FINNISH ROAD ADMINISTRATION

Pentti Lahtinen

Fly Ash Mixtures as Flexible Structural Materials for Low-Volume Roads

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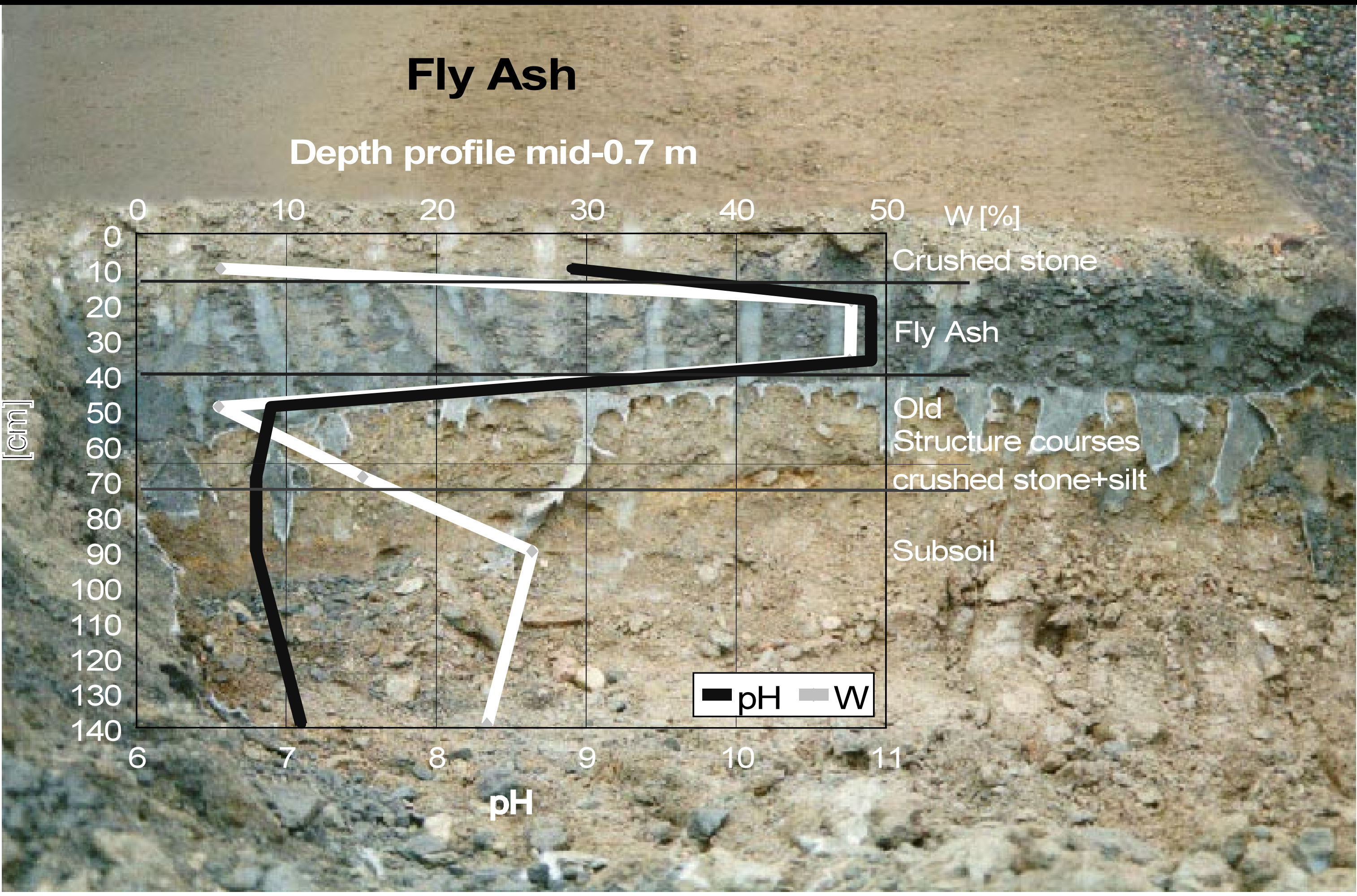

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Pentti Lahtinen: Lentotuhkapohjaiset seokset alempiasteisten teiden elastisena rakennemateriaalina. [Fly Ash Mixtures as Flexible Structural Materials For Low-Volume Roads]. Helsinki 2001. Tiehallinto, Uudenmaan tiepiiri. Finnra Reports 70/2001. 95 s. + liitt. 55 s. ISSN 1457-9871, ISBN 951-726-826-2, TIEH 3200716E.

Asiasanat: uudelleenkäyttö, jätteet, sivutuotteet, tierakennusaineet, tierakenteet, rakentaminen, geotekniikka, ympäristövaikutukset, alempiasteiset tiet, soratiet, lentotuhka

Aiheluokka: 55

TIIVISTELMÄ

Suomessa tehtiin 1990-luvulla lukuisia tutkimuksia teollisuuden sivutuotteiden maarakennushyötykäytöstä teollisuudelle, tielaitokselle ja kunnille. Pääosa tutkimuksista tehtiin SCC Viatek Oy SGT:n laboratoriossa yhteistyössä julkisten tutkimuslaitosten kanssa. Tämä väitöskirja keskittyy Suomessa syntyvien tuhkien ja niiden seosten maarakennushyötