methods.

Separate studies must be performed by a number of limitations since there are a great number of influencing factors that should be investigated. The factors listed under category A are of particularly interesting for contractors, i.e. factors which are directly connected with the mechanical installation process.

It is well known that the mixing work influence the mixing process and the binder dispersion and thereby the strength and deformation properties of the stabilised soil. The present knowledge is mainly based on laboratory and model tests (Terashi et al., 1977; Nakamura et al., 1982; Chida, 1982; Nishibayashi et al., 1984, 1985; Muro et al., 1987a, 1987b; Dong et al. 1996; Hayashi and Nishikawa. 1999; Larsson et al., 1999; Aalto, 2001). The results from very few field tests are available (e.g. Enami et al., 1986; Mizuno et al., 1988; Hayashi & Nishikawa, 1999; Hansson, 2000). It is still uncertain how the mixing work affects the mixing process in different soil types with different binders under field conditions.
The influence of the geometry of the mixing tool was investigated during the 1970s and the 1980s, in Japan (Chida, 1982; Nishibayashi et al., 1984, 1985), and in Sweden (Broms et al., 1978; Wikström, 1979). In the 1990s, the investigations have mainly been performed by testing different geometries against each other (e.g. Johansson & Jons, 1995; LCM, 1996; Dong et al., 1996; Abe et al., 1997; Tränk & Edstam, 1997; Al-Tabbaa & Evans, 1999; Aalto & Perkiö, 2000; Aalto, 2001; Aalto 2003).

The influence of the rotational speed is not well known, as well as the effect of the feed pressure and the amount of air. When air is used to transport the dry binder, the compaction of the mixture and the evacuation of the air trapped in the soil also affect the mixing process. The amount of air can considerably influence the strength properties and the uniformity of the stabilised soil (Aalto, 2001). Different mixing tools and other influencing factors have been studied in the field by e.g. Hansson (2000), Rogbeck et al. (2000), and Nishibayashi et al. (1985). The change of the stress conditions in-situ caused by the installation has not been investigated. Furthermore, the influence of combinations of different factors has not been investigated.

The factors listed under category B have mainly been investigated by laboratory tests. The influence of the sensitivity of the soil has been investigated by Nishida et al. (1996). Different binders and the amount of binder have been investigated by Asano et al. (1996), Chida (1982), Matsuo et al. (1996), and Nishibayashi et al. (1988). Molecular diffusion has mainly been studied in the unstabilised soil around the columns, both in laboratory (Mathew & Narasimha Rao, 1997; Narasimha Rao & Rajasekaran, 1996; Rajasekaran & Narasimha Rao, 1997; Rogers & Glendinning, 1994, 1997) and in the field (Shen et al., 1997, Rogers et al., 2000). The binder can also spread by fractures caused by the mixing tool and by hydraulic (or pneumatic) fracturing (Shen & Miura, 1999).

Larsson (2000) has discussed the mixing process at deep mixing and the influencing factors.

8.3 SUITABLE TEST METHOD

The purpose of the mixing process is to disperse the binder in the soil and to provide the best possible conditions for the chemical reactions. The assessment of the mixing quality with respect to the binder dispersion should therefore be based on an analysis of the binder content (Larsson, 2001). This is expensive and time consuming and therefore less suitable for simple practical studies of the mixing process.

The quality of a mixture depends on the scale at which the mixture it is examined. The scale depends on the volume of segregated binder material which can be considered as incompletely mixed, for a certain application. The test method should be able to detect these regions or clumps of incompletely mixed binder. When assessing the mixing quality, the volume of soil which is tested should be relatively small, and should be distributed over the whole stabilised volume. However, the whole volume can only be tested and sampled if complete columns are extracted (Larsson, 2001). This procedure is expensive and time-consuming. For simple studies of affecting factors on the mixing process and the mixing quality, testing and sampling can be performed in columns that have been excavated. The maximum depth of the excavation is generally 2-4 m, depending on the site conditions.

Column penetration tests are not suitable to assess the mixing quality. The probe is too large to detect the binder dispersion or the strength distribution over the column sections (Axelsson & Larsson, 2003). Other penetration tests such as CPT, SPT, and vane test, are also unsuitable because of the difficulty of determine the exact location of the probe in the columns. Furthermore, it is not possible to carry out several soundings in one column to obtain data for a statistical analysis.

Statistical methods, like multifactor experiments, facilitate the analysis of the factors affecting the mixing process. Statistical methods require a relatively large number of investigated columns if several factors are varied. Since relatively large variations of the results are expected, double or triple tests are required, even when the columns are manufactured in the same way for each combination of the tested factors. Furthermore, statistical methods require a large number of tests.

Table 8.1 Methods for investigation of uniformity by means of strength testing and testing of the binder distribution on excavated column cross-sections.

Method	Scale	Comm.
Hand-operated penetrometer	cm^3 (- dm^3)	Limited test interval. If the columns are stiff or grainy, the method can give no or misleading results. Simple, uncertain reliability (manual test).
Pocket vane test	cm^3 (- dm^3)	Very limited test interval. Not applicable for grainy or stiff columns. Simple, uncertain reliability (manual test).
Visual examination	cm^3-	The visual examination not necessarily reflects the binder distribution. Simple.
Samples for unconfined, triaxial and direct shear tests.	dm^3	The sampling technique is not fully random. Disturbances from sampling to testing. Difficult, costly and time consuming. Uncertain reliability.
Samples for chemical analysis (CaO)	optional	Determination of binder content. Reliable, simple, and costly.
Samples for pH determination	optional	Unsuitable. The pH-value increases to 12.4 already at relatively low binder contents. Indicate on whether binder is present.

References Axelsson (2001); Axelsson & Larsson (1994); Broms & Boman (1975); Hansson (2000); Holm *et al.* (1999); Johansson & Jons (1995); Larsson (2000, 2001); Tremblay (2000); Tränk & Johnson (1997).

Table 8.1 shows a number of methods used for testing and sampling from column sections in Sweden. The hand-operated penetrometer has been found to be suitable to obtain data whish are cost-effective, simple, and fast. The tested volume is small and the results are expected to have relatively large variations. This makes the method suitable for studies of influencing factors on the mixing process. The penetrometer test should be supplemented by e.g. visual examination.

8.4 OUTLINE OF THE TEST METHODOLOGY

General

The main purpose of the proposed test methodology is to analyse simultaneously a number of influencing factors. The analysis should identify the factors that have a significant influence on the mixing process. The proposed test methodology is briefly as follows:

1. Test columns are installed with all combinations of all levels of the factors considered and with two or three replicates.
2. The test columns are excavated down to an appropriate depth. The column sections are tested with a large number of hand-operated penetrometer tests combined by visual examinations.
3. The results from the penetrometer tests are analysed by statistical multi-variable analysis.

Penetrometer tests

A hand-operated penetrometer consists of a spring-loaded cylinder that is pressed into the soil manually. The penetrometer which has been used to determine the relative strength has previously been used by e.g. Johansson & Jons (1995) and Axelsson (2001). The test results have been evaluated with respect to the strength and the coefficient of variation, which have been taken as a measure of the mixing quality. The results have been expressed in terms of the stabilisation effect, S_{eff} (EuroSoilStab, 2002), defined by

$$S_{eff} = \frac{c_{u,col}}{c_{u,soil}} \tag{8.1}$$

where $c_{u,col}$ is the evaluated undrained shear strength of the column and $c_{u,soil}$ is the evaluated undrained shear strength of the unstabilised soil. The undrained shear strength has been evaluated by a bearing capacity equation as

$$c_u = \frac{1}{N} \times \frac{k \times \bar{\delta}}{A} \tag{8.2}$$

where N is a bearing capacity factor, k is the spring coefficient, A is the area of the penetrometer, and $\bar{\delta}$ is the average spring deformation evaluated as

$$\bar{\delta} = \frac{1}{n} \sum_{i=1}^{n} \delta_i \tag{8.3}$$

where δ_i is the spring deformation from each test and n is the number of test over a column section. By the assumption that the bearing factor and the spring coefficient is constant over the whole measured interval, the stabilisation effect S_{eff} (average over the column cross-section) is calculated as

$$S_{eff} = \frac{\overline{\delta}_{col}}{\overline{\delta}_{soil}} \tag{8.4}$$

The coefficient of variation, as a measure of the mixing quality, is calculated as

$$V = \frac{s}{\overline{\delta}} \tag{8.5}$$

where s is the standard deviation calculated as

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\delta_i - \overline{\delta})^2}{n-1}} \tag{8.6}$$

The penetrometer tests over the column sections should be at random. This can be done by dividing the column cross-section into a number of sub-areas of equal size and then draw lots of which areas to be tested.

Reliability and limitations

The evaluation of the stabilisation effect and the coefficient of variation, as a measure of the mixing quality, are based on the assumption that there is a relationship between the binder content and the strength. However, published relationships are mainly based on the results from laboratory tests (e.g. Åhnberg et al., 1995), but under field conditions, the strength properties also depend on a number of other factors such as: compaction ratio; temperature; consolidation pressure and the chemical composition of the soil. Factors, whish not necessarily have an affect on both the binder dispersion and the strength.

The columns are tested in relatively shallow test pits, and the full column lengths can therefore not be tested. At shallow depths, at low confining pressure, heaving during the installation can affect the binder dispersion. The proposed method has been used to investigate different factors affecting the mixing process, and can not be used to investigate whole columns.

Hand-operated penetrometer tests can only be performed on low strength ductile columns with approximately $c_{u,col} < 200\text{kPa}$, since the failure mechanism is uncertain when the column material is brittle. The manual test procedure also set limitations. The columns should be tested relatively shortly after the installation when the strength is still low.

The evaluated coefficient of variation contains errors from of a number of factors such as imperfect mixing, variation due to the penetrometer and the test procedure, and variation due to the excavation of the columns. The evaluated coefficient of variation from the penetrometer tests is consequently greater than the coefficient of variation due to imperfect mixing alone. The contribution from the penetrometer, the test procedure, and the excavation of the column makes the results somewhat uncertain. Large test series and visual examinations can compensate for some of the uncertainty.

Statistical analysis

Multifactor experiments provide an applicable tool for the understanding of complex processes since all input factors can be investigated simultaneously. If the experiment comprehends a number of factors, the tests are often performed with each factor at only two levels, 2^n factorial experiments. The main reasons for using 2^n factorial experiments are to reduce the number of tests. However, since each factor is measured at only at two levels, it is impossible to determine if the influence caused by variations in a factor vary linearly, or e.g. exponentially. For that reason, 2^n factorial experiments are mostly used for screening test, in order to recognise the most affecting factors. The tests should then be followed by experiments where only a few factors are varied at several levels.

The procedure described by Johnson (1994) has been used for the analysis of variances based on two- and 2^n-factorial experiments and tests for the significance of the factorial effects, using the 5% level of significance.

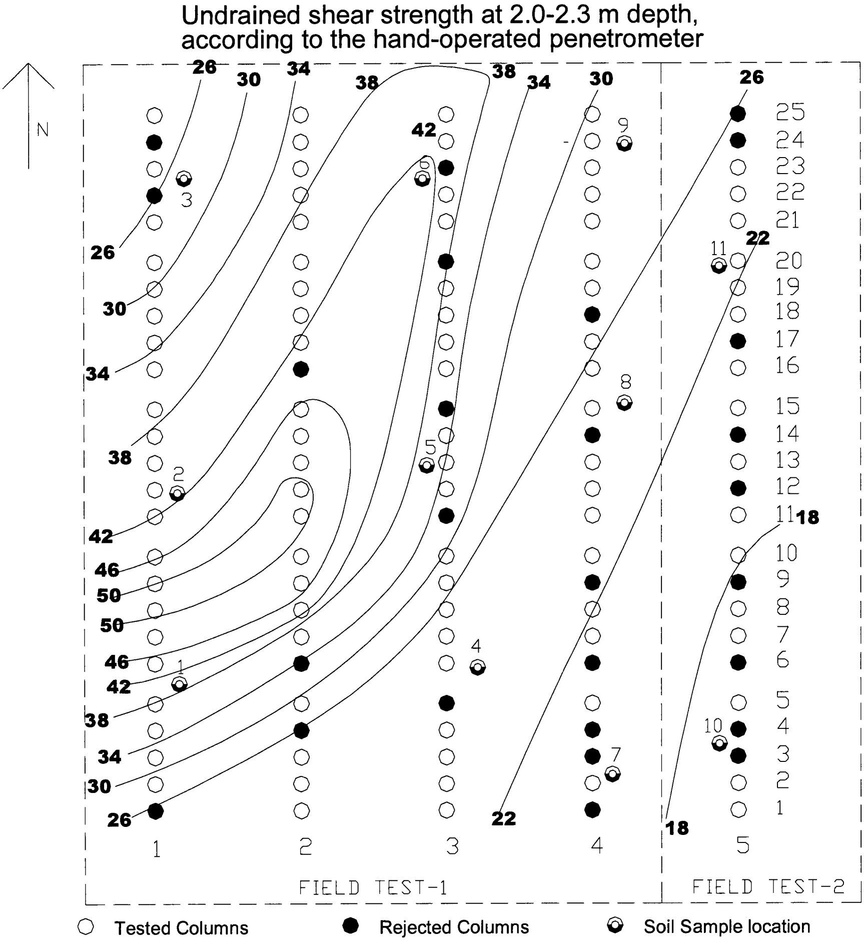
8.5 FIELD TEST

The test site

The test site is located at Håby on Europe Road E6, 20 km north of Uddevalla, on the West Coast of Sweden. The size of the test site is 25 x 25 m^2. The soil properties on the test levels, 2.0 and 2.3 m depth, were evaluated from fall-cone tests on undisturbed samples taken and by the hand-operated penetrometer. Close to every fifth column, about ten penetrometer tests were performed in the unstabilised soft soil. Fig. 8.2 shows the relative strength over the test site evaluated from the hand-operated penetrometer tests. Table 8.2 show the results from the laboratory tests on undisturbed soil samples.

Table 8.2 Soil properties at the test site (2.0-2.3m depth).

No	Soil	γ_t: kN/m^3	w: %	w_l: %	w_p: %	S_t	c_u: kPa	Com.
1	Clay, grey	18.1	45	58	25	4	38	root threads
2	Clay, dark grey	16.8	53	73	32	3	40	
3	Clay, grey (sulphidic spots)	17.5	53	62	22	9	27	
4	Clay, grey	16.5	65	63	23	9	22	shells
5	Clay, grey	17.8	38	46	23	5	45	root threads
6	Clay, grey	18.2	41	53	22	3	40	root threads
7	Clay, grey	16.5	67	65	26	14	17	
8	Clay, grey	16.8	58	60	24	11	19	shells
9	Clay, grey	17.2	56	60	23	12	26	shells
10	Clay, grey	16.2	70	64	23	18	16	
11	Clay, grey	16.2	63	63	24	20	21	



Undrained shear strength at 2.0-2.3 m depth, according to the hand-operated penetrometer

Fig. 8.2 Test site and the test columns.

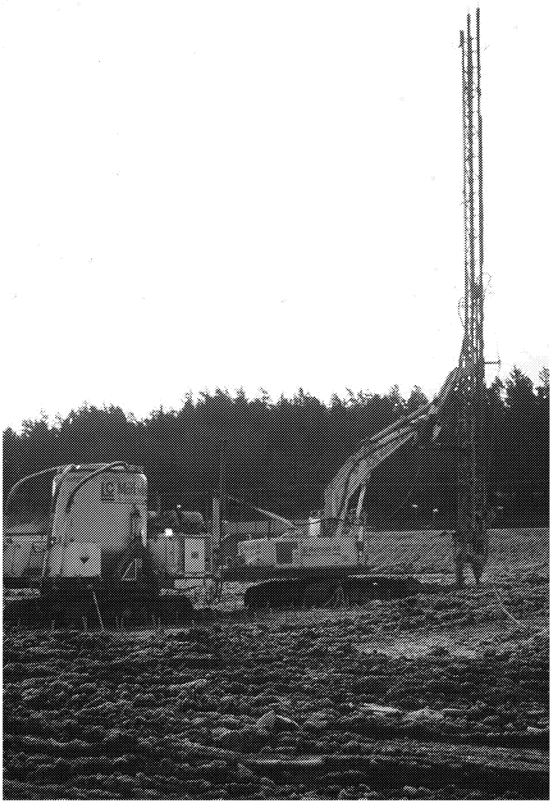


Fig. 8.3 Installation of lime-cement columns at Håby, Sweden.

Input factors

The following factors, connected to the installation process, were investigated;

the retrieval rate; 15 and 30 mm/rev;

the number of blades on the LCM mixing tool "Pinnborr"; 0, 2, 4, 6 and 12 blades (Fig. 8.4-5). A comparison with the Swedish "Standard mixing tool" was made (Fig. 8.5a);

the rotational speed; 80 and 160 rpm;

the air pressure in the storage tank; 350 kPa and 550 kPa;

the diameter of the outlet hole of the mixing tool; 22 and 37 mm.

The retrieval rate and the number of mixing blades is an indirect measure of the extent of the mixing, while the rotational speed is an indirect measure of the intensity of mixing. The air pressure in the storage tank and the diameter of the outlet hole is an indirect measure of the air pressure at the outlet hole. All these factors can influence on the actual mixing work.

Other factors, not directly related to the installation process, were kept constant as far as possible. The proportion of binder was 100 kg/m^3 which corresponds to 28 kg/m, for the 0.6 m column, 50% quicklime and 50% cement. The length of the columns was about 5 to 7 m. The column machine is shown in Fig. 8.3.

Test arrangements

The test columns were installed and tested at two occasions. At Field test 1, 100 columns were installed, of which 82 were tested as shown in Fig. 8.2. At Field test 2, 25 columns were installed, of which 16 were tested. Tables 8.5-7 show the installation data for each column.

Field test 1

In order to study the early stage in the dispersion process, columns were installed with the factors according to Table 8.3. The factors were varied in two levels, low and high respectively. The four mixing tools shown in Fig. 8.4 were investigated in statistical Test 1, with 62 columns.

In statistical Test 2 whish included 18 columns, the Swedish Standard tool was compared with the Pinnborr. Table 8.3 shows the factors which were varied. Fig. 8.5a shows the two mixing tools.

A third test, statistical Test 3 was carried out where the mixing tool had two or six blades according to Table 8.3. All test columns in Test 2 and 3 were installed with an air pressure in the storage tank of 550 kPa, and an outlet hole diameter of 37 mm.

Field test 2

23 test columns were installed at Field test 2. The statistical analysis included two two-factor experiments, according to Table 8.4. In order to study the influence of the location of the blades, with respect to the outlet hole, a mixing tool which was provided with two pair of blades was used where the upper pair of blades had been removed. The outlet hole was located 200 mm above the upper two blades. In order to study the influence of the number of blades further, four columns were installed by a tool provided with 12 blades (Fig. 8.5b). Statistical Test 5 is a complemented statistical analysis, without the mixing tool where the upper pair of blades was removed.

Table 8.3 Experimental design for statistical test 1, 2 and 3 (2^n- factorial experiment).

Test	Factor	Low level	High level
Test 1	With/without blades	No blades	One pair
	Outlet hole (mm)	22	37
	Tank pressure (kPa)	350	550
	Retrieval rate (mm/rev)	15	30
	Rotational speed (rpm)	80	160
Test 2	Mixing tool	Standard (4 blades)	Pinnborr (6 blades)
	Retrieval rate (mm/rev)	15	30
	Rotational speed (rpm)	80	160
Test 3	Number of blades	2 blades	6 blades
	Retrieval rate (mm/rev)	15	30
	Rotational speed (rpm)	80	160

Table 8.4 Experimental design for statistical test 4 and 5 (two factorial experiment)

Factor				
Number of blades	12 blades	6 blades	4 blades[1] (only Test 4)	2 blades
Retrieval rate (mm/rev)	15	30		

[1] The upper pair of blades in connection to the outlet hole is removed

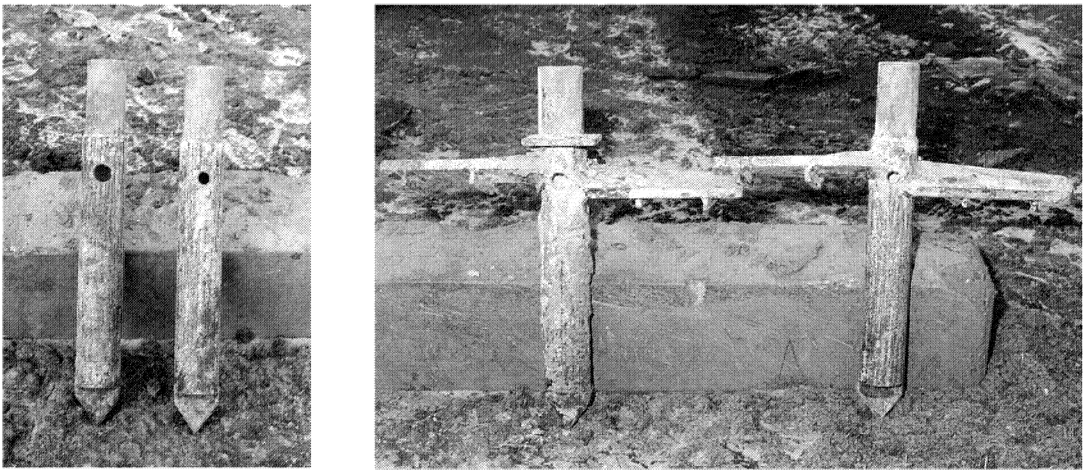

(a) (b)

Fig. 8.4 The mixing tools used in Test 1: (a) mixing tools without blades and (b) mixing tools with two blades.

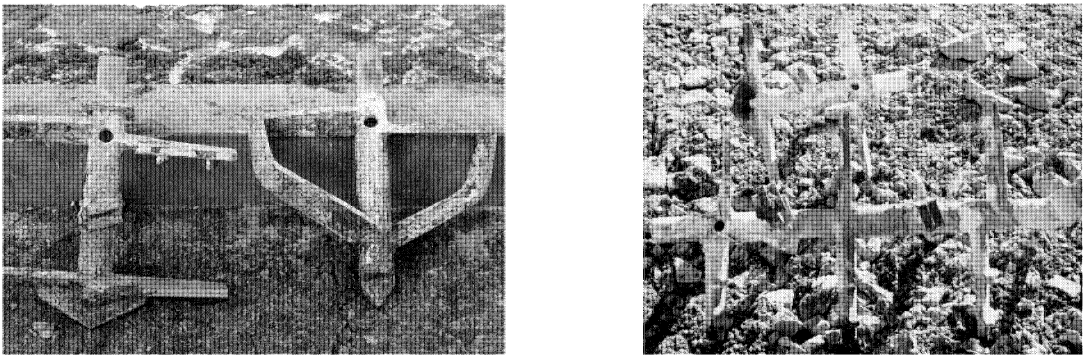

(a) (b)

Fig. 8.5 (a) The Pinnborr and the Swedish Standard mixing tool; and (b) the Pinnborr with 12 blades.

Testing

All penetrometer tests were executed seven to eight days after the installation. In order to compensate for local variations in the axial direction, the tests were performed on two close levels, 2.0 and 2.3 m respectively. The columns were excavated by an excavator provided with a plane bucket, as shown in Fig. 8.6a. Just before the testing the column cross-sections were cut manually by a shovel.

Four templates of plywood were manufactured for random testing. The templates, 0.6 m in diameter, were divided into 104 equal sub-areas, 50 x 50 mm. 20 areas were selected at random where the penetrometer tests were performed. Totally 40 tests were performed on each column.

The penetrometer tests were performed by the same person (Fig. 8.6b). The hand-operated penetrometer which is spring-loaded was pushed down about 30 mm into the stabilised soil. The cylindrical-shaped head has a sliding ring, which moves over a calibrated scale as load is applied. The two tested cross-sections of each column was also investigated visually and photographed.

(a) (b)

Fig. 8.6 **(a) Excavation of test pit; and (b) hand-operated penetrometer tests.**

Table 8.5 Results from the penetrometer tests. Columns manufactured with a two blade mixing tool at Field test 1.

Row	No	Retr rate: mm/rev	Blade rot num: n/m	Rot speed: rev/min	Outl hole: mm	Tank pressure : kPa	$\bar{\delta}$ col (mm)	$\bar{\delta}$ soil (mm)	V	$\frac{w}{w_l}$ 1)	S_{eff}	$V \cdot \frac{w}{w_l}$
1	6	15	133	160	37	550	128	20	0.38	0.63	6.4	0.24
	7	15	133	160	37	550	110	20	0.41	0.63	5.5	0.26
	8	15	133	160	22	550	132	22	0.44	0.57	6.0	0.25
	9	15	133	160	22	550	138	23	0.46	0.54	6.0	0.25
	18	15	133	160	22	350	90	14	0.36	0.82	6.4	0.30
	19	15	133	160	22	350	80	14	0.37	0.82	5.7	0.30
	20	15	133	160	37	350	73	13	0.27	0.85	5.6	0.23
	21	15	133	160	37	350	53	11	0.27	0.92	4.8	0.25
	23	15	133	80	37	350	65	11	0.29	0.92	5.9	0.27
	25	15	133	80	37	350	70	11	0.29	0.92	6.4	0.27
2	11	15	133	80	37	550	108	22	0.42	0.57	4.9	0.24
	12	15	133	80	37	550	132	22	0.43	0.57	6.0	0.25
	13	15	133	80	22	550	118	22	0.47	0.57	5.4	0.27
	14	15	133	80	22	550	104	20	0.38	0.63	5.2	0.24
	24	15	133	80	22	350	81	16	0.41	0.76	5.1	0.31
	25	15	133	80	22	350	98	16	0.40	0.73	5.8	0.29
3	1	30	67	80	37	550	54	11	0.35	0.92	4.9	0.32
	2	30	67	80	37	550	54	11	0.36	0.92	4.9	0.33
	3	30	67	80	22	550	54	11	0.29	0.92	4.9	0.27
	4	30	67	80	22	550	61	11	0.34	0.92	5.5	0.31
	16	30	67	160	22	550	55	14	0.40	0.82	3.9	0.33
	17	30	67	160	22	550	68	14	0.31	0.82	4.9	0.25
	18	30	67	160	37	550	76	15	0.37	0.79	5.1	0.29
	19	30	67	160	37	550	67	15	0.32	0.79	4.5	0.25
4	2	30	67	160	37	350	52	10	0.35	0.95	5.2	0.33
	5	30	67	160	37	350	56	10	0.3	0.95	5.6	0.28
	7	30	67	160	22	350	53	10	0.37	0.95	5.3	0.35
	8	30	67	160	22	350	61	11	0.30	0.92	5.5	0.27
	20	30	67	80	22	350	64	12	0.33	0.88	5.3	0.29
	21	30	67	80	22	350	62	12	0.37	0.88	5.2	0.33
	22	30	67	80	37	350	63	13	0.40	0.85	4.8	0.34
	23	30	67	80	37	350	69	14	0.40	0.85	5.3	0.34

The w/w_l -ratio is evaluated by interpolation, Table 8.2.

Table 8.6 Results from the penetrometer tests. Field test 1, with the Swedish Standard tool and the Pinnborr.

Row	No	Retr. rate: mm/rev	Blade rot num: n/m	Rot speed: rev/min	Mixing tool	$\bar{\delta}$ col (mm)	$\bar{\delta}$ soil (mm)	V	$\frac{w}{w_l}$ 1)	S_{eff}	$V \cdot \frac{w}{w_l}$
1	2	15	267	160	Std	74	12	0.40	0.88	6.2	0.35
	3	15	267	160	Std	92	14	0.37	0.82	6.6	0.30
	4	15	400	160	Pinnb.	125	15	0.21	0.79	8.3	0.17
	5	15	400	160	Pinnb.	100	15	0.28	0.79	6.7	0.22
2	1	30	200	80	Pinnb.	68	11	0.29	0.92	6.2	0.27
	2	30	200	80	Pinnb.	67	11	0.25	0.92	6.1	0.23
	3	30	133	80	Std	62	12	0.46	0.88	5.2	0.41
	5	30	133	80	Std	61	12	0.30	0.88	5.1	0.27
	7	15	267	80	Std	145	19	0.37	0.66	7.6	0.25
	8	15	267	80	Std	158	20	0.34	0.63	7.9	0.22
	9	15	400	80	Pinnb.	168	20	0.27	0.63	8.4	0.17
	10	15	400	80	Pinnb.	140	20	0.30	0.63	7.0	0.19
3	21	30	200	160	Pinnb.	123	18	0.39	0.70	6.8	0.27
	22	30	200	160	Pinnb.	127	18	0.31	0.70	7.1	0.22
	24	30	133	160	Std	118	18	0.4	0.70	6.6	0.28
	25	30	133	160	Std	85	16	0.42	0.76	5.3	0.32
4	24	20	300	160	Pinnb.	90	13	0.21	0.85	6.9	0.18
	25	20	300	160	Pinnb.	97	13	0.16	0.85	7.5	0.14

1) The w / w_l -ratio is evaluated by interpolation, Table 8.2.

Table 8.7 Results from the penetrometer tests. Field test 2.

Row	No	Retr rate: mm/rev	Blade rot.num: n/m	Rot speed: rev/min	Blades: n	$\bar{\delta}$ col (mm)	$\bar{\delta}$ soil (mm)	V	$\frac{w}{w_l}$ 1)	S_{eff}	$V \cdot \frac{w}{w_l}$
5	1	30	400	160	12	60	8	0.19	1.00	7.5	0.19
	2	30	400	160	12	68	8	0.11	1.00	8.5	0.11
	5	15	800	160	12	76	8	0.11	1.00	9.5	0.11
	7	15	800	160	12	73	8	0.14	1.00	9.1	0.14
	8	15	400	160	6	61	8	0.14	1.00	7.6	0.14
	10	15	400	160	6	65	8	0.17	1.00	8.1	0.17
	11	15	267	160	4[2]	43	9	0.48	0.97	4.8	0.47
	13	15	267	160	4[2]	38	9	0.62	0.97	4.2	0.61
	15	15	133	160	2	51	10	0.20	0.94	5.1	0.19
	16	15	133	160	2	44	10	0.19	0.94	4.4	0.18
	18	30	67	160	2	47	10	0.28	0.94	4.7	0.27
	19	30	67	160	2	46	10	0.28	0.94	4.6	0.27
	20	30	133	160	4[2]	58	10	0.32	0.94	5.8	0.30
	21	30	133	160	4[2]	60	11	0.31	0.91	5.5	0.28
	22	30	200	160	6	60	11	0.24	0.91	5.5	0.22
	23	30	200	160	6	73	12	0.19	0.88	6.1	0.17

1) The w / w_l -ratio is evaluated by interpolation, Table 8.2.

2) The upper pair of blades in connection to the outlet hole is removed.

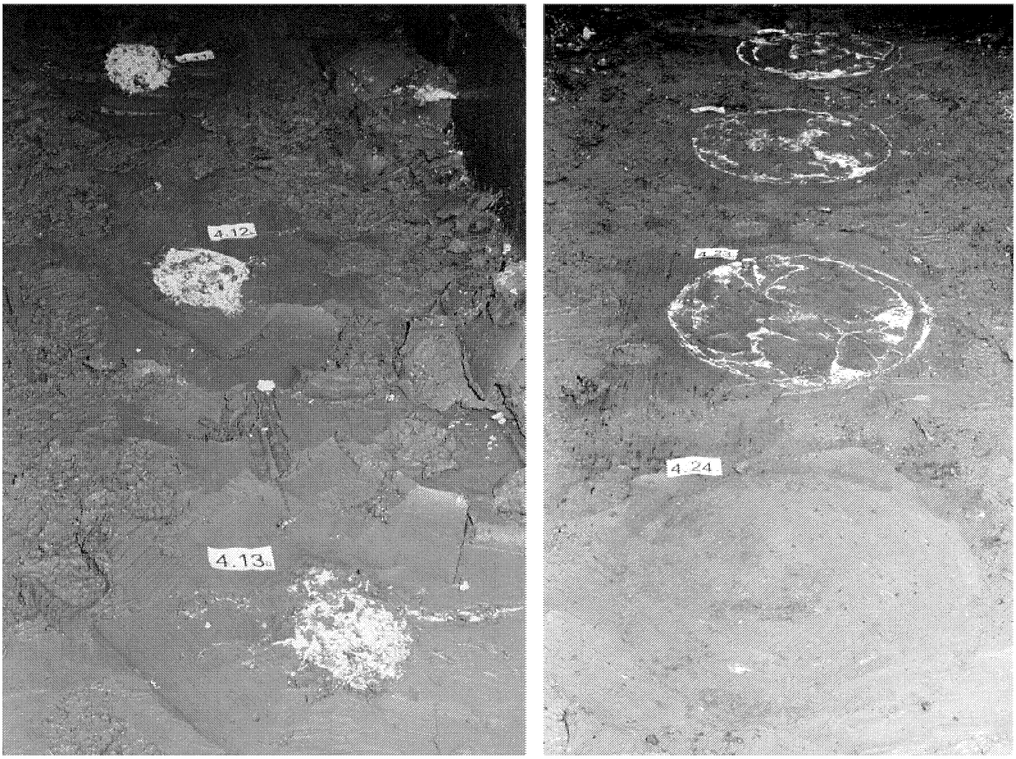
8.6 RESULTS AND DISCUSSION

General

The results from the hand-operated penetrometer tests are presented in Tables 8.5-7. The results of the five statistical tests are presented in Tables 8.8-12. Significant results with respect to the 5% level of significance are market by bold figures. The results from the visual examination have been reported in Larsson et al. (2002b).

Blade location

In statistical Test 1, 64 columns were installed by mixing tools without blades and tools provided by one pair of blades. The visual examination clearly showed that a circular cavity, 0.1-0.2 m in diameter, which was filled by binder, had formed in the 32 columns which had been installed by mixing tools without blades (Fig 8.7). In some columns, the binder was still dry. Most columns were however very stiff. The shapes of the columns were about the same down to 5 to 6 m depth. Penetrometer tests were not performed in these columns, since the results can be misleading because the strength does not correspond to the binder content. Some binder escaped along the shaft during installation probably because of the square cross-section of the shaft which obviously creates an evacuation channel up to the ground surface. The air pre-



(a) (b)

Fig. 8.7 a) Columns installed by mixing tools without blades; and (b) columns installed by the Swedish Standard mixing tool and by the Pinnborr (the nearest column) ssure in the storage tank was 350 and 550 kPa respectively, which could be high enough to fracture the soil, which would improve the binder dispersion. Pneumatic fracturing was observed in 14 out of 32 columns. One to three narrow vertical cracks radiating from the centre of the column (Fig. 8.8), perpendicular to the direction of the principal stress direction, were observed. The cracks were about 10 mm wide and up to 0.5 m long and didn't occupy any major part of the total binder volume. Pneumatic fracturing can not alone be considered as a significant mixing mechanism.

The visual examination indicates that the incorporation and spreading of the binder take part in the cavity formed by the upper pair of blades. The air pressure must be high enough to form the cavity and to create channels up to the ground surface. The tank pressure should however not be too high, causing pneumatic fracturing outside the column periphery. The size and the shape of the cavity at the mixing blades depend very likely on the air pressure. At great depth, there is a risk that the cavity will be too small. The difficulty to create a sufficiently large cavity increases probably with increasing column diameter. A high pressure and insufficient release of the air pressure could cause heaving and uneven dispersion of the binder and insufficient compaction of the mixture especially close to the ground surface.

It has not been possible to recommend a suitable air pressure. Additional studies with a wider interval of the air pressure and of the location of the outlet hole are required. Since the 1980s, a technique to improve the dispersion of the binder by locating the outlet hole just behind the mixing blades has been used in Japan (Chida, 1982). The idea is to reduce the air pressure needed, which results in a possibility to create larger-diameter columns.

In Field test 2, four columns were installed by a mixing tool which was provided with four blades and where the outlet hole was located approximately 200 mm above the blades. The two-factor experiment, Test 4 according to Table 8.11, shows that the number of blades has a significant influence on the stabilisation effect and on the coefficient of variation. The diameter of the four columns varied axially from 0.4 to 0.6 m. Consequently, the four blades on the mixing tool did not distribute the binder over the whole column section. The distribution of binder was limited to a few decimetres.

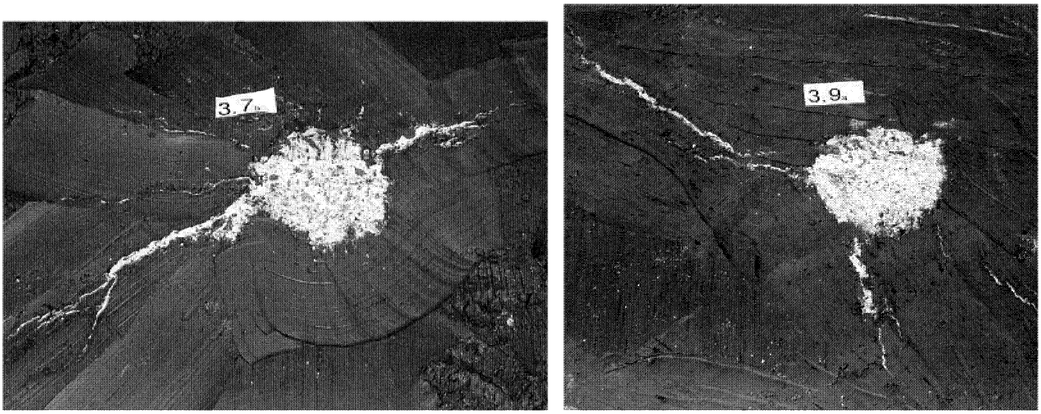


Fig. 8.8 **Pneumatic fracturing of the soil**

Table 8.8 Analysis of variance, 2^4 factorial experiment, Test 1.

Source of variation	$\bar{\delta}_{col}$	S_{eff}	V	$V \cdot \frac{w}{w_l}$
	F	F	F	F
Replication	< 1	< 1	< 1	< 1
Main effects:				
A. Outlet hole	3.3	< 1	4.5	< 1
B. Tank pressure	**56**	2.6	**12**	**7.5**
C. Retrieval rate	**153**	**17**	**7.1**	**22**
D. Rotational speed	< 1	< 1	1.8	2.0
Two-factor interactions:				
AB	3.11	< 1	2.5	1.1
AC	**5.4**	< 1	**13**	4.3
AD	< 1	< 1	2.5	2.1
BC	**51**	1.9	**19**	< 1
BD	**8.4**	< 1	3.6	< 1
CD	< 1	1.3	< 1	< 1
Three-factor interaction				
ABC	1.5	< 1	3.2	1.7
ABD	< 1	2.3	< 1	< 1
ACD	1.7	4.5	< 1	1.2
BCD	< 1	**5.6**	< 1	< 1
Four-factor interaction				
ABCD	3.3	< 1	< 1	< 1

Comment: $F_{0.05}$=4.54 and $F_{0.01}$=8.68 for 1 and 15 degrees of freedom.

Table 8.9 Analysis of variance, 2^3 factorial experiment, Test 2.

Source of variation	$\bar{\delta}_{col}$	S_{eff}	V	$V \cdot \frac{w}{w_l}$
	F	F	F	F
Replication	< 1	< 1	< 1	< 1
Main effects:				
A. Tool; Std-Pinnb.	4.5	5.2	**13**	**13**
B. Retrieval rate	**25**	**15**	1.8	4.5
C. Rotational speed	< 1	< 1	< 1	< 1
Two-factor interactions:				
AB	< 1	< 1	< 1	< 1
AC	2.3	< 1	< 1	< 1
BC	**51**	**5.6**	1.3	2.8
Three-factor interaction				
ABC	< 1	< 1	1.3	1.7

Comment: $F_{0.05}$=5.59 and $F_{0.01}$=12.20 for 1 and 7 degrees of freedom.

Table 8.10 Analysis of variance, 2^3 factorial experiment, Test 3

Source of variation	$\bar{\delta}_{col}$	S_{eff}	V	$V \cdot \frac{w}{w_l}$
	F	F	F	F
Replication	< 1	< 1	< 1	< 1
Main effects:				
A. Two–six blades	**14**	**29**	**28**	**18**
B. Retrieval rate	**57**	**8.2**	< 1	**17**
C. Rotational speed	1.7	< 1	< 1	< 1
Two-factor interactions:				
AB	2.5	< 1	**8.9**	< 1
AC	< 1	< 1	1.3	1.0
BC	**22**	< 1	4.0	2.1
Three-factor interaction				
ABC	**10**	1.5	2.0	< 1

Comment: $F_{0.05}$=5.59 and $F_{0.01}$=12.20 for 1 and 7 degrees of freedom.

Table 8.11 Analysis of variance, Test 4

Source of variation	*Degrees of freedom*		$\bar{\delta}_{col}$	S_{eff}	V	$V \cdot \frac{w}{w_l}$
		$F_{0.05}$	F	F	F	F
Replication	1	5.59	< 1	< 1	< 1	< 1
Main effects:						
A. Number of blades	3	4.35	**21**	**68**	**31**	**28**
B. Retrieval rate	1	5.59	1.2	**7.4**	< 1	1.0
Two-factor interactions:						
AB	3	4.35	**6.4**	**10**	**10**	**10**

Table 8.12 Analysis of variance, Test 5

Source of variation	*Degrees of freedom*		$\bar{\delta}_{col}$	S_{eff}	V	$V \cdot \frac{w}{w_l}$
		$F_{0.05}$	F	F	F	F
Replication	1	6.61	< 1	< 1	< 1	< 1
Main effects:						
A. Number of blades	2	5.79	**20**	**73**	3.8	**7.5**
B. Retrieval rate	1	6.61	< 1	**19**	3.4	**6.8**
Two-factor interactions:						
AB	2	5.79	1.9	4.8	2.4	< 1

Retrieval rate and the number of blades

The strength of the unstabilised soft soil varied within the test site which had a considerable influence on the strength in the columns and on the coefficient of variations. This affected the statistical analysis, but made it possible to study the influence of the unstabilised soil on the mixing process.

In order to involve the influence of the rheological properties of the soil on the mixing process, the results from all penetrometer tests were compared. To obtain an indirect value on the mixing work as a function of the retrieval rate s, and the number of blades on the mixing tool ΣM, the Blade rotation number T, is expressed as

$$T = \sum M \times \frac{1}{s} \tag{8.7}$$

Blade rotation number means the total number of mixing blades passing during 1 m of shaft movement. This term is used as an indirect measure of the degree and efficiency of mixing (used by e.g. Nakamura et al. 1982; Enami et al. 1986a, 1986b; Mizuno et al., 1988; Hayashi & Nishikawa, 1999).

Fig. 8.9 shows the results from 2480 penetrometer tests in 62 columns. Fig. 8.9a shows the spring deformation as a function of the Blade rotation number. The scatter in the results is considerable, which can be attributed to the varying soil properties. Fig. 8.10 shows the same results, but the stabilisation effect according to equation 8.4, as a function of the Blade rotation number. The correlation is good and the relationship is approximately logarithmic.

Fig. 8.9b shows the coefficient of variation as a function of the Blade rotation number. The scatter is considerable high but there is a definite difference between the two tests trials. The coefficient of variation from Field test 2 is lower over the whole interval. The varying soil properties have a clear influence on the results. In order to involve the rheological properties in the soil in the analysis, a number of geotechnical indexes were tested empirically: the ratio between the water content and the liquid limit w/w_l; the liquidity index I_L; and the sensitivity ratio S_t. The ratio between the water content and the liquid limit provided the best fit. Fig. 8.11 shows the coefficient of variation as a function of the quotient between the water content and the liquid limit multiplied by the logarithm of the Blade rotation number ($V = f(w/w_l \times \log(T))$).

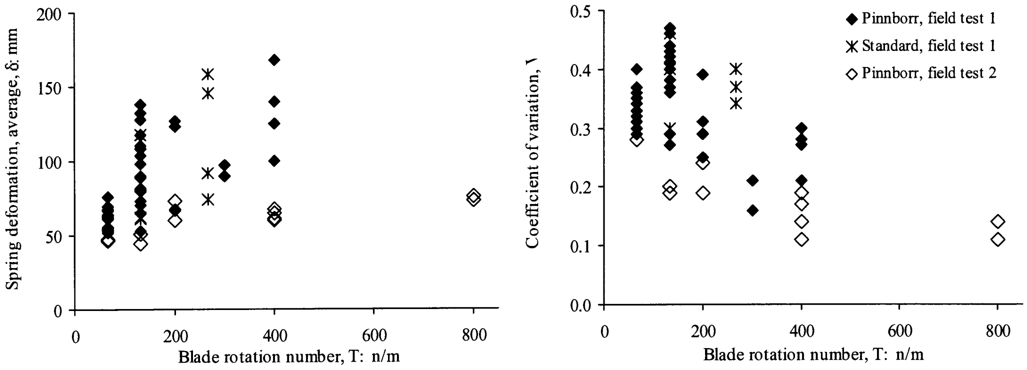


Fig. 8.9 **a) The spring deformation $\bar{\delta}$; and b) the coefficient of variation V, as a function of the Blade rotation number T.**

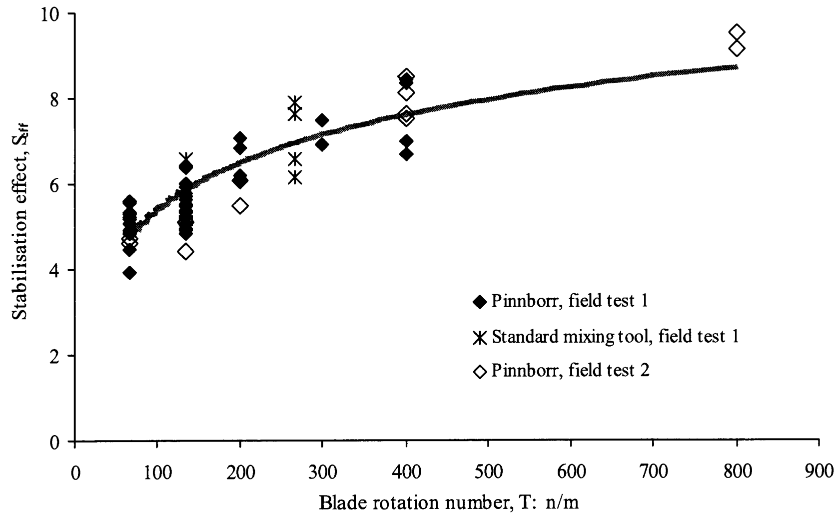


Fig. 8.10 The stabilisation effect S_{eff} as a function of the Blade rotation number T .

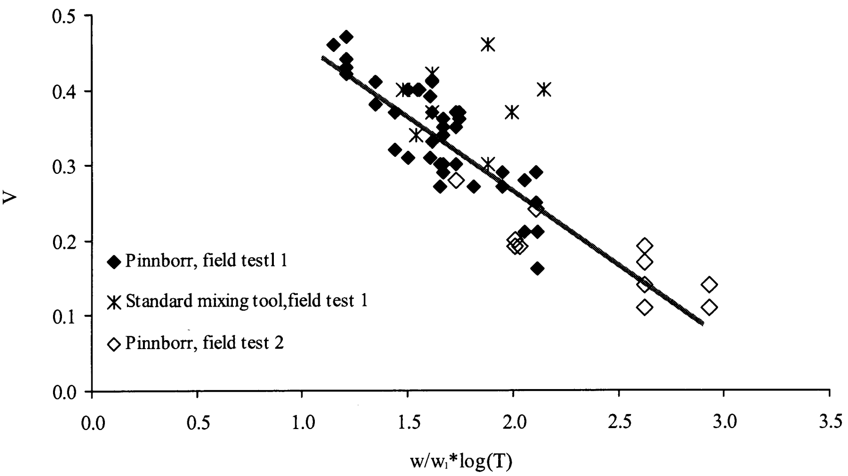


Fig. 8.11 The coefficient of variation V , as a function of the quotient between the water content and the liquid limit multiplied by logarithm of the Blade rotation number $w/w_l \cdot \log(T)$.

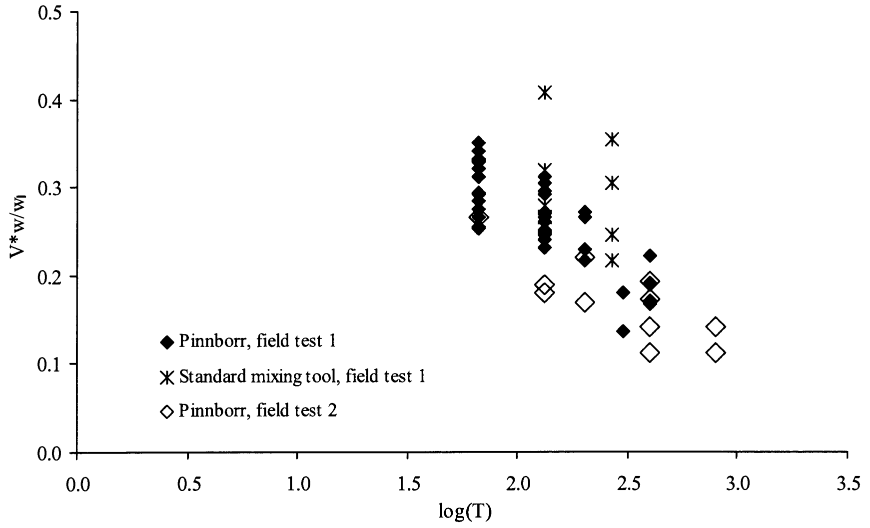


Fig. 8.12 **The adjusted coefficient of variation** $V \cdot w/w_l$ **, as a function of the logarithm of the Blade rotation number** $\log(T)$

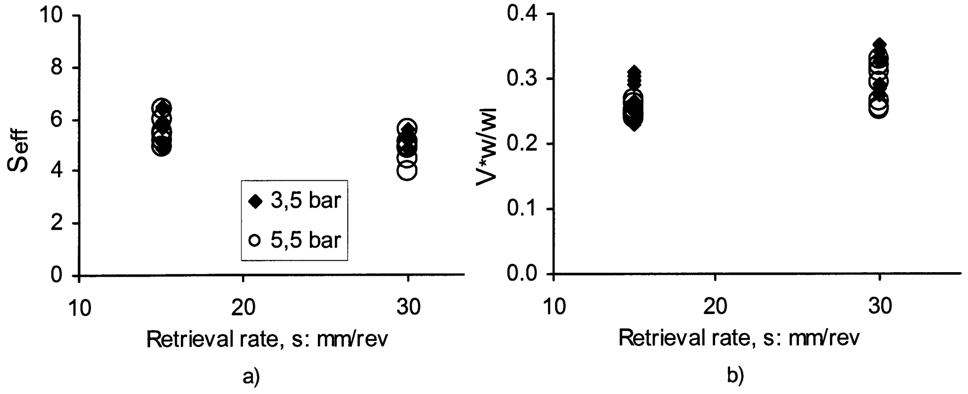
From this relation, an interesting empirical relation is obtained, between mixing quality (with respect to the coefficient of variation) and simple geotechnical parameters, which have influence on the rheological properties. The relation is assumed to have the form

$$V = A - B \cdot w/w_l \cdot \log(T) \qquad (8.8)$$

A is a coefficient, assumed to mainly depend on the tool capacity to spread and to incorporate the binder over the column cross-section (process 2a according to Fig. 6.1). The coefficient B is assumed to depend mainly on the tool capacity to wet the binder and to break down the agglomerates, distribute and to compact the mixture (process 2b-d according to Fig. 6.1). The coefficients A and B can also depend on other factors such as: time; type and content of binder; the chemical composition of the soil etc. The correlation is good for the interval ($0.5 < w/w_l < 1.0$; $67 \leq T \leq 800$) and merits further investigations in the future.

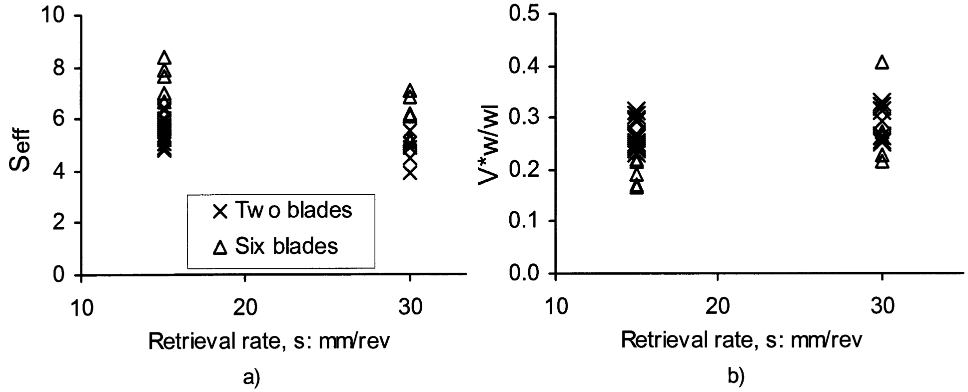
Fig. 8.12 shows another empirical relation with respect to the coefficient of variation, performed in order to facilitate an analysis of the influence of the input factors, where the quotient between the water content and the liquid limit is included. The multifactorial experiments have therefore been expanded to investigate an adjusted coefficient of variation ($V \cdot w/w_l$).

The Statistical analysis of the results from Test 1, Table 8.8, where a mixing tool with two blades was used shows significant influences of several combinations of factors such as the tank pressure in combination with the retrieval rate. These results can however be attributed to the varying soil properties and the fact that the columns were not installed at random. The statistical analysis with respect to the stabilisation effect S_{eff} , and the adjusted coefficient of variation $V \cdot w/w_l$, shows that the retrieval rate has a significant influence. The influence is however relatively weak, as shown in Fig. 8.13. The visual examination indicated that the columns installed at a retrieval rate of 30 mm/rev had a slightly more grainy structure than at 15 mm/rev. However, it was not possible to visually detect any differences in the binder dispersion.



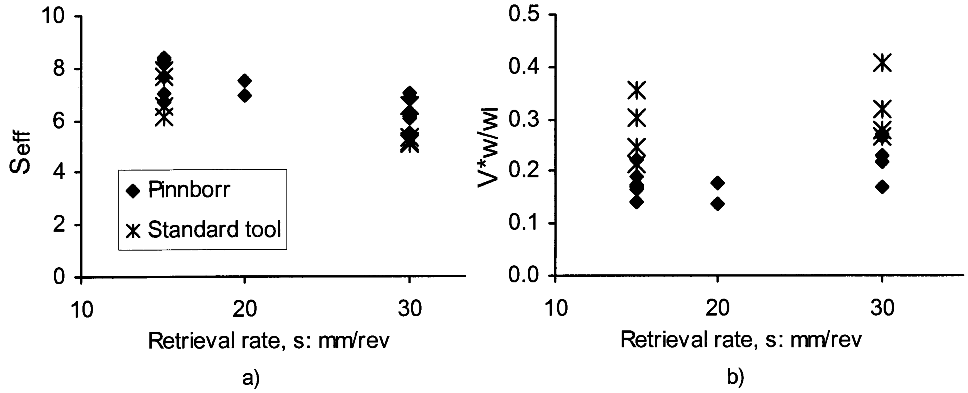
a) b)

Fig. 8.13 **Results from Test 1: a) the stabilisation effect S_{eff} ; and b) the adjusted coefficient of variation $V \cdot w/w_l$, as a function of the retrieval rate**



a) b)

Fig. 8.14 **Results from Test 3: a) the stabilisation effect S_{eff} ; and b) the adjusted coefficient of variation $V \cdot w/w_l$, as a function of the retrieval rate**



a) b)

'Fig. 8.15 **Results from Test 2: (a) the stabilisation effect S_{eff} ; and (b) the adjusted coefficient of variation $V \cdot w/w_l$, as a function of the retrieval rate**

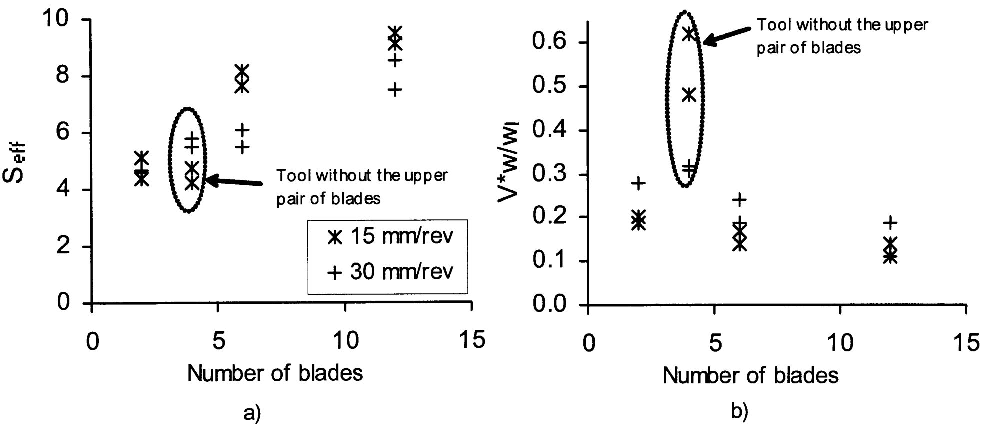


Fig. 8.16 Results from Test 4 and 5: (a) the stabilisation effect S_{eff} ; and (b) the adjusted coefficient of variation $V \cdot w/w_l$ as a function of the number of blades on the mixing tool

In statistical Test 3, the mixing tool Pinnborr was tested with two and six blades respectively. Table 8.10 shows the results from the 2^3-factorial experiment, including 16 test columns. The test shows that the number of blades and the retrieval rate have a significant influence on the stabilisation effect and the adjusted coefficient of variation (Fig. 8.14). These results were validated by the visual examination. It was clear that the binder was more evenly distributed over the column section by a mixing tool with six blades instead of two blades.

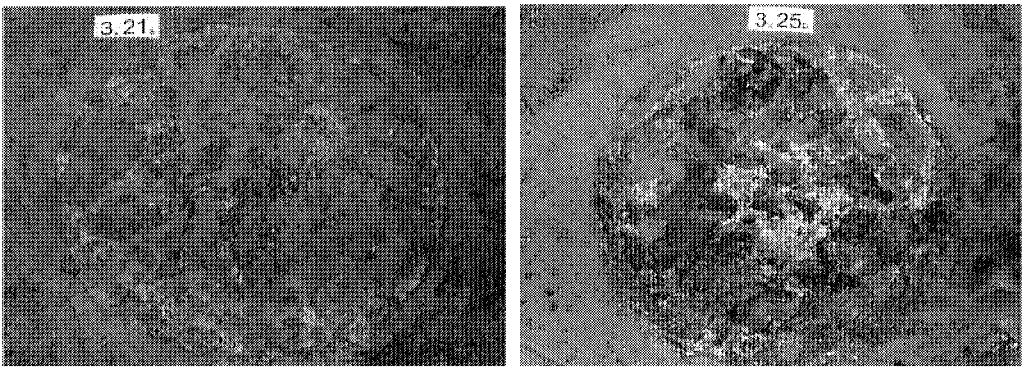
In Field test 2, mixing tools which were provided with two, six, and twelve blades, were used. The results are shown in Table 8.12. Also this test showed that the number of blades and the retrieval rate have a significant influence on the stabilisation effect and the adjusted coefficient of variation. The adjusted coefficient was low for all columns installed by the mixing tool provided by 12 blades, whether the retrieval rate was 15 mm/rev ($V \cdot w/w_l = 0.11$ and 0.14), or 30 mm/rev ($V \cdot w/w_l = 0.11$ and 0.19).

The retrieval rate and the number of blades have thus a significant influence on the stabilisation effect and the strength variation. It can be technically favourable to provide the mixing tool with more blades and thereby improve the mixing quality, according to equation 8.8 and Figs. 8.10 and 8.11. The retrieval rate can most probably be increased in proportion to the number of blades with preserved mixing quality. This argu-ment is supported by the statistical analysis where the combination of the retrieval rate and the number of blades did not have significant influences, which indicate that these factors are independent variables.

It is interesting to note that Larsson et al. (1999) and Walter (1998) obtained similar results at laboratory tests with quick lime and cement which was mixed with the undisturbed soil directly in the sampling tubes by a rotating mixing tool. The strength, evaluated from unconfined compression tests, increased approximately as a linear function of the logarithm on the mixing work. Also Nishida et al. (1996) have reported that the strength increases approximately linearly as a function of the logarithm on the mixing work.

Standard tool - Pinnborr

Table 8.6 shows the results from the penetrometer test performed in the 16 test columns for statistical Test 2, installed by a six blade mixing tool and the Swedish Standard mixing tool (four blades). The results, Table 8.9, show that the retrieval rate has a significant influence on the stabilisation effect (Fig 8.15a). The tool type had not a significant influence. However, the six blade tool had a significant lower adjusted



(a) (b)

Fig. 8.17 **Columns installed by: (a) the Pinnborr and; (b) installed by the Swedish Standard mixing tool**

coefficient of variation ($V \cdot w / w_l = 0.17$ to 0.27), compared to the Swedish Standard mixing tool ($V \cdot w / w_l =$ 0.22 to 0.41), as illustrated in Fig. 8.15b. A possible explanation is that the blades on the mixing tool Pinnborr are provided by small crests.

The visual examination clearly showed that the six blade mixing tool dispersed the binder more evenly over the column cross-section, which had an even dark colour, with no visual accumulations of binder (Fig. 8.7b and 8.17).

LCM (1996) has previously investigated the difference between the Pinnborr and the Swedish Standard mixing tool by column penetration tests. It was found that the Pinnborr increased the undrained shear strength by 20% to 30% compared with the Swedish Standard tool. The two mixing tools have also been investigated by Tränk & Edstam (1997) by column penetration tests. They founded from a relatively small number of tests that the configuration of the mixing tool had little effect on the strength.

The rotational speed

The influence of the rotational speed was tested in Test 1, 2 and 3. The results show that the rotational speed had no significant influence. Further examination for a wider span is desirable since it is economical to use high rotational speeds.

Tank pressure and the size of the outlet hole

The influence of the tank pressure and the diameter on the outlet hole were tested in Test 1. The results (Table 8.8) show that the diameter of the outlet hole had no significant influence. The tank pressure had, however, a significant but weak influence on the adjusted coefficient of variation, as illustrated in Fig. 8.13. The results are uncertain since the tank pressure and the diameter of the outlet hole were only investigated for one test, where only mixing tools with two blades were used. These factors should therefore be tested further and supplemented by other types of mixing tools.

Combinations of parameters

A number of combinations of factors had a significant influence according to the statistical analysis, mainly with respect to the spring deformation and the coefficient of variation. These results can probably be attributed to the varying soil properties within the test site and that the columns were not installed at random. The combinations of factors that influence the mixing process could therefore not be identified.

8.7 CONCLUSIONS

An experimental field study, based on the stabilisation effect and the coefficient of variation determined by hand-operated penetrometer tests, has been performed to study the mixing process for deep mixing of lime-cement columns. The influence of several factors was investigated using analysis of variances based on two- and 2^n-factor experiments. It was concluded;

a) that it is possible to study at the same time the influence of several factors affecting the mixing process;

b) that the upper pair of mixing blades, in connection with the binder outlet hole, has a significant and determining influence on the binder dispersion. The study showed that the binder is incorporated and spread in the cavity formed by the mixing blades during rotation;

c) that pneumatic fracturing, as a mixing mechanism, had a minor influence on the binder dispersion;

d) that neither the rotational speed nor the diameter of the binder outlet hole had a significant effect on the stabilisation effect and the coefficient of variation;

e) that the retrieval rate and the number of blades influenced significantly the mixing process. The study indicates that the stabilisation effect and the coefficient of variation is a function of the logarithm of the Blade rotation number;

f) that the strength and deformation properties of the soil have a major influence on the strength of the columns and the coefficient of variation. According to an empirical correlation, the coefficient of variation depends on the quotient between the water content and the liquid limit.

9. Uniformity of lime-cement columns; Field test in Strängnäs

9.1 INTRODUCTION

The work presented in this paper covers findings of a research project which is a part of the work of the Swedish Deep Stabilization Research Centre (SD) concerning development of the installation process for lime-cement columns by deep mixing. The process which is considered is dry deep mixing, where compressed air is used as the medium for the transport of dry binder from the tank to the soil. An essential factor in the success of this ground improvement technique is to ensure that the binder is uniformly dispersed throughout the stabilised soil. The initial stage of the work, presented and discussed by Larsson *et al.* (2002a, 2002b), include a summary of the literature on factors influencing the mixing process, a simple field method for the study of several influential factors in the mixing process of lime-cement columns. The test method facilitates the development of mixing processes in the field, and the method was employed in a field study at Håby, Sweden. The influence of several parameters in the installation process were investigated by statistical multifactor analyses. The study included the influence of the number of blades on the mixing tool, the retrieval rate, the rotation speed, the diameter of the binder outlet and the binder air tank pressure. The aim was not to promote any specific combination of installation parameters, but to illustrate the influence of various factors. It was concluded that the upper pair of mixing blades, in connection with the binder outlet hole, has a significant and determining influence on the binder dispersion and that the retrieval rate and the number of blades influence the mixing process significantly. However, since the strength of the unstabilised soft soil varied within the test site, which has a considerable influence on the mean value and the coefficient of variation of the strength in the columns evaluated from hand-operated penetrometer tests, the findings were somewhat uncertain. It was therefore not possible to detect any influences of combinations of factors.

This paper presents results from a complementary field test carried out at Strängnäs, Sweden. The purpose is to verify the findings from the previous tests and to further investigate the mixing process in a different soil. With a few exceptions, the experimental design procedure was similar with the test at Håby. Hand-operated penetrometer tests on excavated column sections were used for testing the strength characteristics, one week after the column installation. The effects of the number of blades on the mixing tool, the retrieval rate, the rotational speed, the diameter of the outlet hole situated on the mixing tool, and the binder tank pressure were evaluated using a statistical design approach and analysis of variances.

9.2 THE TEST SITE

The selected site is located at Strängnäs on Road E20, 80 km west of Stockholm. A specific area of the site was allocated to the tests, where the soil consisted of a 6 to 8m soft clay. The soil profile and properties are shown in Fig. 9.1. The soil can be divided into four representative layers, namely the dry crust with grey-brown clay, gyttja bearing clay, varved grey clay, and silty clay. The size of the test site was 25 x 50 m^2. The soil properties at the test levels, 1.9 and 2.3 m of depth, were evaluated from fall-cone tests on undisturbed samples, and by a hand-operated penetrometer. Table 9.1 shows the results from the laboratory tests on undisturbed soil samples and Fig. 9.2 shows a plan over the test site and the location of the samples. Five penetrometer tests were performed in the unstabilised soft soil close to every second column on the two test levels.

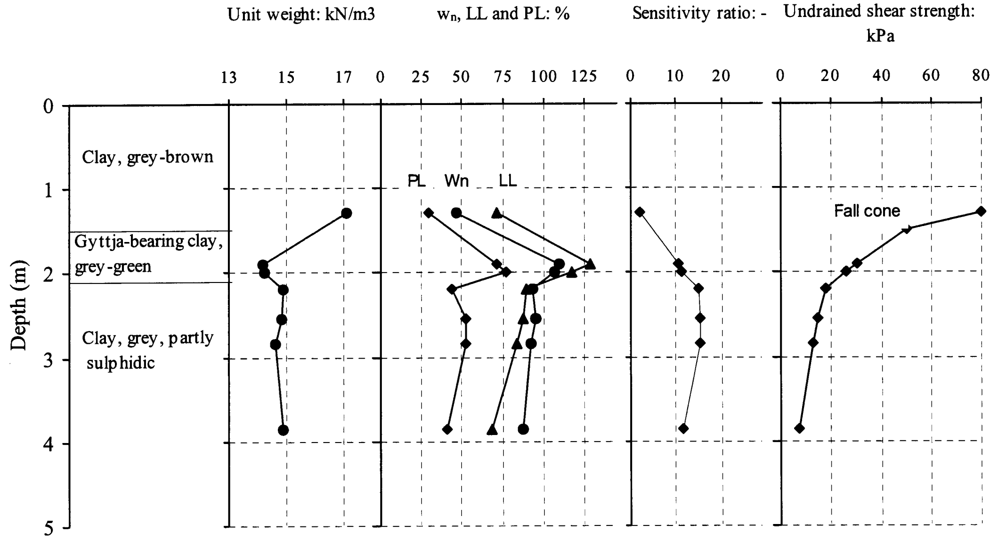


Fig. 9.1 **Soil profile and soil properties at the test site. The samples are taken at the columns marked EX 1 to EX 6, according to Fig. 9.2.**

Table 9.1 Soil properties at the test site (1.9-2.2m depth).

No	Soil	γ_t: kN/m^3	w: %	w_l: %	w_p: %	S_t	c_u: kPa	Com.
1..9	Clay, grey	15.5	85.3	82.6	34.1	13	16	roth threads
1.24	Clay, grey, partly sulphidic	15.1	81.5	76.4	31.7	12	13	
1.29	Gyttja bearing clay, grey	15.4	84.9	84.9	33.5	12	19	sand particles
1.44	Clay, grey, partly sulphidic	15.9	74.1	72.4	32.8	12	16	
2.23	Clay, grey, partly sulphidic	14.9	111.4	105.6	48.6	12	14	roth threads
2.30	Gyttja bearing clay, grey	14.9	99.3	94.3	44.1	15	17	
2.10	Gyttja bearing clay, grey-brown	14.4	99.0	102.5	39.9	13	24	
3.8	Gyttja bearing clay, grey-brown	14.5	122.7	118.4	61.9	12	16	
3.22	Gyttja bearing clay, grey-brown	14.2	112.4	117.2	70.0	11	20	
4.7	Gyttja bearing clay, grey-brown	14.2	110.5	121.7	76.9	11	26	
4.15	Gyttja bearing clay, grey-brown	14.3	119.3	128.6	82.3	10	20	
4.24	Gyttja bearing clay, grey-brown	14.2	135.7	144.4	76.8	11	21	

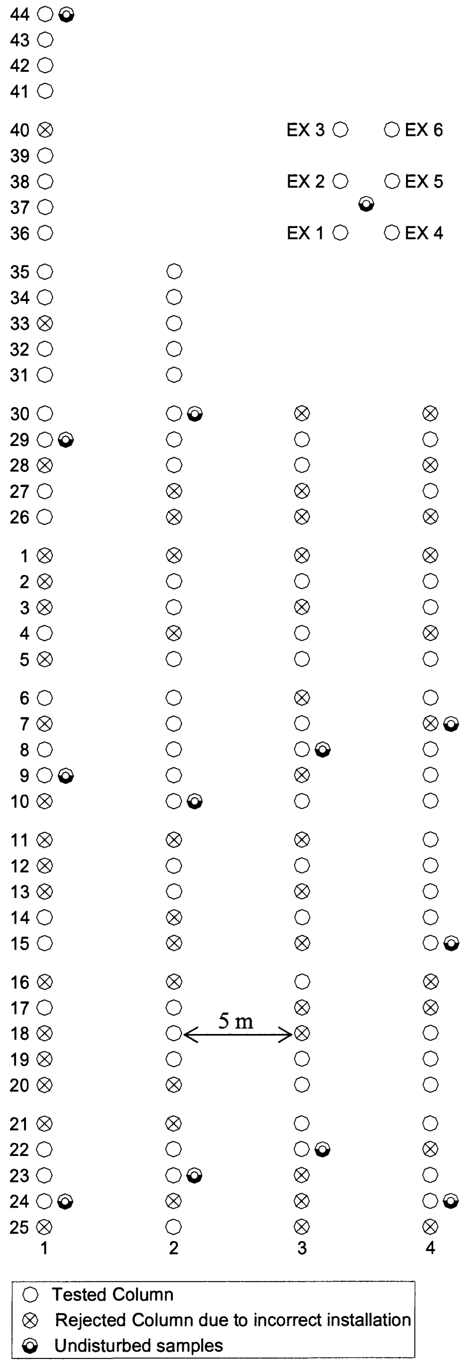


Fig. 9.2 **Test site and the test columns.**

9.3 EXPERIMENTAL PROGRAMME

Testing procedure

Details of the testing methodology were previously presented and discussed in Larsson *et al.* (2002a, 2002b). The methodology is briefly described below.

The test columns were excavated down to 1.9 and 2.3 m deep open test pits, as shown in Fig. 9.3a. Each column section was tested directly after the excavation. The tests were performed by a large number of hand-operated penetrometer tests, 6 to 7 days after installation of the columns. The hand-operated penetrometer was provided with a spring-loaded cylinder, 12 mm in diameter, and was pushed approximately 30 mm into the soil. The cylindrical-shaped head has a sliding ring, which moves over a calibrated scale as load is applied.

The penetrometer tests were carried out at two adjacent levels (1.9m and 2.3m respectively), in order to compensate for local variations in the axial direction. The test results have been evaluated with respect to the strength and the coefficient of variation, which have been taken as a measure of the mixing quality. The penetrometer tests were reported in terms of the spring deformation directly rather than via an assumed correlation with undrained shear strength since the failure mechanisms in stabilised soil are unlikely to be the same as those in the unstabilised surrounding soft soil. The results have been expressed in terms of the stabilisation effect S_{eff} , in this study defined by

$$S_{eff} = \frac{\overline{\delta}_{col}}{\overline{\delta}_{soil}} \tag{9.1}$$

where $\overline{\delta}_{col}$ and $\overline{\delta}_{soil}$ are the average spring deformation in the column and in the surrounding soil respectively. S_{eff} is thus an average value for the column cross-section. $\overline{\delta}_{col}$ and $\overline{\delta}_{soil}$ are evaluated from 20 and 5 penetrometer tests respectively, on the two test levels. All data has been presented for comparatively purposes and should therefore only be used as an index for strength properties.

The coefficient of variation $V_{\delta\, col}$, as a measure of the mixing quality, is calculated as

$$V_{\delta\, col} = \frac{s_{\delta\, col}}{\overline{\delta}_{col}} \tag{9.2}$$

where $s_{\delta\, col}$ is the standard deviation calculated as

$$s_{\delta\, col} = \sqrt{\frac{\sum_{i=1}^{n} (\delta_{i,col} - \overline{\delta}_{col})^2}{n-1}} \tag{9.3}$$

(a) (b)

Fig. 9.3 **(a) Excavation of test pit; and (b) the column machine used in Strängnäs.**

where $\delta_{i,col}$ is the spring deformation from each test and n is the number of tests over a column cross-section.

In order to make random testing possible, four templates of plywood were used, the templates, 0.6 m in diameter, were divided into 104 equal sized areas, where of 20 were randomly selected for testing. Before testing a column section, one of the four templates was chosen out of random. A total of 40 tests were performed for each column.

The penetrometer tests were complemented by visual examination for each cross section. The visual examination contained photographs and recorded subjective judgments.

Statistical design approach

Multifactor experiments were used in order to try to distinguishing influencing factors in the mixing process. The use of multifactor experiments is a popular and useful tool in the study of the effect of different factors in complex chemical- and physical processes, and increasingly used in geotechnical engineering. Multifactor experiments provide an applicable tool for the understanding of complex processes since all input factors can be investigated simultaneously. If the experiment comprehends a number of factors, the tests are often performed with each factor at only two levels, *2^n factorial experiments*. The main reasons for using 2^n factorial experiments are to reduce the number of tests. However, since each factor is measured at only at two levels, it is impossible to determine if the influence caused by variations in a factor vary linearly, or e.g. exponentially. For that reason, 2^n factorial experiments are mostly used for screening test, in order to recognise the most affecting factors. The tests should then be followed by experiments where only a few factors are varied at several levels.

Table 9.2 Experimental design for statistical test 1. (2^n- factorial experiment)

Factor	Low level	High level
Number of blades	2	6
Retrieval rate (mm/rev)	15	30
Rotational speed (rpm)	80	160
Outlet hole (mm)	22	37
Tank pressure (kPa)	350	550

Table 9.3 Experimental design for statistical test 2. (two factorial experiment)

Factor				
Number of blades	2	6	8	12
Retrieval rate (mm/rev)	15	30		

Com; rot. speed=160 rpm; outlet hole= 37mm; tank pressure= 550 kPa.

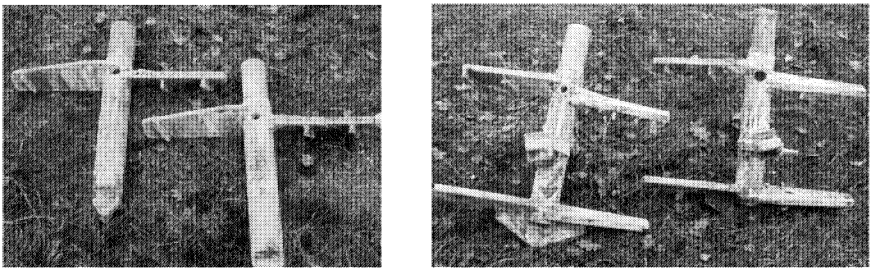

(a) (b)

Fig. 9.4 The mixing tools used in Test 1: (a) mixing tools with two blades and (b) mixing tools with 6 blades.

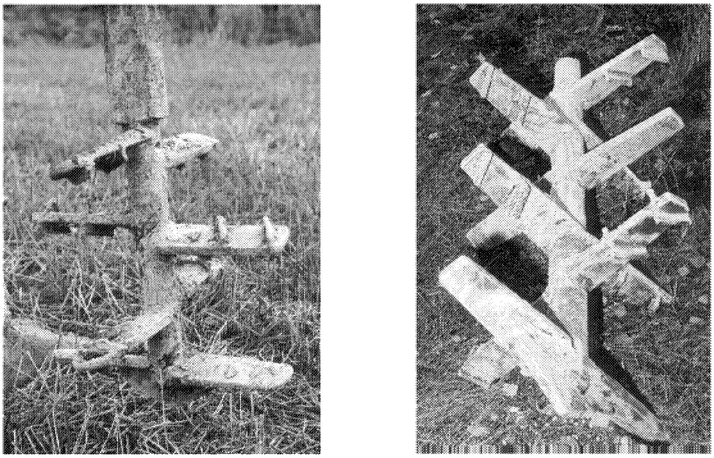

(a) (b)

Fig. 9.5 (a) The Pinnborr provided by; (a) 8 blades; and (b) 12 blades.

The statistical analysis used is an analysis of variances, ANOVA, that segregates different sources of variation in the results. The procedure described by Johnson (1994) has been used for the analysis of variances based on two- and 2^n-factorial experiments and tests for the significance of the factorial effects, using the 5% level of significance. The statistics in ANOVA is the F-test of difference of group means, testing if the means of the groups formed by values of the independent factor, or combinations of values for multiple independent factors, are different enough not to have occurred by chance. A null hypothesis condition was used to accept or reject the differences between the group means. If the group means do not differ significantly then it is inferred that the independent considered factor did not have an effect on the dependent parameter. If the F-test shows that overall the independent considered factor is related to the dependent parameter, then the multiple comparison tests of significance are used to explore just which value groups of the independent considered factor have the most to do with the relationship.

Five factors according to Table 9.2, connected to the installation process, were investigated in Test 1. This test included 2560 penetrometer tests in 64 columns. Other factors were kept constant as far as possible. The quantity of binder was 88 kg/m^3 which corresponds to 25 kg/m, for the 0.6 m column, with the proportion 50% quicklime (CL90-O) and 50% cement (white cement, CEM II/A-LL). The tolerance for the binder content was set to ±10%, this is the common practice in Sweden. The length of the columns are about 5 m. White cement was used to facilitate the visual examination. Table 9.4 shows the installation data for each column and Fig. 9.2 shows the location at the test site. The column machine used for the column installation can be seen in Fig. 9.3b.

In order to study the influence of the number of blades in a wider interval, 16 columns were installed, with mixing tools provided by 2, 6, 8, and 12 blades respectively. A number of these mixing tools are shown in Figs. 9.4-9.5. The statistical test, Test 2, was performed as a two-factor experiment according to Table 9.3. All columns included in Test 2 were installed with a rotation speed of 160 rpm, an air pressure in the binder storage tank of 550 kPa, and an outlet hole diameter of 37 mm. Table 9.5 shows the installation data for the columns.

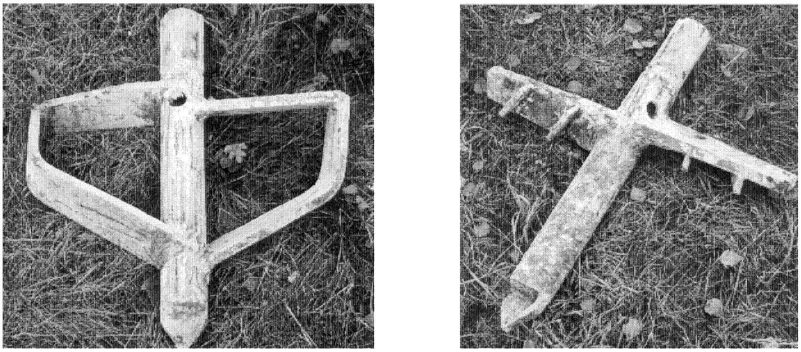

(a) (b)

Fig. 9.6 **(a) The Swedish Standard mixing tool; and (b) the Pinnborr with 2 blades and the binder outlet hole placed behind the blade.**

Additional comparisons

A number of additional limited comparisons were performed in addition to the factors investigated in Test 1 and 2. No statistical tests were performed due to the limitation and fractional characteristics of the tests.

1. A simple comparison by the Swedish "Standard tool" (SGF, 2000) was performed (Fig 9.6a). Only the retrieval rate was varied and the comparison included therefore four columns.

2. As a simple comparison, a mixing tool was tested with the outlet hole placed just behind the blade, as shown in Fig. 9.6b. Only the binder air tank pressure was varied, 350 and 500 kPa respectively. The purpose for testing this mixing tool was to study the influence of the location of the outlet hole in relation to the mixing blades. It was assumed that the placing of the outlet hole, just behind one of the blades, would influence the spreading of the binder. However, it is uncertain whether the result is that the binder is more evenly spread or if the binder ends up around the column periphery.

3. Four columns were installed by a mixing tool without blades in order to investigate the binder distribution caused by the air pressure. Only the binder air tank pressure was varied, 350 and 500 kPa respectively. The purpose of this limited comparison was to verify the findings at Håby where a large number of columns were installed without any mixing tool, and where it was observed that pneumatic fracturing, as a mixing mechanism, had a minor influence on the binder dispersion

Table 9.6 shows the installation data for the columns.

9.4 RESULTS

General

The results from the hand-operated penetrometer tests are presented in Tables 9.4-9.6. The results presented are the mean values evaluated from the performed tests at the two test levels, 1.9m and 2.3m respectively. The results of the two statistical tests are presented in Tables 9.7-9.8. No statistical tests were performed for the additional comparisons since the number of columns tested was inadequate. The results from these penetrometer tests are therefore presented and commented under the discussion section.

Table 9.4 Installation data and results from the penetrometer tests in columns included in Test 1.

Column repetition		Blades: n	Retr rate: mm/rev	Rot speed: rev/min	Outl hole: mm	Tank pressure: kPa	Rep.1		Rep.2	
1	**2**						S_{eff}	$V_{\delta col}$	S_{eff}	$V_{\delta col}$
1:4	1:6	2	15	80	37	350	10.0	0.27	13.5	0.31
1:8	1:9	6	15	80	37	350	14.1	0.09	15.0	0.15
1:14	1:15	2	15	160	22	350	9.8	0.27	9.6	0.35
1:17	2:5	6	15	80	22	350	13.8	0.11	15.7	0.11
1:22	1:23	2	15	80	37	550	12.4	0.30	12.3	0.30
1:24	2:10	6	15	80	37	550	13.9	0.25	17.1	0.14
1:26	1:27	6	30	160	37	550	12.1	0.33	12.5	0.17
1:29	1:30	2	30	160	22	550	6.7	0.55	6.8	0.59
1:31	1:32	6	30	160	22	550	13.7	0.17	10.8	0.40
1:36	1:37	2	30	160	37	350	4.3	0.51	6.5	0.40
1:38	1:39	6	30	160	37	350	11.8	0.18	15.5	0.23
1:41	1:42	2	30	160	22	350	6.5	0.52	4.9	0.51
1:43	1:44	6	30	160	22	350	12.1	0.28	10.3	0.32
2:2	2:3	2	15	80	22	350	13.5	0.32	9.4	0.40
2:6	2:7	6	15	80	22	550	9.2	0.35	16.3	0.13
2:8	2:9	2	15	80	22	550	7.6	0.31	7.0	0.49
2:12	2:13	6	15	160	37	350	13.6	0.12	13.4	0.31
2:17	2:18	2	15	160	37	350	9.7	0.33	9.4	0.47
2:22	2:23	6	15	160	22	350	17.4	0.27	16.6	0.15
2:25	3:2	6	15	160	22	550	19.4	0.16	11.1	0.24
3:14	3:16	2	15	160	22	550	14.2	0.37	11.1	0.32
3:19	3:20	2	15	160	37	550	9.4	0.39	6.2	0.43
3:21	3:22	6	15	160	37	550	20.1	0.13	14.3	0.22
4:2	4:3	6	30	80	37	350	14.9	0.24	12.3	0.22
4:5	4:6	2	30	80	37	350	4.5	0.51	7.5	0.42
4:8	4:9	2	30	80	22	350	6.1	0.47	7.2	0.45
4:10	4:11	6	30	80	22	350	13.3	0.17	13.5	0.25
4:12	4:13	6	30	80	22	550	12.9	0.22	14.1	0.18
4:14	4:15	2	30	80	22	550	6.9	0.48	6.6	0.54
4:18	4:19	6	30	80	37	550	14.1	0.24	13.9	0.22
4:20	4:21	2	30	80	37	550	8.2	0.39	7.4	0.57
4:23	4:24	2	30	160	37	550	7.8	0.54	6.2	0.42

The results from the two ANOVA tests, analysis of variances, are presented in Table 9.7-9.8. The analyses show an estimate of the main effect of the factors (independent variables) and the interaction effects. Results presented by bold figures are significant for the 5% level. A main effect is the direct effect of a factor (independent variable) on the measured parameter (dependent variable). An interaction effect is the joint effect of two or more factors on the measured parameter. It is important to emphasize the fact that the proposed test methodology does not show whether or not, the studied factors have a definite influence on the mixing process. The test methodology show if the factors and their combinations have a significant influence with reference to the present test method.

Test 1

Test 1, included 64 columns installed by mixing tools provided by two and six blades, respectively. Table 9.7 shows the results from the statistical analyses with respect to the spring deformation $\bar{\delta}_{col}$, the stabilisation effect S_{eff} and the coefficient of variation $V_{\delta\, col}$, based on the 2560 penetrometer tests in the 64 columns.

Table 9.5 Installation data and results from the penetrometer tests in columns included in Test 2.

Column repetition 1	2	Tool	Blades: n	Retr rate: mm/rev	Blade rot. number: n/m	Rep.1 S_{eff}	$V_{\delta col}$	Rep.2 S_{eff}	$V_{\delta col}$
1:26	1:27	Pinnb	6	30	200	12.1	0.33	12.5	0.17
1:34	1:35	Pinnb	8	30	267	14.3	0.24	14.7	0.25
2:28	2:29	Pinnb	12	30	400	14.0	0.14	15.3	0.16
3:4	3:5	Pinnb	8	15	533	15.9	0.18	18.1	0.10
3:7	3:8	Pinnb	12	15	800	21.9	0.09	18.7	0.11
3:19	3:20	Pinnb	2	15	133	9.4	0.39	6.2	0.43
3:21	3:22	Pinnb	6	15	400	20.1	0.13	14.3	0.22
4:23	4:24	Pinnb	2	30	67	7.8	0.54	6.2	0.42

Table 9.6 Installation data and results from the penetrometer tests in columns installed by the Swedish standard tool, the special 2-blade Pinnborr, and the mixing tool without blades.

Column repetition 1	2	Tool	Blades: n	Retr rate: mm/rev	Rot speed: rev/min	Outl hole: mm	Tank pressure: kPa	Rep.1 S_{eff}	$V_{\delta col}$	Rep.2 S_{eff}	$V_{\delta col}$
2:30	2:31	Std	4	30	160	37	550	8.6	0.44	10.9	0.38
3:10	3:12	Std	4	15	160	37	550	18.5	0.19	13.5	0.36
3:28	3:29	Spec	2	30	160	37	550	4.1	0.49	7.0	0.43
4:27	4:29	Spec	2	30	160	37	350	8.7	0.48	6.8	0.51
2:32	2:33	-	0	15	160	37	350	-	-	-	-
2:34	2:35	-	0	15	160	37	550	-	-	-	-

Table 9.7 Analysis of variance, 2^5 factorial experiment, Test 1.

Source of variation	$\bar{\delta}_{col}$ F	S_{eff} F	$V_{\delta col}$ F
Replication	< 1	< 1	< 1
Main effects:			
A. Number of blades	**121**	**116**	**123**
B. Retrieval rate	**8.3**	**32**	**27**
C. Rotational speed	**8.9**	< 1	2.9
D. Outlet hole	< 1	< 1	1.2
E. Tank pressure	< 1	< 1	1.8
Two-factor interactions:			
AB	**6.1**	2.7	**4.8**
AC	1.6	< 1	< 1
AD	1.1	< 1	< 1
AE	0.5	< 1	< 1
BC	**8.6**	1.4	< 1
BD	< 1	< 1	< 1
BE	< 1	< 1	< 1
CD	< 1	2.4	< 1
CE	< 1	< 1	< 1
DE	1.4	1.0	< 1
Three-factor interaction			
ABC	2.5	1.8	< 1
ABD	< 1	< 1	< 1
ABE	< 1	< 1	< 1
ACD	2.6	1.1	1.4
ACE	2.4	< 1	< 1
ADE	< 1	< 1	< 1
BCD	< 1	3.6	**4.7**
BCE	1.4	< 1	1.0
BDE	< 1	1.0	< 1
CDE	0.7	1.7	< 1
Four-factor interaction			
ABCD	1.1	< 1	< 1
ABCE	< 1	< 1	< 1
ABDE	< 1	2.3	< 1
ACDE	< 1	1.6	< 1
BCDE	1.8	< 1	< 1
Five-factor interaction			
ABCDE	< 1	2.6	< 1

Comment: $F_{0.05}=4.17$ and $F_{0.01}=7.56$ for 1 and 31 degrees of freedom.

The analysis with respect to spring deformation $\bar{\delta}_{col}$, shows that the number of blades on the mixing tool, the retrieval rate and the rotation speed have a significant influence. There are additional number of combinations of factors with significant influence. However, the significant influence of the rotational speed is most likely a consequence of the number of columns installed by 80 rpm where the shear strength of the unstabilised soil was about 26 kPa. As shown in Table 9.1, the undrained shear strength in the unstabilised soft soil varied from 13 to 26 kPa over the test site (1.9 m to 2.3 m depth). The analysis with respect to the stabilisation effect S_{eff}, showed that only the number of blades on the mixing tool, and the retrieval rate had a significant influence. Similar results are shown by the analysis with respect to the coefficient of variation $V_{\delta\,col}$. As expected, the effect of the number of blades is stronger than the effect of the retrieval rate. The analysis with respect to the coefficient of variation $V_{\delta\,col}$ also showed that the combination of number of blades and the retrieval rate has a significant influence. These results were expected since the number of blades was varied by a factor of 3 and the retrieval rate was varied by a factor of 2. However, the analysis with respect to the stabilisation effect S_{eff}, did not show a significant effect of the combination of these two factors. The diameter of the outlet hole and the binder tank pressure showed no significant influences on the stabilisation effect S_{eff}, or the coefficient of variation $V_{\delta\,col}$. However, the analysis only show that the rotational speed, the diameter of the outlet hole and the binder tank pressure do not have significant effect in the relatively narrow varied intervals.

Test 2

In order to study the influence of the number of blades in a wider interval, the columns in Test 2 were installed with mixing tools provided by 2, 6, 8, and 12 blades. Table 9.8 shows the result from the two factorial experiment, including 16 test columns. Also this test shows that the number of blades and the retrieval rate have a significant influence on the stabilisation effect S_{eff} and the coefficient of variation $V_{\delta\,col}$.

Table 9.8 Analysis of variance, two factorial experiment, Test 2

Source of variation	*Degrees of freedom*		$\bar{\delta}_{col}$	S_{eff}	$V_{\delta col}$
		$F_{0.05}$	F	F	F
Replication	1	5.59	1.5	1.5	< 1
Main effects:					
A. Number of blades	3	4.35	**18**	**21**	**21**
B. Retrieval rate	1	5.59	**13**	**13**	**5.8**
Two-factor interactions:					
AB	3	4.35	1.5	1.3	< 1

9.5 DISCUSSION

General

The results from the field test in context of the findings from the field test at Håby presented by Larsson *et al.* (2002a, 2002b), are discussed in the following sections. It should be noted that the discussion only refers to the conditions existing during the tests. The findings are only valid for the parameters, intervals and combinations tested.

Test 1 and 2

From the two statistical tests, based on a hypothesis test by analysis of variances and the traditional significance level of 5 %, it can be concluded that the retrieval rate and the number of blades have a significant influence on the stabilisation effect S_{eff} and the coefficient of variation $V_{\delta_{col}}$. The two parameters, retrieval rate and number of blades, can most likely be combined by the coupled factor "Blade rotation number", provided that the blades have similar geometry. The Blade rotation number T , is expressed as (modified after Nakamura et al., 1982)

$$T = \sum M \times \frac{1}{s} \qquad (9.4)$$

where ΣM is and the number of blades on the mixing tool and s is the retrieval rate. The Blade rotation number is the total number of mixing blades passing during 1 m of shaft movement.

Figs. 9.7-9.9 show the results from 3200 penetrometer tests in 80 columns. Each point represents 40 penetrometer tests. Fig. 9.7 shows the spring deformation as a function of the Blade rotation number. The scatter in the results is considerable, which can partly be due to the varying soil properties but also to the fact that the test procedure has a number of sources of errors, as discussed by Larsson *et al.* (2002a, 2002b). Furthermore, the binder content throughout the columns is not uniform. Fig. 9.8 shows the same

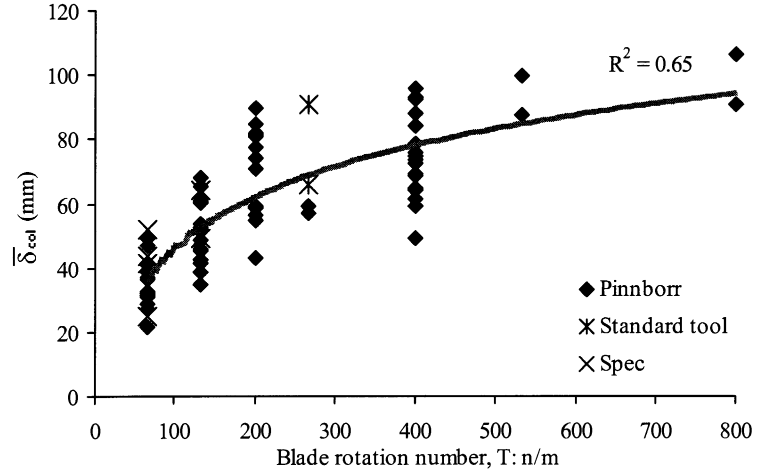


Fig. 9.7 The spring deformation $\overline{\delta}$ as a function of the Blade rotation number T .

results, but the stabilisation effect according to equation 9.1, as a function of the Blade rotation number. The correlation is good over the present interval and the relation is approximately logarithmic. Fig. 9.9 shows the coefficient of variation $V_{\delta\,col}$ as a function of the Blade rotation number T. The scatter is high but the correlation is good over the tested interval and the relation is approximately logarithmic. An approximately logarithmic or a power law relation between the column strength and the mixing work has previously been reported by e.g. Muro *et al.* (1987a, 1987b), Larsson *et al.* (1999) and Nishida *et al.* (1996). However, it is not possible to predict the strength magnitude based only upon the mixing work since the strength in stabilised soil highly depends on the composition and the conditions during the curing period.

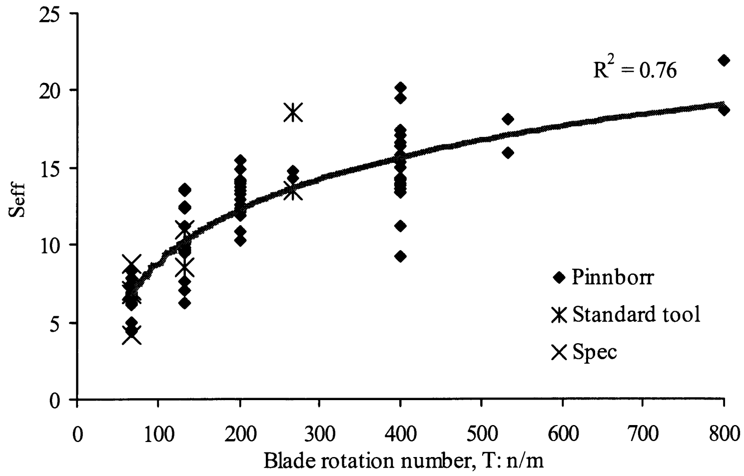


Fig. 9.8 **The stabilisation effect S_{eff}, as a function of the Blade rotation number T.**

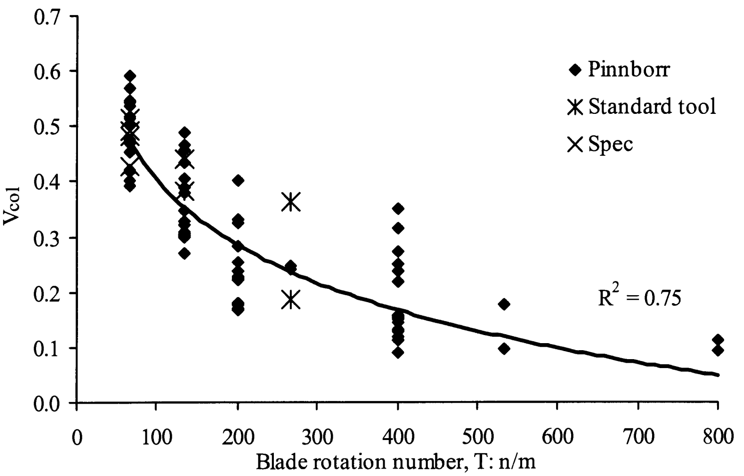


Fig. 9.9 **The coefficient of variation $V_{\delta\,col}$, as a function of the Blade rotation number T.**

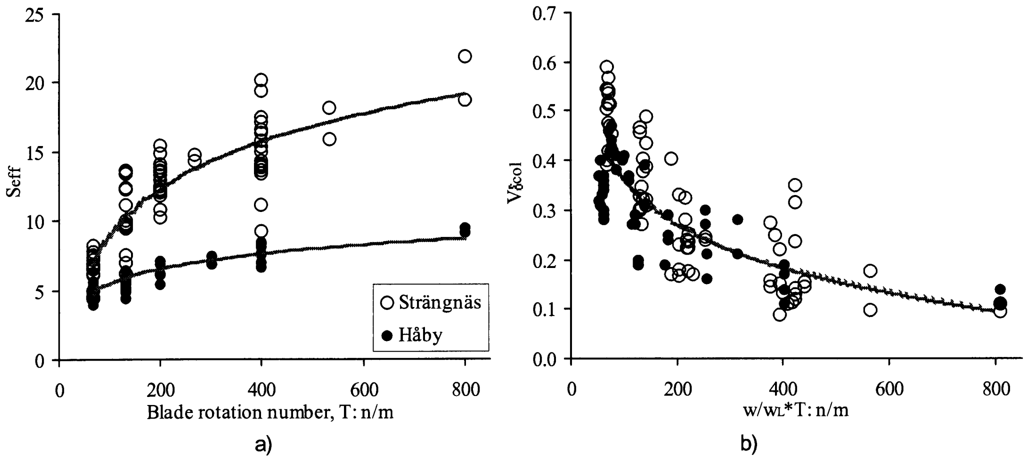


Fig. 9.10 a) The stabilisation effect S_{eff}, as a function of the Blade rotation number T ; and b) the coefficient of variation $V_{\delta\,col}$, as a function of the quotient between the water content and the liquid limit multiplied by the Blade rotation number $w/w_l \cdot T$.

Fig. 9.10 shows the results from the two field tests at Håby and Strängnäs. The magnitude of the stabilisation effect S_{eff} after one week differs from the two sites as can be seen in Fig. 9.10a. At Håby, an empirical relation was found where the coefficient of variation $V_{\delta\,col}$ depends on the quotient between the water content w and the liquid limit w_L. In the presented study, the quotient between the water content and the liquid limit had no significant influence on the statistical analysis since the quotient varied in a narrow interval ($0.9 < w/w_L < 1.1$). Fig. 9.10b shows the coefficient of variation $V_{\delta\,col}$ as a function of the quotient between the water content and the liquid limit multiplied by the Blade rotation number, $w/w_L \cdot T$. Similar results are obtained from the two test sites with the exception of the low interval $T < 200n/m$, where the coefficient of variation is somewhat higher at the test site in Strängnäs. According to the figure, for $w/w_L \cdot T \geq 400n/m$, the result has a relatively low coefficient of variation $V_{\delta\,col}$. The stabilisation effect depends much on the soil composition, while the coefficient of variation is similar at the two test sites.

Similar results of the strength variation, mostly presented by the coefficient of variation, have previously been reported by others. A sufficiently good column quality is normally achieved when the Blade rotation number exceeds 360 n/m, according to Mizuno et al. (1988). Based on model tests, Dong et al. (1996) recommend $T > 250n/m$, depending on the strength required. Hayashi & Nishikawa (1999) recommend $T = 400 - 500n/m$ for sufficiently good uniformity and enhance cost-effectiveness for stabilisation of peaty ground. However, a somewhat higher value on the coefficient of variation was reported.

Muro *et al.* (1987a, 1987b), and Nishida *et al.* (1996) have reported a power law relation and an approximately logarithmic relation respectively, between the mixing quality with respect to a mixing index and the mixing work. However, the mixing work, evaluated as mixing energy and mixing time, can not be transformed and compared with the Blade rotation number.

It is well known that the mixing work influence the mixing process. However, most studies, just like this presented study, present results of the influence of indirect measures of the mixing work, e.g. the Blade rotation number, the retrieval rate, mixing time or the lifting speed in combination with the rotational speed. The mixing energy per cubic meter of stabilised soil (in terms of J/m^3) can probably be a combining key factor. However, the mixing energy is not well investigated and it has not been clearly tested and shown whether the mixing energy is a combining factor. In Sweden, the mixing energy is normally not measured or recorded. It is a tradition to focus on the retrieval rate as an indirect measure of the mixing work. If the mixing energy is a combining factor, the test series can be reduced and the focus can be transferred to parallel comparisons of several different mixing tools, which is the main objective of the proposed test method. In that case, comparisons with fundamentally different geometries can be performed, such as screws, kneaders, vertical paddles etc.

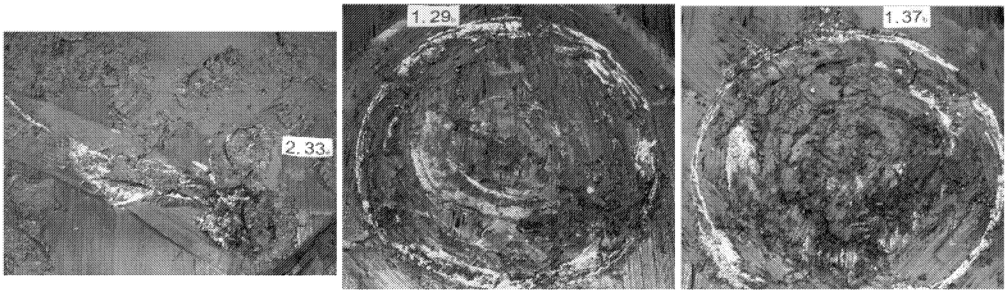
The results from the two extensive test series do not clarify whether the studied factors influence the mixing process, by means of strength distribution, since most of the studied factors were only varied in two relatively narrow levels. Furthermore, it is important to emphasize that all tests are performed at shallow depths where the confining pressure is low during column installation. However, the results shows that a number of factors do not considerably influence within the studied intervals and existing conditions. For practitioners, these results facilitate the discussions concerning the mixing process and causes for heterogeneities in manufactured columns since the number of influencing factors can be reduced. In order to increase the knowledge of the fundamental mechanisms occurring when binder and soft soil are mixed, the factors in the installation process must be further investigated in wider intervals and at greater depths.

Visual examination

A visual examination can not be used for quality assessment since the visual impression is not necessarily equivalent to the binder distribution (Larsson, 2001). Visual judgements are associated with human senses, and are therefore highly individual and subjective. For example, it is difficult for the human sight and feeling to detect strength variations for high strength materiel. However, since visual examination is simple it is tempting to judge the column quality based on individual visual assessments.

In this study, the visual examinations were used to support the statistical analyses. Even if there are uncertainties with visual judgements, the visual binder dispersion and the subjective impression of the strength appeared to correspond to the results obtained from the hand-operated penetrometer. Fig 9.11 shows a selection of photographs on column sections manufactured by different Blade rotation number. A trend can be seen where the visible clumps and layers of unmixed binders decrease when the Blade rotation number increases. Furthermore, the coefficient of variation decreases when the columns become more uniform and obtain a colour similar to the surrounding soft soil. The majority of the columns installed by $T \geq 400n/m$ are visually similar. It appears that there are no visual differences over the column section when the coefficient of variation is less than approximately 0.20. When the column strength becomes relatively uniform or high, the visual examination can not distinguish any differences.

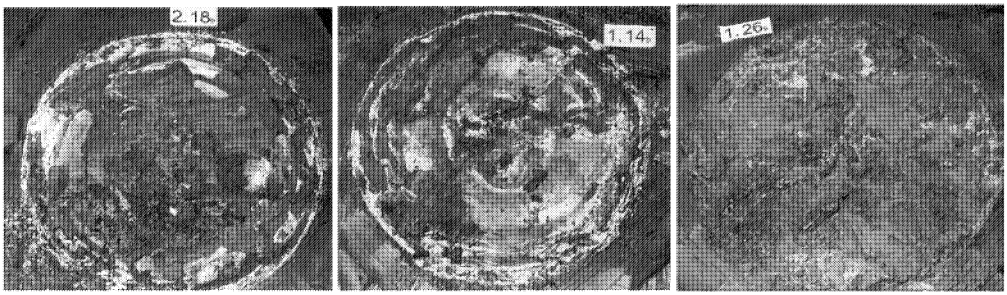
The visual examination also reflects the scatter in the results even when the columns are equivalently installed. In Fig. 9.11, four column sections installed by $T = 400n/m$ are shown. A distinct difference in visual appearance can be observed and the coefficient of variation differs correspondingly. As shown in Fig. 9.8 and 9.9, there are two results that deviate from the trend (column 2.6 and column 3.2). These two columns have a low stabilisation effect and high coefficient of variation. The visual examination also



Column 2.33 T= 0 n/m

Column 1.29; T=67 n/m
$S_{eff}=6.7$ $V_{\delta col}=0.55$

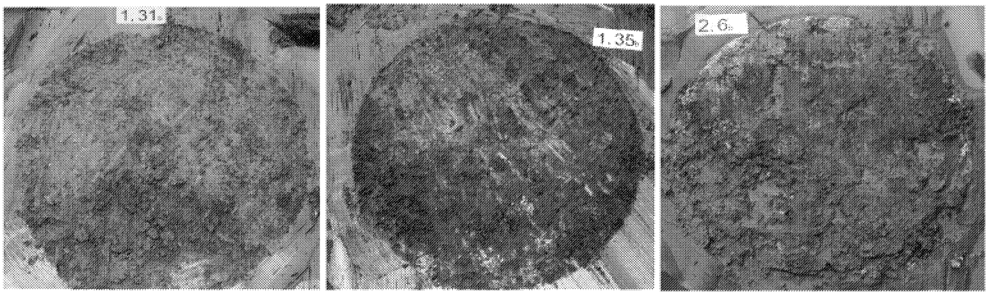
Column 1.37; T=67 n/m
$S_{eff}=6.5$ $V_{\delta col}=0.40$



Column 2.18; T=133 n/m
$S_{eff}=9.4$ $V_{\delta col}=0.47$

Column 1.14; T=133 n/m
$S_{eff}=9.8$ $V_{\delta col}=0.27$

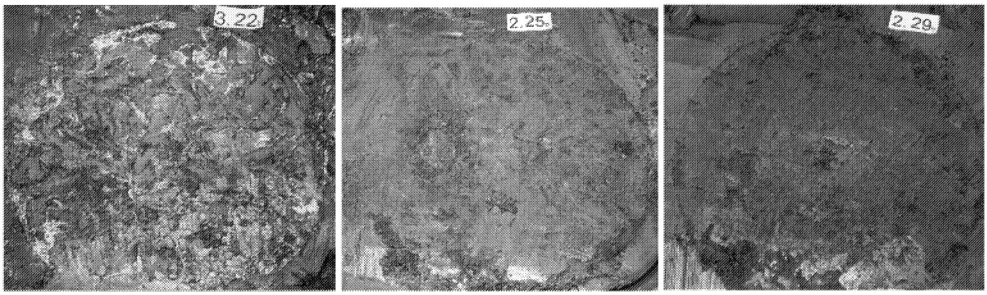
Column 1.26; T=200 n/m
$S_{eff}=12.1$ $V_{\delta col}=0.33$



Column 1.31; T=200 n/m
$S_{eff}=13.7$ $V_{\delta col}=0.17$

Column 1.35; T=267 n/m
$S_{eff}=14.7$ $V_{\delta col}=0.25$

Column 2.6; T=400 n/m
$S_{eff}=9.2$ $V_{\delta col}=0.35$



Column 3.22; T=400 n/m
$S_{eff}=14.3$ $V_{\delta col}=0.22$

Column 2.25; T=400 n/m
$S_{eff}=19.4$ $V_{\delta col}=0.16$

Column 2.29; T=400 n/m
$S_{eff}=15.3$ $V_{\delta col}=0.16$

Fig. 9.11 Twelve examples of column sections where the Blade rotation number differs.

showed that these two column sections differed from all other columns installed by $T = 400n/m$. As shown in Fig. 11, there were sharp traces of unmixed binders in clumps and layers, and the character was grainy, whereas the others had a more even grey colour tone, similar to the unstabilised surrounding soft soil. There is no clear reason for this deviation but it shows that single columns can differ considerably even if the installation is performed with great care.

Additional comparisons

Mixing tool without blades

The four columns installed without mixing blades had different shapes as shown in Fig. 9.11. The air jet has expanded or cut a circular cavity, 0.1-0.2 m in diameter, which was filled by the binder. Pneumatic fracturing was observed in all four column sections. The extent of this fracturing was limited to one vertical channel going out from the centre of the column. The channels were about 10 to 50 mm wide and up to 500 mm long. The vertical channels were somewhat wider than the once observed at the Håby-tests. The reason is probably due to the lower shear strength in the soft soil at Strängnäs. However, pneumatic fracturing can not be considered as a significant mixing mechanism even though the shear strength is low.

The placing of the outlet hole

Four columns were installed by a mixing tool provided with two blades and the binder outlet hole was placed close to one of the blades. The stabilisation effect and the coefficient of variation did not differ from the other columns, as can be seen in Figs. 9.8-9.9. According to the visual examination a thin binder ring could be observed in the column periphery. The thin ring was somewhat thinner than the binder-rings in the column periphery observed in other columns installed by $T = 67n/m$ (Fig. 11).

This limited comparison does not show whether or not the placing of the outlet hole has an effect on the binder dispersion over the column length. Further investigations are required, where larger-diameter columns and lengths, with higher *in-situ* stresses, need to be looked upon.

The Swedish Standard mixing tool

The Swedish Standard mixing tool was used for four of the columns. As shown in Figs. 9.8-9.9 there are no significant difference between the Swedish Standard mixing tool and the Pinnborr, provided that they are equipped with the same number of mixing blades. The results were as expected, but the comparison is based on a limited amount of tests. The visual examination did not show any significant difference.

Development of the test method

It should be investigated whether the test method can be used for columns with higher strengths-, and undrained shear strength approximately higher than 150 kPa. The reason for testing the columns short after installation is the uncertainty in the failure mechanism if the shear strength is high and the column material is brittle. If the test can be performed with a sufficiently high reliability, the columns can be tested when they reached their full strength. Given the strength magnitude and the variation, together with the critical failure mechanism and the scale of scrutiny, such tests can support probabilistic design. Statistical design approaches for deep mixing have been proposed by Honjo (1982) and Omine *et al.* (1998, 2001). However, probabilistic design has not yet been common practice for the design of deep mixing.

According to the Japanese design guide (CDIT 2002), the *in-situ* design strength can be derived from field test by incorporating the strength deviation. The average strength measured from *in-situ* stabilised soil is normally reduced with respect to the standard deviation. The resulting variance is, however, relatively large when it is determined by a penetrometer test with a small selected test volume. It should be investigated whether a variance reduction can be adopted with respect to present failure mechanisms and scale of scrutiny. The application of a proper variance reduction will have an affect on the design strength, as the variance has a large influence on the probability of failure. With knowledge of the present failure mechanism and a proper scale of scrutiny, the installation process can be designed to attain a sufficient mixing quality, with respect to the resulting property variance.

With an increased knowledge of the mixing quality as a function of the mixing work, the test method may be a useful tool for the cost-optimization of the mixing process. Reflections of cost-optimization analysis have previously been discussed by e.g. Nishida *et al.* (1996) and Hayashi & Nishikawa (1999).

In order to reduce the number of tests a fractional statistical experiment design can be adopted. Such a statistical design approach facilitates tests where a number of different mixing tools are compared, since the number of columns is reduced in the test.

9.6 CONCLUSIONS

The influence of the number of blades on a mixing tool, the retrieval rate, the rotational speed, the diameter of the outlet hole situated on the mixing tool, and the binder tank pressure on the strength over shallow excavated column sections was investigated. The stabilisation effect and the coefficient of variation with respect to the results from a hand-operated penetrometer were evaluated. The results should be interpreted in the context of the conditions at the two sites. Based upon the results presented in this paper, the following conclusions can be drawn;

a) The number of blades and the retrieval rate are shown to exhibit significant influence on the stabilisation effect and coefficient of variation. The two factors can be linked to the coupled factor “Blade rotation number”, which is the total number of mixing blades passing during one meter of shaft movement. The study indicates that the stabilisation effect and the coefficient of variation is a function of the logarithm of the Blade rotation number.

b) Neither the rotational speed, the binder tank pressure nor the diameter of the binder outlet hole have any significant influence on the stabilisation effect or the coefficient of variation.

c) The visual examination appeared to be a complementary tool to the hand-operated penetrometer. The visible clumps and layers of unmixed binders reflected the coefficient of variation as a measure of the mixing quality.

d) The tests show that the column quality can differ even though they are installed in the same way. The strength is highly stochastic with large variations even if the installation is performed with great care. Single or few tests can therefore result in misleading conclusions.

The proposed method can also be used with other sets of binders and soils, in order to study influence factors such as mixing work and mixing tool geometry.

10. On the concept of sufficient mixture quality

10.1 INTRODUCTION

This chapter discusses the concept of sufficient mixture quality, or the effect of a variability of a property, with respect to an analysis of the mechanical system of columns. The thesis has so far dealt with the mixing process for ground improvement by deep mixing; mixing mechanisms; influencing factors; and the concept of mixture quality. However, an important issue remains. "What is sufficient mixture quality with respect to a given application?" This question can only be answered if we know the nature of the mechanical system and the safety requirements. The link between the mixing process and the mechanical system is visualized by Fig. 10.1, and forms a foundation for the discussion in this chapter.

The mixing process generates a mixture with certain properties. The stabilised soil has high property variability and the average and variability, e.g. the coefficient of variation, can be evaluated by test samples. However the measures of the average value and variability are related to the test method, the test- and sample size as well as the statistical sample size. The analysis of the problem includes an analysis of the mechanical system and the related scale of scrutiny, a concept that is thoroughly discussed in the next section. The variability of a property in the stabilised soil is related to the scale of scrutiny and the correlation structure, i.e. how the property varies from one point to another in space. The variance related to the mechanical system may thus differ from the variance obtained from samples and testing. The design values can subsequently be evaluated by taking the concept of failure probability and safety into consideration.

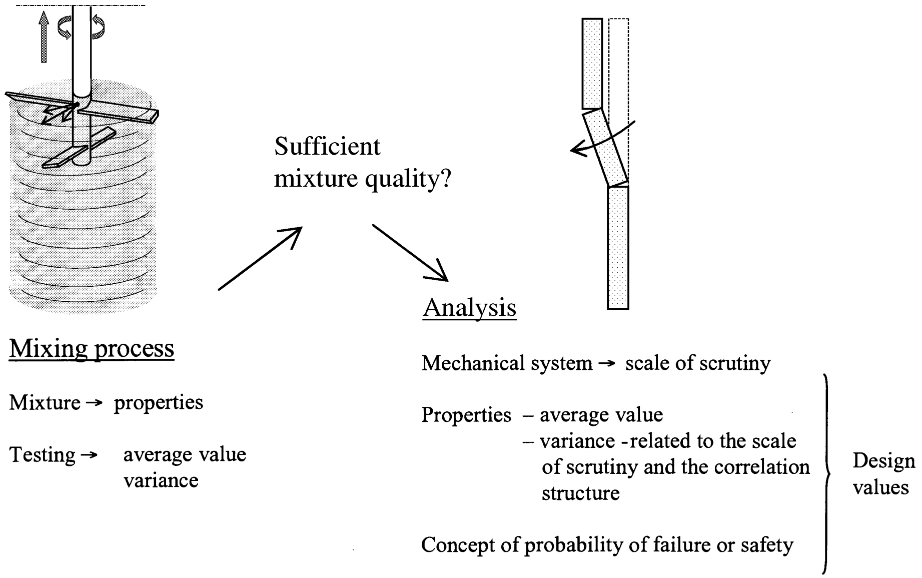


Fig. 10.1 **The link between the mixing process and the mechanical system.**

The concept of sufficient mixture quality is dealt with respect to the mechanical system, the scale of scrutiny, and the correlation structure. The chapter discusses the scale of scrutiny and whether the mixing process influences the mechanical system with respect to the strength variability over singular column cross-sections. The discussion is limited to the dry method used in the Scandinavian countries, which means lime-cement columns, with compressive strength approximately less than 300 kPa. The analysis includes the evaluations of spatial correlation structures and the scale of fluctuation for a large number of column cross-sections, based on the results obtained from the field tests in Håby and Strängnäs. A number of analyses of variances, ANOVA, have been performed in order to test whether some installation factors have an influence on the evaluated scale of fluctuation. The Chapter also briefly considers the choice of partial factors, production quality assessment, and the influence changes have in the mixing process on the mixture quality from an economical point of view. Proposals for further research are given gradually in the discussion section.

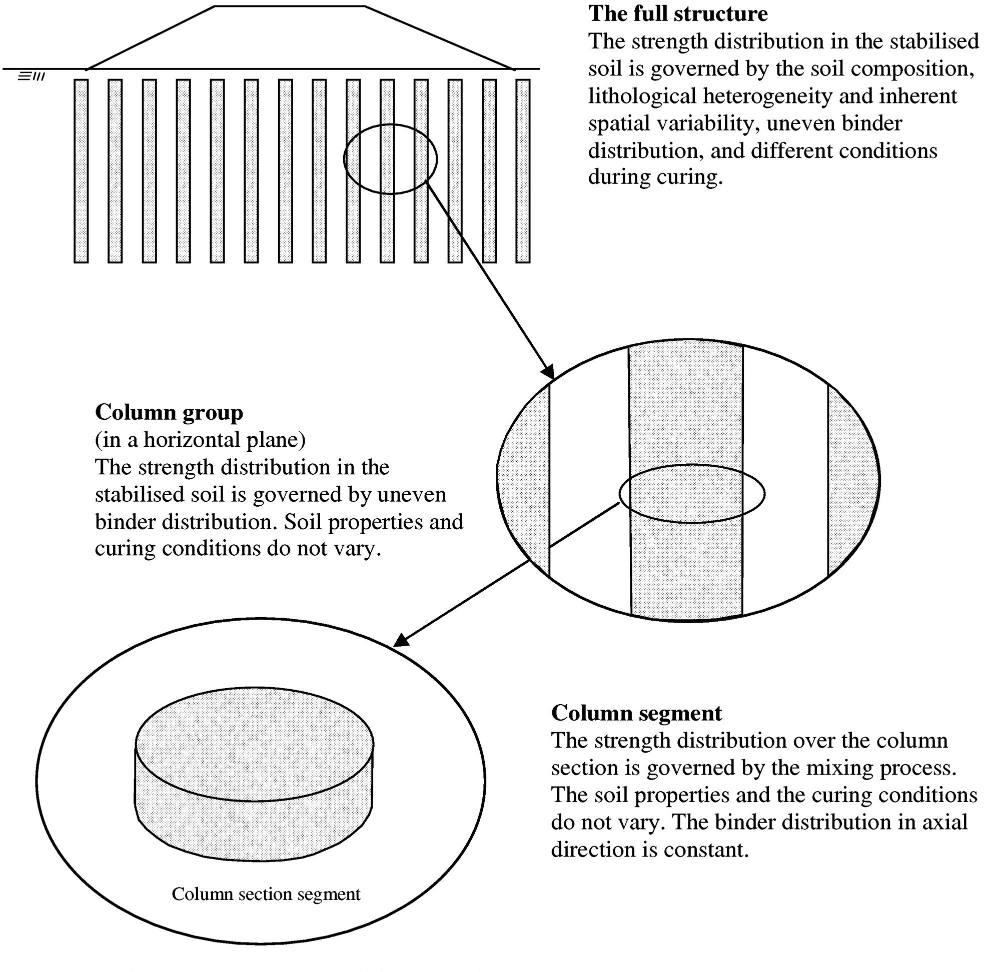
10.2 THE SCALE OF SCRUTINY

The concept of the scale of scrutiny was previously discussed in Chapter 4.3. According to Dankwerts (1953), the scale of scrutiny can be defined as "the minimum size of the regions of segregation in the mixture that would cause it to be regarded as imperfectly mixed for a specified purpose". Consequently, according to Dankwerts definition the scale of scrutiny is related to the mixture quality, e.g. the variability in a certain property. In this work it is chosen to relate the scale of scrutiny to the mechanical system. The scale of scrutiny is thereby determined from the particular application and the adherent mechanical system. A proper estimation of the scale of scrutiny determines a limitation on the maximum size or volume of the samples to be analysed.

There are a number of parameters influencing the strength properties in stabilised soil; the characteristics of the binder: the characteristics of the soil; the mixing process; and the curing conditions (e.g. Terashi 1997, Babasaki et al. 1997). Similarly, there are variability's associated to each of these parameters. Furthermore, the variability associated to each of the parameter is connected to a certain scale, i.e. the parameters may influence in different scales. The scale may differ considerable and what's seems to be a scatter in a certain scale may be a trend in a smaller scale. Consequently, it is important to determine the correlation structure for each parameter related to the scale of scrutiny. This thesis is limited to the study of the mixing process and consequently only correlation structures associated with the mixing process is concerned.

As for natural soils, it can be seen that stabilised soils also have variable properties and are not homogeneous. The stress- and strength properties are associated to a certain scale. In this thesis, stabilised soil heterogeneity is separated into three categories, according to Fig. 10.2. The first category, "the whole structure", the strength distribution in the stabilised soil is governed by the soil composition, lithological heterogeneity and inherent spatial variability, uneven binder distribution, and different conditions during curing. The second category, "column group", is manifested in the form of varying binder contents due to uneven binder distribution during the mixing process. This variable binder distribution is associated with the difficulty to achieve an even air pressure at the binder outlet hole situated on the mixing tool. Soil properties and curing conditions are assumed not to vary. The variable binder distribution results in variability's in the axial direction in the column but also variabilities between adjacent columns. The third category, "column segment", is ascribed to inherent spatial variability, which is the variation in properties from one point to another due to the performance of the mixing process. The soil properties and the curing conditions are assumed to be constant. The binder distribution in the axial direction is considered to be constant. The mixing process is considered to have an influence on the strength variability in a relative small scale, associated to the binder dispersion over the column cross-section.

In practice, it is difficult to separate the three types of categories. The "column group" category and the "column segment" category can only be entirely separated in practice if the binder distribution, through the outlet hole on the mixing tool, is kept completely constant. It may be difficult to separate the sources of variabilities from e.g. column penetrometer tests since the variability in one single column may be caused by all sources of variabilities, i.e. the single column may be observed with respect to the first category.



The full structure
The strength distribution in the stabilised soil is governed by the soil composition, lithological heterogeneity and inherent spatial variability, uneven binder distribution, and different conditions during curing.

Column group
(in a horizontal plane)
The strength distribution in the stabilised soil is governed by uneven binder distribution. Soil properties and curing conditions do not vary.

Column segment
The strength distribution over the column section is governed by the mixing process. The soil properties and the curing conditions do not vary. The binder distribution in axial direction is constant.

Fig. 10.2 Strength variability in different scales.

10.3 THE MECHANICAL SYSTEM

Stabilised soil is complex with respect to its spatial strength- and deformation properties. The stabilised soil as natural soil is in-homogenous; the properties are anisotropic and non-elastic. It can generally be said that the higher the strength of the stabilised soil, the more brittle the material becomes.

The mechanical system as a whole can be described as an interaction between the stabilised soil and the surrounding soft soil. The failure may be slow and related to plastic failure, but as the strength ratio between the stabilised soil and the surrounding soft soil increases, the failure may be brittle and progressive (Broms 1999b). The knowledge of the stabilised soil mechanical system is limited, owing to the fact that the strength- and deformation properties are dependent on a largely number of factors. The uncertainty is both due to insufficient understanding of the individual failure processes in the singular, groups or rows of columns and the extent of the interactions between failure processes and between the stabilised soil and the surrounding soil. The proceeding analysis is discussing the scale of scrutiny with respect to the bearing capacity of singular columns.

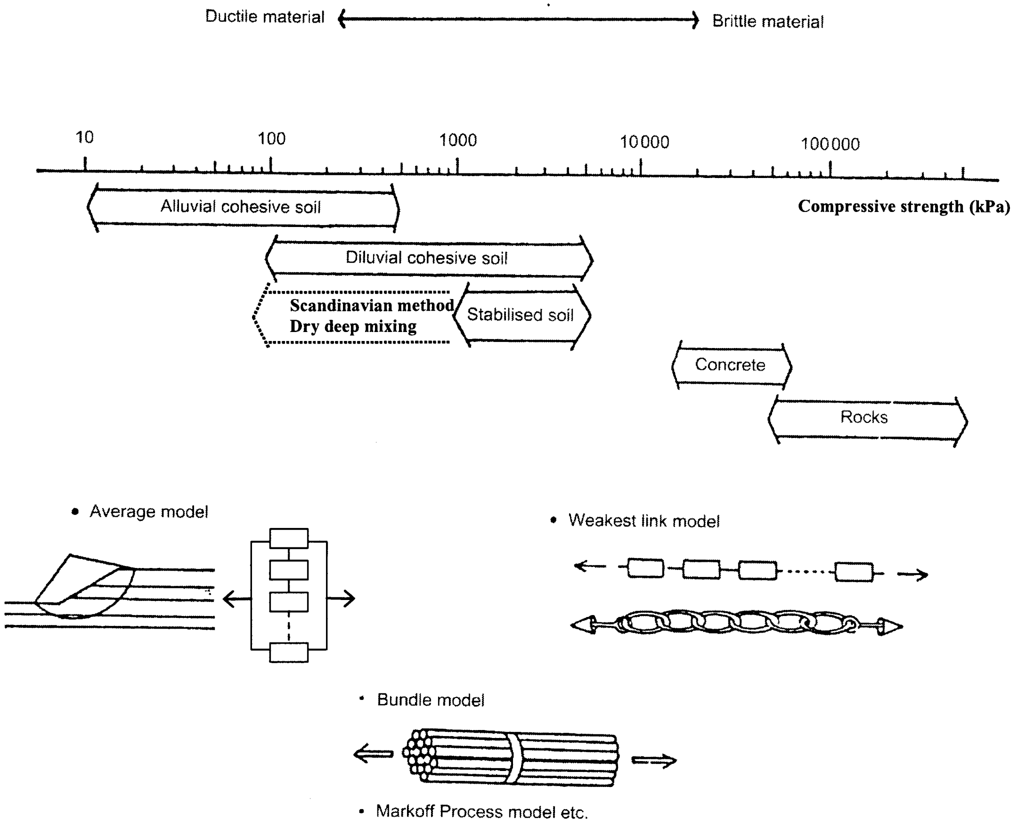


Fig. 10.3 Model selection considerations, modified after Honjo (1982).

According to Swedish practice, stability calculations are based on the assumption that the columns and surrounding soft soil behave as a composite material (SGF 2000). Failure is assumed to occur along a slip surface through the columns and the surrounding soil. An averaging failure model, a parallel system (see Fig. 10.3) is assumed in the full structure scale as well as the smaller column section scale. The averaging model can be assumed provided that the characteristic undrained shear strength of the stabilised soil is less than 150 kPa. The stress-strain relationship is assumed to be elastic-plastic, i.e. all parts of the column cross-section interact at failure. To increase the shear resistance of the columns in the direct shear zone, overlapping columns are installed in rows. However, the calculation methods used in Sweden do not take into account the various failure mechanisms that may occur.

The proceeding analysis is based on ultimate limit state design for singular columns proposed by Kivelö (1998). This investigation shows that there are a number of failure mechanisms that can occur, depending on the loading and the soil conditions. Possible failure modes for single columns, where the columns are subjected to a lateral force and the columns are assumed to act as dowels, are shown in Fig. 10.4.
The failure mode a) occurs when the soil mass flows around the column. The moment capacity of the column is in this case sufficient to resist the lateral pressure. The failure mechanism is similar for mode g), where the whole column moves as a rigid body.

Failure modes b) to f) occur when the depth of the slip surface increases. These modes occur when one or two plastic hinges develops at the maximum bending moment in the column, Fig. 10.5. The column fails when the maximum moment exceeds the moment capacity of the column. The shear resistance, or the dowel force, is governed by the moment capacity, the diameter of the column, the length of the column above and beneath the slip surface, the shear strength of the surrounding soft soil, and the soil bearing capacity factor. The moment capacity is governed by the compressive strength of the column, the axial

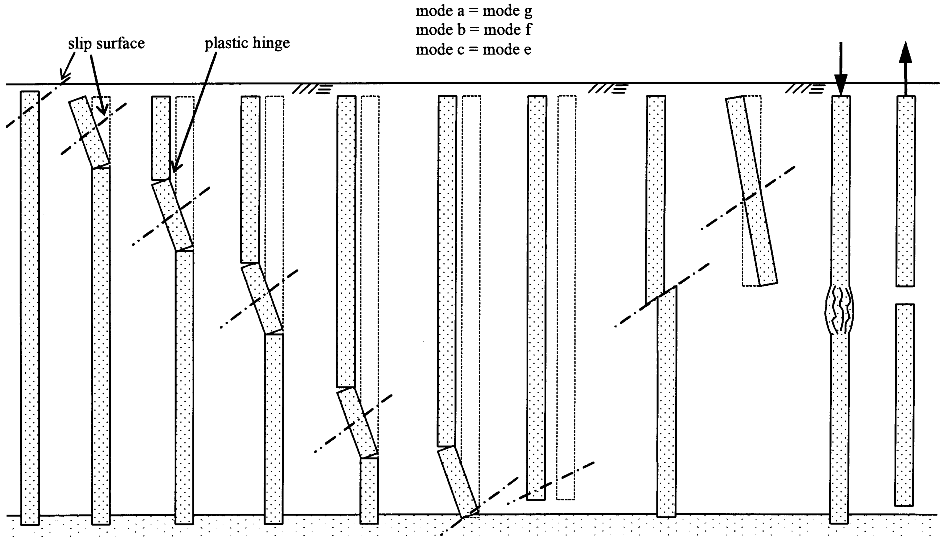


Fig. 10.4 Failure modes for single columns (after Broms 1999a and Kivelö 1998).

stress in the column, and the column diameter. The moment capacity is strongly dependent on the axial stress since the stabilised soil is not reinforced and can therefore not resist tensile stresses. The shear resistance increases with the axial stress up to half the axial bearing capacity of the column, which corresponds to the maximal moment capacity. Depending on the axial load and the compressive strength, the area of the plasticized zone varies. The mixing process has a significant influence on the compressive strength of the column, the magnitude and the distribution over the column cross-section.

Failure mode h) is a direct shear failure, where the shear resistance of the column is governed by the shear strength of the stabilised soil. The shear forces are assumed to act over the whole column cross-section

The failure mode i) occurs when the soil fails and the column rotates as a rigid body. The moment capacity of the column is in this case sufficient to resist the lateral pressure. This type of failure may occur for relatively short columns installed in very soft soil. However, according to Kivelö (1998), this failure mode is believed to be uncommon.

Failure mode j) occurs when the axial ultimate bearing capacity is exceeded, and failure mode k) when the tensile strength is exceeded. For booth of these failure modes, the whole cross-section of the column is assumed to interact.

The failure modes b) to f), proposed by Kivelö (1998), have not yet been fully scientifically validated by field observations. Lateral shear resistance of stabilised soil have preferably been investigated in model tests, centrifuge tests (Miyake et al. 1991, Miyake & Wada 1996, Kitazume et al. 1996, Karastanev et al.

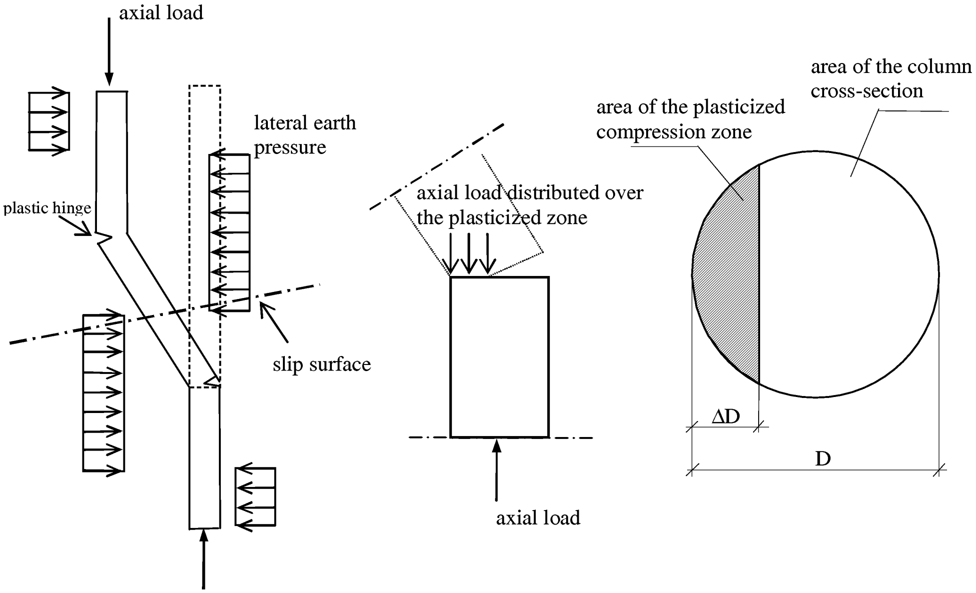


Fig. 10.5 Shear resistance of a single column acting as a dowel (after Kivelö 1998).

1997, Kitazume 2000), and 1g tests (Larsson 1999, Larsson & Broms 2000). Bending failure modes has been taken as reasonable explanations for some failures (Kivelö 1998, Broms 1999a) and this way of looking at single column behaviour is getting more and more accepted but is still controversial.
The bearing capacity for whole constructions and progressive failure as discussed by Kivelö (1998) and Broms (1999a, 1999b), and the interaction with the surrounding soft soil is not considered in the following analysis.

In lime-cement columns it has been observed that there are almost no marks after column penetration tests, i.e. the stabilised column material seems to heal, a short time after the test, possibly due to migration of calcium ions (Axelsson & Larsson 2003). This observation leads to the assumption that there are no fractures in the lime-cement columns when the strength is relatively low. These observations and the previous arguments imply that the elastic-plastic parallel system seems reasonable for the following discussion on sufficient mixture quality.

A further argument for the averaging model, however weak and somewhat speculative, is that there are few failures reported where the columns have been placed in active zone and are preferably axially loaded. An averaging model has so far been reasonably utilized in design. A weakest link model should have had resulted in several failures, since columns often are loaded over the plasticized limit and exhibit high variability in strength properties.

For high strength stabilised soil and/or stabilised soil containing a high amount of cement, other failure models may be appropriate to use. Honjo (1982) applied the bundle model on stabilised soil, Fig. 10.3. A bundle is somewhat between the average model and the weakest link model. Omine et al. (1998) proposed a failure model combining the weakest link model and the bundle model. The model called "a combined model" considers the amount of cracks in the stabilised soil and expresses the size effect on the strength, caused by the extent of potential cracks.

10.4 PROBABILITY DISTRIBUTION AND SPATIAL CORRELATION STRUCTURE

There are a number of reasons why it is important to assign the probability distribution in different scales and categories, according to Fig. 10.2. The probability distribution and the spatial correlation structure are of importance in relation to the, probability of failure, and the choice of partial factors. It is appropriate to perform the design with statistical methods, since the properties in stabilised soil vary. However, probabilistic design is not well established for deep mixing and one reason is that it is not obvious how to predict and evaluate strength- and deformation properties in stabilised soil in relation to the mechanical system. The probability distribution is important in connection to the production quality assessment with reference to strength- and deformation properties, since it has an influence on the extent of the control. The spatial correlation structure, i.e. an assessment of the variation of properties from one point to another in space, has an influence on the distance between the tests in order to obtain representative measures of properties. The spatial correlation structure has thus an influence on the requisite test- and sample sizes. Since the mixing process continues after the mechanical mixing, as molecular diffusion of calcium ions, the mixture quality may improve over time and consequently, the time for examination may have an influence on the spatial correlation structure.

Probability distribution

The probability distribution of mechanical properties in the scale associated to the mixing process has not been well investigated. Honjo (1982) proposes the Gaussian normal distribution based on unconfined compressive tests on samples from two sites. In a MSc thesis included in this project (Hedman & Kuokkanen 2003), a special investigation in connection to the Strängnäs field tests was performed. With respect the results from hand-operated penetrometer tests on excavated column sections, the probability distribution was tested using the Kolmogorov-Smirnov normality test. The normality tests were based on 48 penetrometer tests per column cross-section. A total of 42 columns were tested. The conclusion from these tests was that the strength distribution can be modelled by the Gaussian normal distribution.

Spatial correlation

Variability of stabilised soil properties can be described by means of random fields. The values taken by a given property at different points are then considered as a realization of such a field, defined by classical statistical characteristics, such as the mean, coefficient of variation, probability distribution and spatial correlation (e.g. Vanmarcke 1983). The spatial correlation describes the variation of properties from one point to another in space. To proceed with a stochastic analysis the limit of spatial continuity must be identified; beyond which no or small correlation between data exists. Connected to spatial variation is the sample and test size, i.e. spatially varying properties will manifest different values in different sample and test sizes. In order to assess the strength correlation structure associated to the mixing process, the size or volume of the samples and tests must be relatively small, much less than the area of the column cross-section.

The spatial correlation structure can be expressed in terms of the variogram which describes the dissimilarity between two points in space, separated by a distance h. The variogram of a property $Z(x)$ is expressed as (e.g. Deutsch 2002):

$$2\gamma(h) = E(Z(x_i) - Z(x_i + h))^2 \qquad (10.1)$$

$2\gamma(h)$ is the variogram value at a separation distance h. $Z(x_i)$ is the value of the random variable at location x_i, and $Z(x_i + h)$ is the value of the random variable at distance h from $Z(x_i)$. The relation is valid for stationary random fields where the mean and variance are constant throughout the specific volume; the value of the variogram depends only on the separation distance h and not on the location x_i of the measured value $Z(x_i)$. The spatial correlation structure in stabilised soil is however expected to be anisotropic, especially in the vertical direction reflecting the soil stratum. This is however beyond the scope of this study. The semivariogram, or the experimental variogram, based on experimental data is expressed as (e.g. Deutsch 2002):

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left[Z(x_i) - Z(x_i + h)\right]^2 \qquad (10.2)$$

where n is the number of data. Spatial correlation structures are characterised by their model types. These models are parametric relationships used to curve fit the variogram obtained from measured data.

Frequently used semivariogram models are shown in Fig. 10.6 (e.g. Deutsch 2002); sill (nugget effect) semivariogram model; exponential semivariogram model; spherical semivariogram model; and Gaussian semivariogram model;

Sill semivariogram model $$\gamma(h) = \gamma_r \tag{10.3}$$

Exponential semivariogram model $$\gamma(h) = \gamma_r\left(1 - e^{-3h/a}\right) \tag{10.4}$$

Gaussian semivariogram model $$\gamma(h) = \gamma_r\left(1 - e^{-3h^2/a^2}\right) \tag{10.5}$$

Spherical semivariogram model $$\gamma(h) = \gamma_r\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\frac{h^3}{a^3}\right) \quad \text{when} \quad h \le a$$

$$\gamma(h) = \gamma_r \quad \text{when} \quad h > a \tag{10.6}$$

where γ_r is a variogram model value called the sill, in this study quantified as the equalweighted variance of the measured data (s^2) entering the variogram calculation. h is the separation distance, and the spatial range a is the separation distance, called the range, at which the variogram reaches the sill and correlation between data no longer exists.

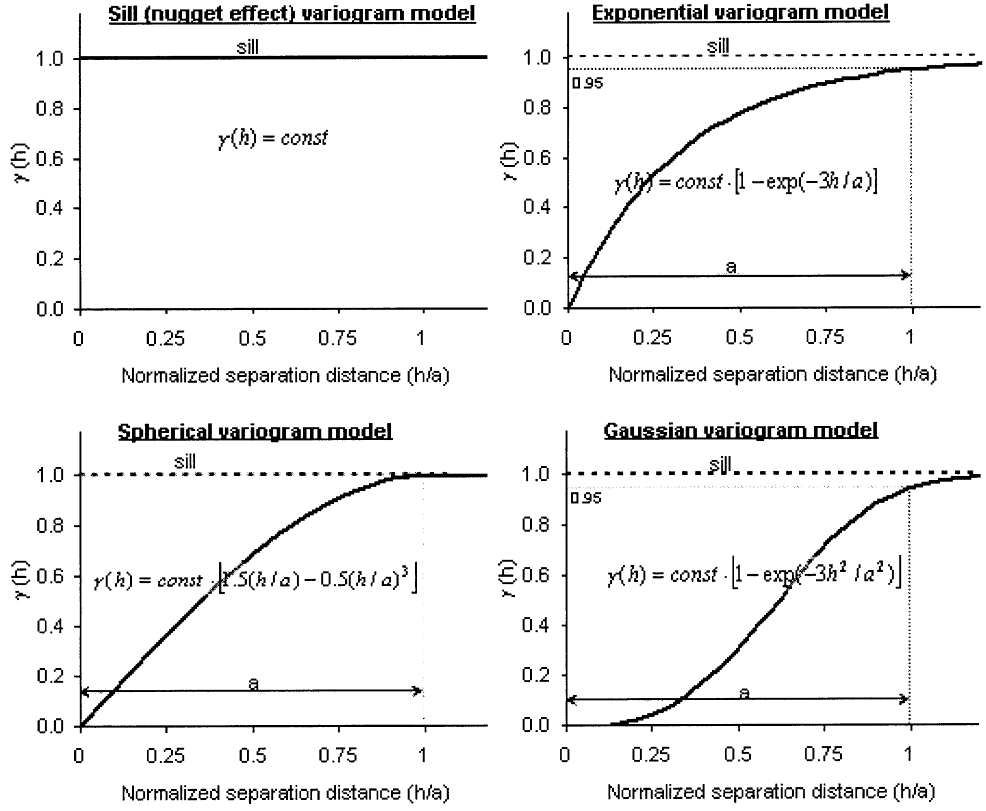


Fig. 10.6 Examples of variogram models commonly used in practice (after Elkateb et al. 2003).

Volume-variance relationship

It is well known that the variance of the mean value of a random variable in a given domain decreases as the size of the domain increases (e.g. Olsson 1986). The volume-variance relationship must be identified, which helps the assessment of the variance reduction. The variance of the mean value σ_{Γ}^{2} over volume V can be correlated to the sample variance σ^{2} using the variance reduction factor Γ_{V}^{2} through (Vanmarcke 1977):

$$\sigma_{\Gamma}^{2}=\Gamma_{V}^{2}\times\sigma^{2} \tag{10.7}$$

The variance reduction factor Γ_{V}^{2} depends on the volume, type of correlation structure and the limit of spatial correlation between field data, which is determined by the semivariogram.

The solutions for the different variogram models are shown in Fig. 10.6 (e.g. El-kateb et al. 2003). However, Vanmarcke (1977) proposed a simplified expression for a "standard" reduction factor $\Gamma(T)$ given by (Fig.10.7)

$$\Gamma(T)=\begin{cases}1 & T\leq\theta\\ \sqrt{\dfrac{\theta}{T}} & T\geq\theta\end{cases} \tag{10.8}$$

where θ is the scale of fluctuation which estimates the distance within which the soil property shows relatively strong correlation. T represents the size of the average length, area or volume. The above expression is valid for the one-dimensional case.

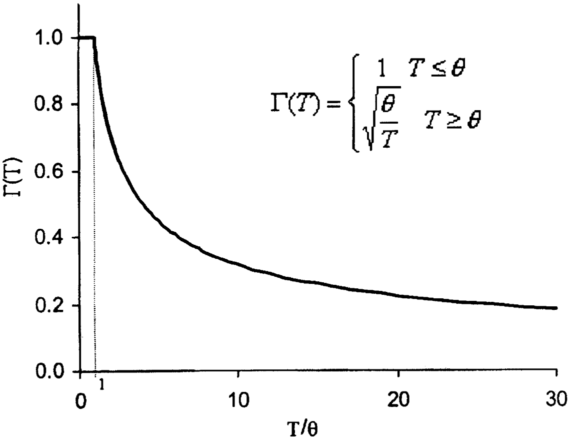


Fig. 10.7 **Simplified reduction factor $\Gamma(T)$ as a function of the ratio between the average length T and the scale of fluctuation θ , proposed by Vanmarcke (1977).**

The scale of fluctuation θ can be expressed as a function of the range a for the exponential-, the Gaussian-, and the spherical semivariogram models (Vanmarcke 1983):

Exponential semivariogram model $$\theta = \frac{2}{3}a \qquad (10.9)$$

Gaussian semivariogram model $$\theta \approx a \qquad (10.10)$$

Spherical semivariogram model $$\theta = \frac{3}{4}a \qquad (10.11)$$

By assuming separable correlation structures in the two-dimensional case, the variance reduction factor Γ_A^2 can be expressed as the product of its one-dimensional components

$$\Gamma_A^2 = \Gamma_X^2 \cdot \Gamma_Y^2 \qquad (10.12)$$

where Γ_X^2 and Γ_Y^2 are the variance reduction factors in the x-, and y- directions respec-tively. The procedure can be extended for the three-dimensional case, in a similar way.

It must be emphasized that the variance reduction is only true when the property can be considered as a sum, i.e. when the failure mode can be considered as a ductile parallel system with respect to the shear and compressive strength. This is probably not the case for high strength stabilised soil. When the strength increases the material becomes more brittle and the properties of high strength stabilised soil is therefore size dependent. For the utilization of higher strengths in the design, other failure models than the averaging model must be considered.

10.5 ANALYSIS OF THE RESULTS FROM HÅBY AND STRÄNGNÄS FIELD TESTS

General

The analyses are based on the results from the two field tests, Håby and Strängnäs, presented in Chapter 8 and 9, respectively. The soil properties at the test levels are summarised in Table 10.1. Installation records are shown in Table 10.2, and data concerning the test procedure are shown in Table 10.3. Details concerning the two test sites can be found in Chapter 8 and 9, respectively.

All columns were tested approximately one week after installation. The undrained compression strength was less than approximately 300 kPa, and the columns are hence considered as low to medium strength columns (according to Tielaitos 1997). All tests are performed by a hand-operated penetrometer, executed by one person. The mixture quality is defined as the coefficient of variation with respect to the results from the penetrometer tests. The analyses are performed disregarding the fact that the coefficient of variation contains a number of errors such as imperfect mixing, variation due to the penetrometer and the test procedure, and variation due to the excavation of the columns, as discussed in Chapter 8.4. The evaluated coefficient of variation consequently greater than the coefficient of variation due to imperfect mixing alone.

Table 10.1 Soil properties at the test lewels.

Property	Håby	Strängnäs
undrained shear strength; kPa	16-45	13-26
water content; %	38-70	74-136
liquid limit; %	46-73	72-144
sensitivity	3-20	10-15

Table 10.2 Installation records.

Property	Håby	Strängnäs
diameter; mm	600	600
mixing tool	Std/Pinnborr	Std/Pinnborr
retrieval rate; mm/rev	15/30	15/30
blade rotation number; n/m	67-800	67-800
rotational speed; rev/min	80/160	80/160
air pressure; kPa	350/550	350/550
binder type	lime/cement	lime/cement
binder content; kg/m^3	100	88

Table 10.3 Test data.

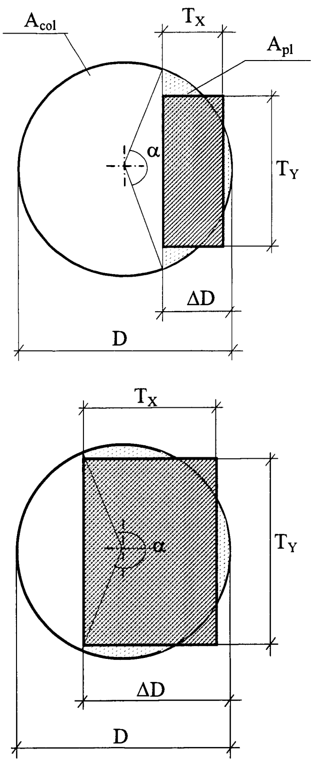
Property	Håby	Strängnäs
number of columns	62	77
column age; days	7	7
test levels; m	2.0-2.3	1.9-2.3
number of tests	2500	3100

All columns are tested at two shallow depths, 1.9 to 2.3 below the ground surface. The two depths are named the upper and the lower test layer, respectively. Similar soil and constant binder content (no variability in the binder distribution) are assumed. The study is assumed to be limited to the column section scale associated with the mixing process according to Fig. 10.2.

Spatial correlation and volume-variance relationship

The experimental semivariogram is used to assess the spatial correlation over the column cross-sections for the results obtained from the hand-operated penetrometer tests. The four semivariogram models based on equations 10.3 to 10.6 are used to fit the experimental semivariograms. The spatial correlation structure is assumed to be equal in all directions in the horizontal plane, i.e. the omnidirectional semivariogram is determined for each column cross-section. The software package VARIOWIN 2.2 was used for the statistical processing using 10 lags and lag space 50 mm. The lag space is chosen with respect to the smallest test spacing, i.e. 50mm. Correlation structures with the scale of fluctuation less than 50mm can not be detected and therefore is the lowest value on the scale of fluctuation chosen to 50mm.

The reduction factor Γ_A is evaluated using equations 10.8 and 10.12. To simpllify, the area of the plasticized compression zone is replaced with a square section as shown in Fig. 10.8. The scale of fluctuation for each column cross-section is evaluated using equations 10.9 to 10.11. The reduction factor is evaluated with respect to the area of the column cross-section subjected to shear or compression stresses, i.e. the scale of scrutiny with respect to the mechanical system.



$$A_{col} = \pi D^2/4$$

$$A_{pl} = \frac{D^2}{8}(\alpha - \sin\alpha) = T_X \cdot T_Y$$

$$\cos\frac{\alpha}{2} = 1 - \frac{2\cdot\Delta D}{D}$$

$$T_X = \begin{cases} \sqrt{\pi}/2\cdot\Delta D & T_X \le D/2 \\ 2\cdot A_{pl}\big/\left(D\cdot\sqrt{\pi}\right) & T_X \ge D/2 \end{cases}$$

$$T_Y = \begin{cases} A_{pl}/T_X & T_Y \le D/2 \\ D\sqrt{\pi}/2 & T_Y \ge D/2 \end{cases}$$

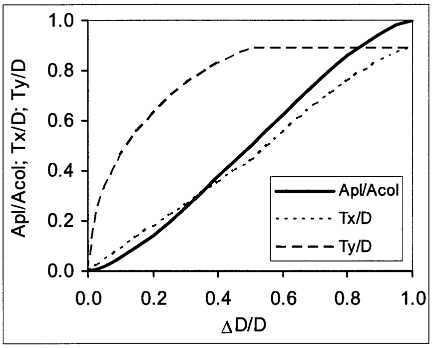


Fig. 10.8 A simplification where the plasticized circular column cross-section is replaced by a square cross-section.

The experimental programme and the statistical design approach, in connection to the field tests at Håby and Strängnäs, entailed the possibility to test whether a number of installation factors have an influence on the scale of fluctuation θ, i.e. the distance within which the soil property shows relatively strong correlation. Five statistical analyses of variances, ANOVA, according to Tables 8.3, 8.4, 9.2, and 9.3 were performed with reference to the assessed scale of fluctuation. The scale of fluctuation is evaluated for 124 cross-sections at the test site in Håby, and for 154 cross-sections at the site in Strängnäs.
The statistical tests are performed based on the 0-hypotheses that the following factors do not have an influence on the scale of fluctuation, using the 5% level of significance:

the number of blades on the mixing tool; 2, 4, 6, 8, and 12 blades;

the mixing tool; Standard and Pinnborr;

the retrieval rate; 15 and 30 mm/rev;

the rotational speed; 80 and 160 rpm;

the binder outlet hole; 22 and 37 mm;

the binder tank air pressure; 350 and 550 kPa.

The test concerning the influence of the retrieval rate and the number of mixing blades on the mixing tool is of special interest. Throughout the thesis it has been considered that the mechanical mixing only influences the binder dispersion in a relatively small scale, preferably in the radial direction from the centre of the column. This assertion has been founded on the discussion in Chapter 5, concerning the visco-elastic properties in clay soils, and subjective judgements based on experiences. However, this assertion has not been fully validated through field tests. The statistical tests concerning the influence of the retrieval rate and the number of mixing blades provide the opportunity to test this assertion, based on the assumption that the scale of fluctuation increases when the mechanical mixing distributes the binder in an increasing scale;

> 0-hypothesis; the retrieval rate and the number of mixing blades have no significant influence; the blades generate motions in a small scale, less than the scale of fluctuation caused by the spreading and incorporation process.
>
> Alternative hypothesis; the retrieval rate and the number of mixing blades have a significant influence; the blades generate motions to a greater extent than the scale of fluctuation caused by the spreading and incorporation process.

The 0-hypothesis, for the unidirectional case, is visualised in Fig. 10.9. The strength in the stabilised soil increases and the coefficient of variation V decreases, when the mechanical mixing with respect to the blade rotation number T increases. Since the mechanical mixing is assumed to influence the binder dispersion in a smaller scale than the binder spreading and incorporation process, the scale of fluctuation θ is assumed to be essentially unaffected.

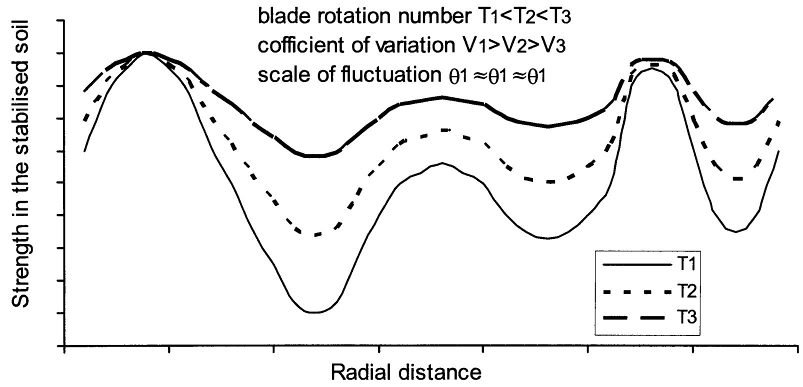


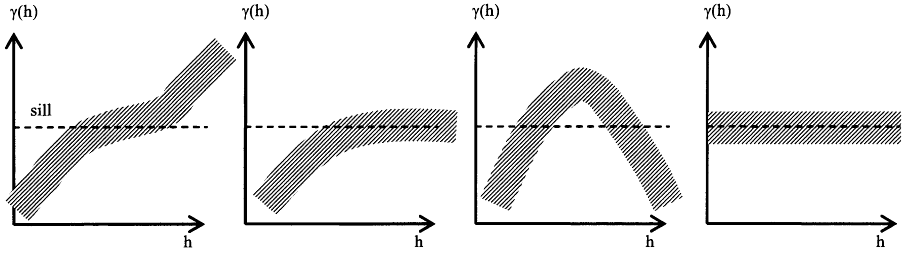
Fig. 10.9 **Schematic of the increase of the column strength when the blade rotation number increases.**

10.6 RESULTS AND DISCUSSION

Spatial correlation

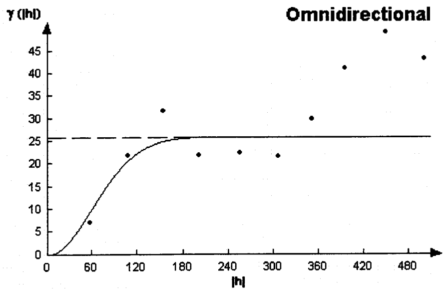
From the total of 278 evaluated experimental semivariogram structures from the two test sites, four characteristic structures were obtained, as shown in Fig. 10.10. Eight examples of these experimental variogram from the two test sites are shown in Figs. 10.11 and 10.12. The strengths over the cross-section of the columns are visualized from ordinary kriging interpolation, using the software package SADA, version 3.0 (ordinary kriging "serves to estimate a value at a point of a rigion for which a variogram is known, using data in the neighborhood of the estimation location.", Wackernagel 1995). The most frequent structure, and the most expected, is type 2, according to Fig. 10.10. The semivariogram models used corresponds well to this experimental semivariogram over the whole column cross-section. There is a separation distance between test data at which there is insignificant correlation. The semivariogram reaches the sill and correlation between data no longer exists. For the experimental semivariogram type 1, the semivariogram value increases over the whole domain. The experimental semivariogram type 3 reaches a value somewhat higher than the sill, and then decreases at greater distance. Semivariogram type 4 corresponds to the nugget effect variogram model, i.e. the semivariogram value is constant and the range is equal to zero. However, since the minimum test distance was 50mm, the semivariogram does not give information of the correlation in a scale less than 50mm.

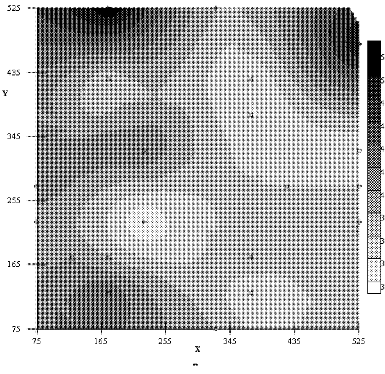
Semivariogram type 1 and 3 indicate that the mean and standard deviation are not constant across the column cross-section, i.e. the section is not a stationary random field. Semivariogram type 1 appears when the strength is higher at one side of the column cross-section as shown in Fig. 10.11. Semivariogram type 3 appears when the strength is radial correlated from the centre of the column; the strength forms circle structures where the strength is either higher or lower close to the column centre, as shown in Fig. 10.12. There are no strengths structures visualised for the two type 4 structures in Fig. 10.12, since there is no correlation between the obtained test data.



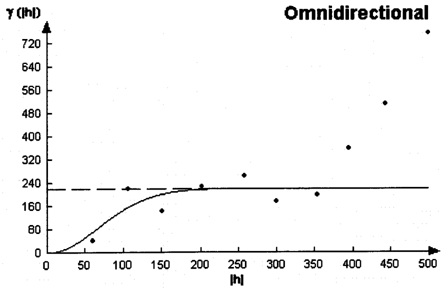
	Type 1	Type 2	Type 3	Type 4
Strängnäs	23%	44%	16%	17%
Håby	14%	48%	19%	19%

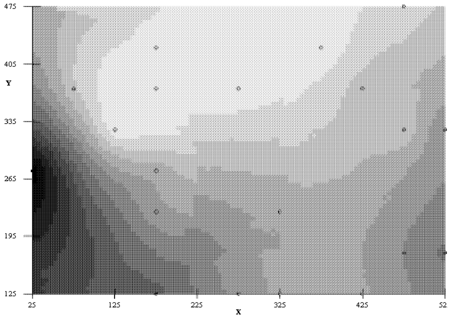
Fig. 10.10 Four characteristic experimental semivariogram correlation structures.



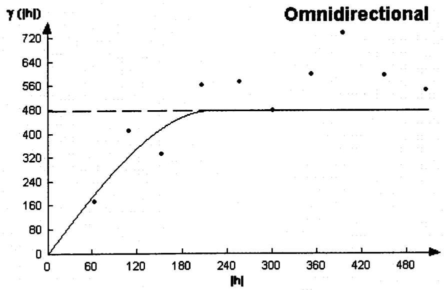


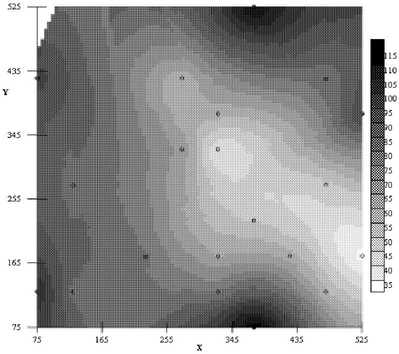
Column 4.25a Håby; T=300 n/m
S_{eff}=7.5 $V_{\delta col}$=0.16



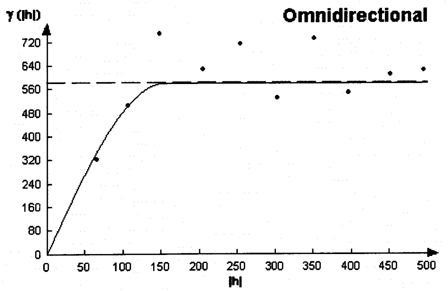


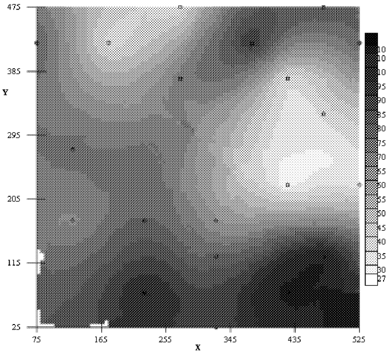
Column 1.23b Strängnäs; T=133 n/m
S_{eff}=13.1 $V_{\delta col}$=0.29





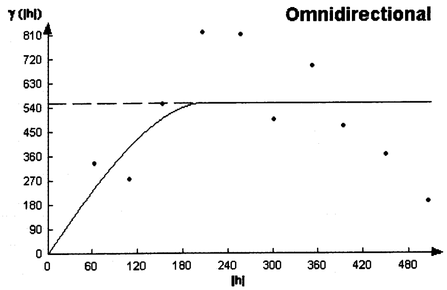
Column 2.1a Håby; T=200 n/m
S_{eff}=6.2 $V_{\delta col}$=0.29





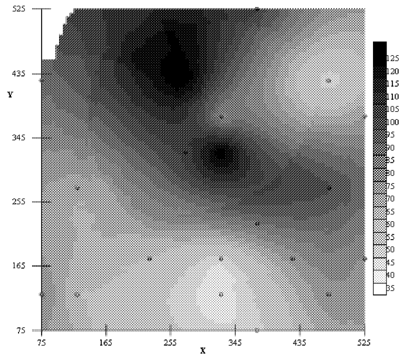
Column 3.12b Strängnäs; T=267 n/m
S_{eff}=14.1 $V_{\delta col}$=0.37

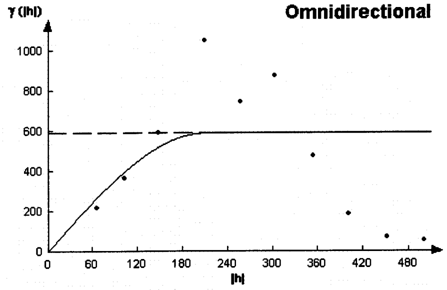
Fig. 10.11 Four examples of evaluated correlation structures, type1 and 2.



Column 1.18b Håby; T=133 n/m

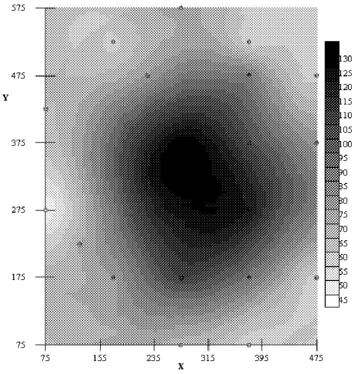
S_{eff}=6.4 $V_{\delta col}$=0.36

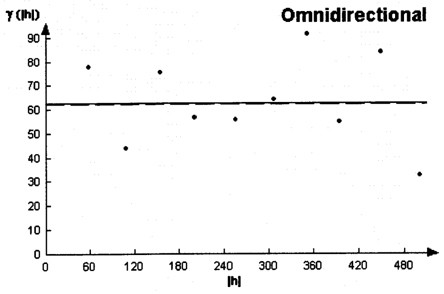




Column 2.13a Strängnäs; T=400 n/m

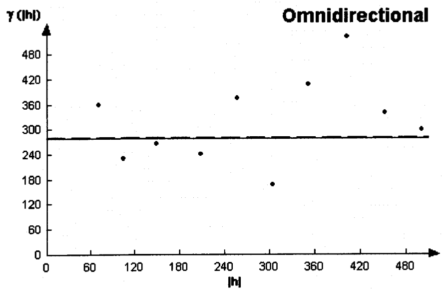
S_{eff}=13.6 $V_{\delta col}$=0.31





Column 5.16b Håby; T=133 n/m

S_{eff}=4.4 $V_{\delta col}$=0.19



Column 2.6b Strängnäs; T=400 n/m

S_{eff}=11.5 $V_{\delta col}$=0.30

Fig. 10.12 Four examples of evaluated correlation structures, type3 and 4.

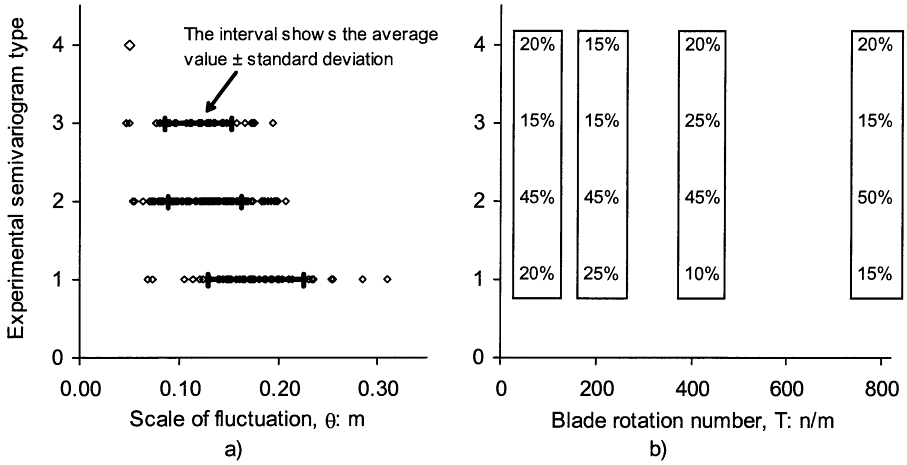


Fig. 10.13 **The distribution of the determined experimental semivariogram types related to; a) the evaluated scale of fluctuation θ and; b) the blade rotation number T .**

There are no substantial differences between the experimental semivariogram types with respect to the evaluated scale of fluctuation, as shown in Fig. 10.13a. Furthermore; as shown in Fig. 10.13b, there are no correlation between the semivariogram type and the blade rotation number, and there are no correlation between the coefficient of variation and the scale of fluctuation, indicating that the mechanical mixing work does not significantly influence the type of correlation structure. The evaluated scale of fluctuation with respect to the omnidirectional semivariogram models used is in the range of 0.05 to 0.31m. However, all structures evaluated with a scale of fluctuation greater than 0.21m are of type 1. The scale of fluctuation is in the same range for correlation structure type 2 and 3, 0.05-0.21m.

Statistical analysis of variances, ANOVA, were performed in order to investigate whether the retrieval rate, the number of blades on the mixing tool, the type of mixing tool, the rotational speed; the air pressure in the storage tank, or the diameter of the outlet hole of the mixing tool have an influence on the scale of fluctuation. Some selected results from five ANOVA tests are presented in Tables 10.4-10.8.

There are only two significant results obtained, as shown in Table 10.4; the outlet hole for the upper layer; and the retrieval rate for the lower layer. Since the influences of these two factors are only obtained for these two separate tests, the 0-hypotheseis can not be rejected. To sum up, the 0-hypothes, i.e. the factors do not have an influence, can not be rejected basted upon the present results.

The most notable result is that the retrieval rate and the number of mixing blades do not have an influence on the scale of fluctuation. However, for the small size tests it is obvious that these two factors have a significant influence on the stabilisation effect and coefficient of variation, as shown in Chapter 8 and 9. Figs. 10.14a and 10.14b show the relation between the coefficient of variation and the scale of fluctuation. The figures clearly show that there is no correlation between the scale of fluctuation and the coefficient of variation. The results are an indication that the mechanical mixing work, with respect to the blade rotation

Table 10.4 Analysis of variance with respect to the scale of fluctuation, 2^4-factorial experiment, Håby.

Source of variation	*upper test layer* F	*lower test layer* F
Replication	< 1	< 1
Main effects:		
Outlet hole	**9.3**	< 1
Tank pressure	2.1	< 1
Retrieval rate	< 1	**9.5**
Rotational speed	< 1	< 1

Comment: $F_{0.05}$=4.54 and $F_{0.01}$=8.68 for 1 and 15 degrees of freedom.

Table 10.5 Analysis of variance with respect to the scale of fluctuation, 2^3-factorial experiment, Håby.

Source of variation	*upper test layer* F	*lower test layer* F
Replication	< 1	3.8
Main effects:		
Tool; Std-Pinnb.	< 1	< 1
Retrieval rate	< 1	< 1
Rotational speed	4.3	< 1

Comment: $F_{0.05}$=5.59 and $F_{0.01}$=12.20 for 1 and 7 degrees of freedom.

Table 10.6 Analysis of variance with respect to the scale of fluctuation, Håby

Source of variation	*Degrees of freedom*	$F_{0.05}$	*upper test layer* F	*lower test layer* F
Replication	1	6.61	2.0	2.4
Main effects:				
Number of blades	2	5.79	< 1	1.4
Retrieval rate	1	6.61	4.3	< 1

Table 10.7 Analysis of variance with respect to the scale of fluctuation, 2^5-factorial experiment, Strängnäs.

Source of variation	*upper test layer* F	*lower test layer* F
Replication	4.1	1.8
Main effects:		
A. Number of blades	1.7	2.6
B. Retrieval rate	< 1	< 1
C. Rotational speed	1.3	< 1
D. Outlet hole	< 1	< 1
E. Tank pressure	1.3	< 1

Comment: $F_{0.05}$=4.17 and $F_{0.01}$=7.56 for 1 and 31 degrees of freedom.

Table 10.8 Analysis of variance with respect to the scale of fluctuation, two factorial experiment, Strängnäs

Source of variation	*Degrees of freedom*	$F_{0.05}$	*upper layer* F	*lower layer* F
Replication	1	5.59	< 1	**5.9**
Main effects:				
Number of blades	3	4.35	1.8	< 1
Retrieval rate	1	5.59	< 1	< 1

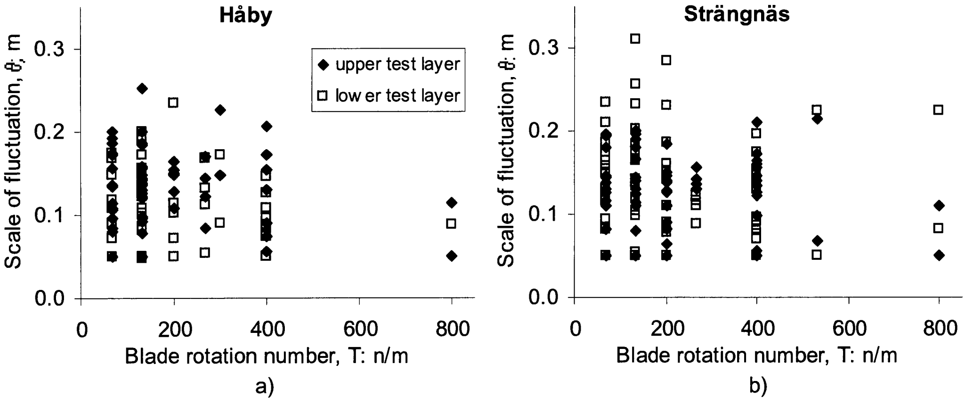


Fig. 10.14 Relation between the blade rotation number T and the scale of fluctuation θ.

number, influences the spatial correlation structure in a relatively small scale, only a few centimetres. This explanation strengthens the assertion that the most important part of the mixing process is the spreading and incorporation of binder in the early stage of the dispersion process, as shown in Fig. 6.1. An uneven spreading of the binder over the column cross-section can not be adjusted without extensive mixing work.

The conclusion that none of the investigated factors have a significant influence on the correlation structure is strengthened by the results presented in Chapter 7 (Larsson 2001), where the mixture quality was assessed based on the binder content determination in samples taken from different columns and from different depths. The conclusion from this test was that the correlation structure with respect to the binder dispersion differed between the columns in spite of the fact that they were equally installed. This conclusion can also be drawn from the tests by Hedman and Kuokkanen (2003), from hand-operated penetrometer tests on a number of column cross-sections tested at different depths. Furthermore, the field test in Håby, Chapter 8, clearly showed that the upper pair of mixing blades, in connection with the binder outlet hole, had a significant and determining influence on the binder dispersion. The study showed that the binder is incorporated and spread in the cavity formed by the mixing blades during rotation The observations from all these test indicate that the spreading and incorporation of the binder in the early stage of the mixing process are the crucial factors and have a determining influence on the binder dispersion and the spatial correlation characteristics over the column cross-section. However, this conclusion should be further investigated with respect to drained soil parameters before a generic conclusion can be drawn.

The observation that the correlation structure appears to vary independently of the mixing work and the depth, shows that the type of correlation structure probably has a minor influence on the mechanical system. A few column sections with the correlation structure type 1 and 3 may not have a negative effect with respect to the shear resistance for the whole structure. The likelihood that several column cross-sections have the same type of correlation structure at the same depth is regarded as low. Whether different types of correlation structures have an influence on the mechanical system with reference to the full structure is an interesting subject for further research.

The results from Håby and Strängnäs are probably time, site, and parameter specific and it is therefore not possible to draw conclusions with respect to generic distribution patterns and correlation structures for stabilised soil properties. The correlation structures were assessed by the experimental omnidirectional semivariograms, i.e. the spatial correlation is assumed to be equal in all directions. It should be investigated whether anisotropy in the horizontal plane can influence the results. It should be investigated whether the horizontal trends, experimental semivariogram type 1 and 3 according to Fig. 10.10, have an influence on the determined scale of fluctuation. This can be investigated using directional variograms or using experimental semivariogram that are determined based on polar coordinates. It is of special interest to study the influence of time on the correlation structure. It is uncertain whether the mixture quality improves over time or not. Furthermore, the analyses should be extended to three dimensions and linked to the correlation structure including the variability caused by uneven binder distribution in axial direction. In addition, the analyses should be extended to include the soil variability.

In order to further study correlation structures over column cross-sections, test methods which only consider a relatively small part of the cross-section should be used, much less than the scale of fluctuation. The tests must be performed with a relatively large amount of tests distributed over the whole cross-section. The probe size on the column penetrometer test, the most common test method in Sweden (Axelsson & Larsson 2003), is far too large for the assessment of the correlation structure at this small scale as the tool is so large that it causes a physical variance reduction.

Further investigations should be performed on the correlation structures between spatial averages of the stabilised soil properties in column groups, i.e. assessing the correlation structure for column groups. It is of interest to study the volumetric correlation between the average strength- and deformation properties within different columns, separated by the column spacing. The correlation structures between spatial averages affect the testing frequency. The spatial averages should be determined by test methods where a relatively large part of the column cross-section is tested. Based on the probe size, the column penetrometer test is the most suitable test method today for this purpose. A method for the assessment the correlation structure between spatial averages is presented by Vanmarcke (1977). The correlation structures for stabilised soil properties in the full scale will facilitate the determination of a proper selection of partial factors.

Volume-variance relationship

The reduction factor Γ_A as a function of the evaluated scale of fluctuation and the ratio between the considered area, in the present analysis the plasticized zone A_{pl}, and the area of the column cross-section A_{col} has been evaluated according to equations 10.8 and 10.12. The analyses are based on the evaluation of the omnidirectional scale of fluctuation for 278 column cross-sections. The results for the two test sites are shown in Fig. 10.15. The function is a result of the simplification of the increasing plasticized zone on column cross-sections as shown in Fig. 10.8. The reduction factor Γ_A decreases relatively rapidly due to the increase of the averaging length T_Y when the plasticized zone increases. Fig. 10.15 also shows the standard deviation as a measure of the variability with respect to the evaluated reduction factor. The standard deviation is calculatedd based on the evaluated scale of fluctuation θ for the column cross-sections. The relatively large standard deviation is due to the large variability of the evaluated scale of fluctuation, $\theta = 0.05 - 0.31m$. The reduction factor is similar, since the range of the evaluated scale of fluctuation is similar for the two test sites.

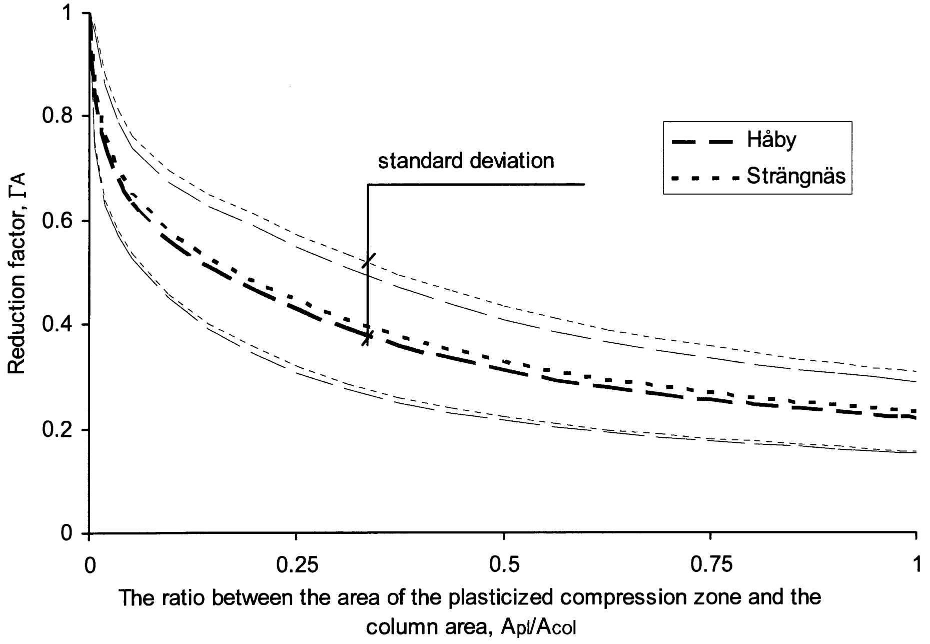


Fig. 10.15 The column cross-section reduction factor Γ_A, as a function of the ratio between the area of the plasticized compression zone and the column area A_{pl}/A_{col}.

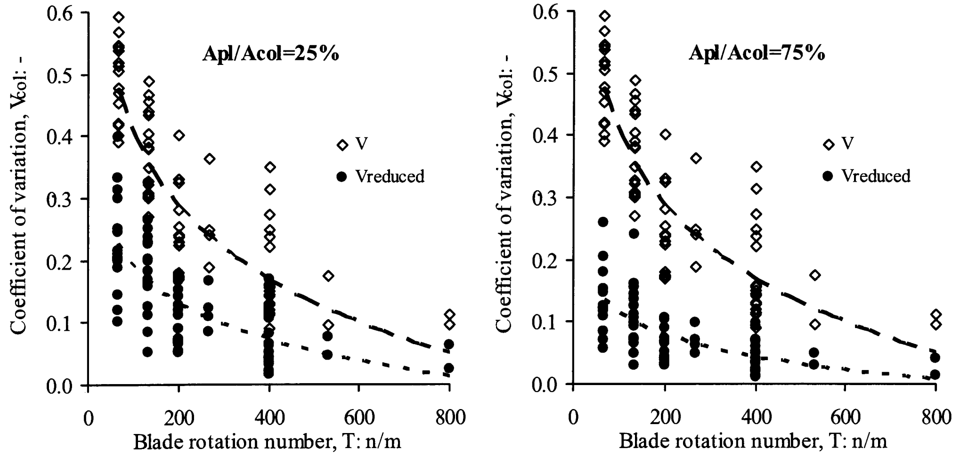


Fig. 10.16 The effect of a reduced coefficient of variation $V_{reduced}$ with respect to the ratio between the area of the plasticized compression zone and the column area A_{pl}/A_{col} based on the results from Strängnäs field tests.

When the plasticized zone increases, the coefficient of variation decreases, as a consequence, the influence of the mechanical mixing work on the strength variability decreases. However, the strength variability can not be considered as negligible and should be considered in design. The reduction factor Γ_A with respect to the coefficient of variation, evaluated from the hand-operated penetrometer tests, is approximately in the range $\Gamma_A = 0.5 - 0.3$ for a column section where the axial load is in the range of 25% to 75% of the ultimate axial load. If the considered area is equal to the column area, which is the case for the failure mode h) and j) according to Fig. 10.4, the reduction factor is approximately in the range of $\Gamma_A = 0.2 - 0.3$.

Special considerations must be taken when columns are installed in slopes to improve stability. The axial load can be low and consequently, the plasticized zone can be small when the column is subjected to lateral forces and reaches the ultimate state with respect to the maximum shearing resistance. In this case the variability in the stabilised soil properties can have a considerable influence on the shear resistance since the reduction in variance can be small. As an example, Fig. 10.16 shows that if A_{pl}/A_{col} = 25%, and the blade rotation number is equal to 400 n/m, the coefficient of variation can be reduced to approximately 10%. If A_{pl}/A_{col} = 75%, the coefficient of variation can be reduced to approximately 10% when the blade rotation number equals 200 n/m.

It is not possible to give general recommendations for the specifications regarding the mechanical mixing work since design values for strength properties depends on the mechanical system, the scale of scrutiny, the spatial correlation structure, and the concept of safety, i.e. the concept of sufficient mixture quality is problem specific. The present analysis indicates that it would be beneficial to install larger diameter columns or columns structures in order to increase the plasticized compression zone, i.e. increase the scale of scrutiny. However, it is important to ensure a uniform distribution of the binder throughout the column section, which can be more difficult as the column diameter increases.

The volume-variance relationship has only been analysed in the horizontal plane, using a simplified expression as the reduction factor. The results are somewhat conservative and the influence of a three-dimensional analysis should therefore be investigated, i.e. an analysis including the variability in the axial direction.

Design considerations

This section deals with a brief design consideration with respect to the mixing process. Previously, the mixing process has been discussed with respect to different failure mechanisms. However, a discussion concerning the choice of design values remains. It is chosen to base the discussion on partial factors of safety that are more nuanced than the conventional total safety factor (Stille et al. 2003). The partial factors of safety make it possible to consider the variability and the concept of probability of failure and safety. The purpose of this brief discussion is to introduce some statistical considerations in determining partial factors for the compressive strength of stabilised soil.

For a variable that is normal distributed the partial factor γ_i is defined by (e.g. Olsson et al. 1989)

$$\gamma_i = \frac{x_{ki}}{\mu_i + \alpha_i \cdot \beta \cdot \sigma_i} \tag{10.13}$$

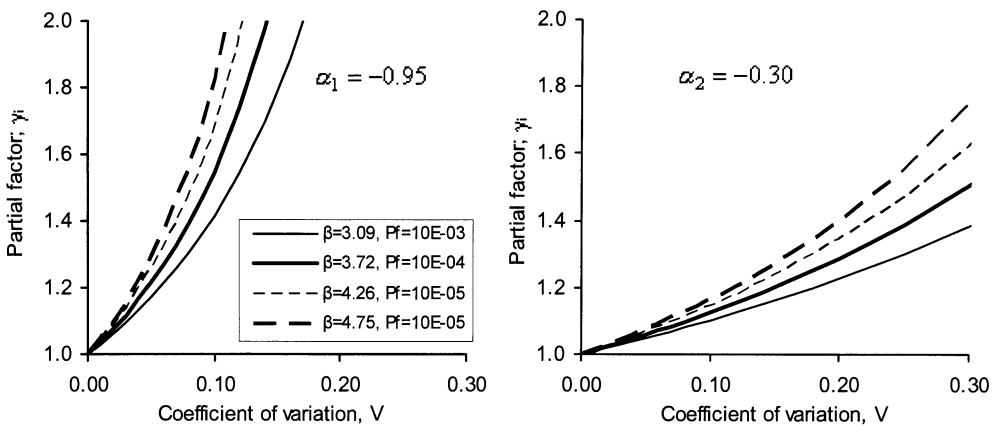
where x_{ki} is the characteristic value of variable i, μ_i is the mean value of variable i, α_i is the sensitivity factor of variable i, σ_i is the standard deviation of variable i, and β is the required safety index. A characteristic value equal to the mean gives a partial factor defined by

$$\gamma_i = \frac{1}{1 + \alpha_i \cdot \beta \cdot V_i} \tag{10.14}$$

where V_i is the coefficient of variation of variable i. In the case of a parallel failure model, the reduced coefficient of variation with respect to the scale of fluctuation and the scale of scrutiny should be utilized.

For the present consideration the safty index β and the sensitivity factor α_i are assigned using simplifications. For the normal probability distribution (Gaussian probability distribution) there is a unique relation between the safety index β and the probability of failure P_f. The sensitivity factor α_i is estimated using a simplified method proposed by Olsson et al. (1989) and Bengtsson et al. (1991). The variables are ranked with respect to the failure criterion and the coefficient of variation. The sensitivity factors are assigned:

$$\alpha_1 = \sqrt{0.9} = 0.95$$
$$\alpha_2 = \sqrt{0.9 \cdot (1 - 0.9)} = 0.3$$
$$\alpha_3 = \sqrt{0.9 \cdot (1 - 0.9 - 0.09)} = 0.1$$



a) b)

Fig. 10.17 Partial factor γ_i as a function of the coefficient of variation V for different failure probabilities; a) sensitivity factor $\alpha_1 = -0.95$ and; b) sensitivity factor $\alpha_2 = -0.30$.

For resistance variables the sensitivity factor becomes negative, and for load variables the sensitivity factor becomes positive. If two variables are equally ranked the available part of $(\alpha_i)^2$ is equally divided between them, i.e. the two highest ranked variables are then assigned $\alpha_1 = \alpha_2 = 0.7$.

Fig. 10.17 shows the partial factor γ_i as a function of the coefficient of variation V_i, for different probabilities of failure P_f. Fig. 10.17a shows the relation with respect to the sensitivity factor $\alpha_1 = 0.95$, and Fig. 10.17b shows the relation with respect to $\alpha_2 = 0.3$.

The simple consideration, as shown in Fig. 10.17, shows that a proper analysis of the mechanical system and the adherent properties, and the possibility to utilize variance reduction, has a major influence on the determination of the partial factor. When the strength of the stabilised soil is ranked as α_1, the mixture quality has a major influence on the determination of the partial factor. The results from the assessment of the correlation structures in Håby and Strängnäs, and the reduction factor Γ_A as shown in Fig. 10.15, show the importance of considering the variance reduction. In the second case, as shown in Fig. 10.17b, the strength of the stabilised soil is ranked as α_2. In this case the mixing quality has a lesser influence, but still significant.

Production quality assessment

For the quality assessment of columns with respect to the strength and continuity, the average value may be of greatest importance for most applications. The uncertainty in the evaluation of the average value is probably decisive for the total uncertainty since the part which is governed by the spatial correlation structure is significantly decreased by the variance reduction (Olsson 1986). As discussed in Chapter 8, hand-penetrometer tests are not suitable for production quality assessment. The volume tested is too small and the results with respect to the determination of strength properties are questionable.

In the early stage of the lime-cement column method development, it was concluded that static penetration tests were unsuitable for production quality assessment because of the small test-volume and the difficulty of knowing the exact position of the probe (Boman et al. 1980). In cooperation with the Swedish National Road Administration, Torstensson (1980) developed the lime column probe, which is the most used column penetrometer test today.

The most used field test methods for production quality assessment in the Nordic countries are column penetration tests. These methods are reviewed and discussed by Axelsson (2001) and Axelsson & Larsson (2003). Fig. 10.18 shows results from column penetration tests from Arboga together with results from unconfined compression tests and triaxial tests on 50 mm diameter samples. There is a considerable difference in strength over the column length that is most likely a consequence of the different soil layers and variation in soil properties. Soil layering and large variations in the soil properties are typical for the region around the Lake Mälaren. The results show clearly that the soil composition has a considerably influence on the strength properties. Considerable variation can be seen in results from samples taken at shallow depths. The coefficient of variation is about 0.5 at 0-4 m and is about 0.15 for samples taken at 4-5 m. The upper layer consists of a crust with grey-brown, low sensitive, soft clay with a water content being below the liquid limit. This type of soil is known to cause mixing problems when the overburden stress is low. As shown in Fig. 10.18 the column penetration tests show less variation in the test result due to the large volume investigated. There is also a small variation between the different penetration tests. In

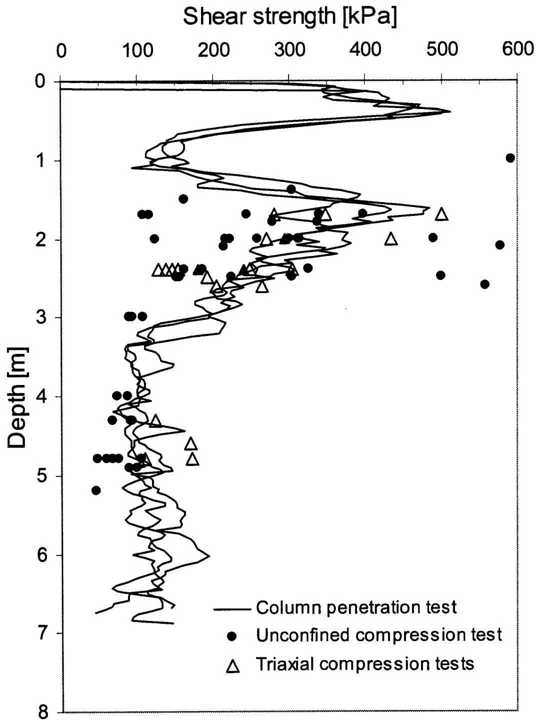


Fig. 10.18 **Comparison between the evaluated undrained shear strength from column penetration tests, unconfined compression tests and from triaxial tests (Axelsson & Larsson 2003).**

order to assess an average value from the small 50 mm diameter samples, a number of samples must be taken from different parts of the column cross-section. Single test can give misleading results. The main conclusion from this study is that the most suitable method for quality assessment is still column penetration tests and reversed column penetration since a relatively large volume has been tested.

These observations are strengthened by the results from this thesis. The scale of fluctuation with respect to the small scale tests is less than 300 mm. Consequently, the results from single tests where a small volume is tested can be misleading. Small scale tests such as the standard penetrometer test, SPT, and vane test can thus be unsuitably due to the small probe sizes. Sampling for the determination of the binder content must be done in a sufficiently large scale, preferable the same size as the scale of scrutiny. Sampling by auger boring or core drilling can be unsuitable due to the small scale and the uncertainty of knowing the position of the sampler device.

Economical view

The discussion has been focused on the spatial variability and the influence on the strength variability with respect to variance reduction. However, the mixing process also has a significant influence on the strength magnitude, i.e. the strength magnitude and the variability are not independent variables. It is therefore convenient to briefly discuss the influence on the strength magnitude. A higher strength magnitude and a lower variability is of course favourable, but is it economically reasonable to use the mixing work to adjust the strength magnitude compared to use the binder type and content as the primary instrument to adjust the strength magnitude? Furthermore, is it economically reasonable, by means of the mechanical mixing process, to regulate the variation in the properties in the stabilised soil due to different soil compositions?

The stabilisation effect S_{eff}, defined as the average strength in the stabilised soil divided by the strength in the unstabilised soft soil, was found empirically to be approximately a function of the logarithm of the blade rotation number T , according to Fig. 9.10. The effect of the mechanical mixing with respect to the blade rotation number depends on a great number of factors, such as soil composition, binder type and content, time, and the curing conditions. The mixing has different influences in different type of soils types which is clearly shown by the two field tests in Håby and Strängnäs, Fig. 9.10. The increase of the stabilisation effect as a function of the logarithm of the blade rotation number indicates that it may be uneconomical to use the mechanical mixing to adjust the strength magnitude.

The average cost, for a column can be simplified and expressed as the sum of a fixed cost and a variable cost. It is assumed that the variable costs for installation is inversely proportional to the retrieval rate and thereby proportional to the blade rotation number divided by the number of blades on the mixing tool. Consequently, the effect of the retrieval rate on the cost depends on the proportion between the fix cost and the variable cost. When the variable cost is high in relation to the fixed cost, the retrieval rate may have a considerable influence on the total cost. It may be profitable to increase the mixing work with respect to the retrieval rate only if the share of the variable costs is low.

The most rational course of action to increase the strength magnitude and to improve the mixture quality is to provide the mixing tool with more blades or construct mixing tools that achieves more mixing work. It is the author's belief that the strength magnitude should be adjusted primary by the binder type and amount of binder. In layered soils a series system must be considered, i.e. a weakest link system. It is economically defensible to concentrate on the right type and amount of binder for the weakest part or layer.

10.7 CONCLUSIONS

The concept of sufficient mixture quality has been discussed with respect to the mechanical system, the scale of scrutiny, and the correlation structure of the strength over column cross-sections. The correlation structure and the scale of scrutiny have been evaluated based on the results obtained from the field tests in Håby and Strängnäs where the strength was indirectly evaluated from hand-operated penetrometer tests on excavated column sections in test pits. Based on the consideration of an averaging failure, with a parallel failure system, the variability obtained from small scale tests were reduced with respect to a variance reduction factor. The variance reduction factor depends on the scale of scrutiny and the scale of fluctuation, which in this case were determined by experimental semivariograms.

Statistical analysis of variances, ANOVA, were performed in order to investigate whether the retrieval rate, the number of blades on the mixing tool, the type of mixing tool, the rotational speed; the air pressure in the storage tank, or the diameter of the outlet hole on the mixing tool have an influence on the scale of fluctuation.

The chapter also briefly consider design consideration with respect to the mixing process, the influence on the strength magnitude from an economical point of view and some considerations concerning production quality assessment.

Based on the results from the analyses presented in this chapter, the following conclusions can be drawn;

a) Different types of correlation structures can be obtained between different columns in spite of the fact that they were equally installed. The mechanical mixing work does not significantly influence the type of correlation structure.

b) The results from the analysis of variances, ANOVA, show that none of the investigated factors have a significant influence on the scale of fluctuation.

c) The results are an indication that the mechanical mixing work, with respect to the blade rotation number, influences the spatial correlation structure, expressed as the scale of fluctuation, in a relatively small scale, only a few cm. The observations from the tests indicate that the spreading and incorporation of the binder in the early stage of the mixing process are the crucial factors and have the determining influence on the binder dispersion and the spatial correlation characteristics over the column cross-section.

d) The evaluated scale of fluctuation is in the same range at the two test sites, 0-0.3 m. The reduction factor with respect to the coefficient of variation, evaluated from the hand-operated penetrometer tests, is approximately in the range 0.5 to 0.3 for a column section where the considered area is in the range 25% to 75% of the column area.

e) A simple consideration shows that the possibility to utilize variance reduction and the assignment of the sensitivity factor have a major influence on the determination of the partial factor of safety.

f) The most rational course of action to increase the strength magnitude and to improve the mixture quality is to provide the mixing tool with more blades or construct mixing tools that achieves more mixing work. It is not considered profitable to increase the mixing work with respect to the retrieval rate.

g) The most suitable method for production quality assessment is still column penetration tests and reversed column penetration since a relatively large volume is tested. Single test from small size tests or small size samples can give misleading results due to large variabilities. The test or sample size for single test should preferable have the same size as the scale of scrutiny.

It is not possible to give general recommendations for the specifications regarding the mechanical mixing work since design values for strength properties depends on the mechanical system, the scale of scrutiny, the spatial correlation structure, and the concept of safety, i.e. the concept of sufficient mixture quality is problem specific.

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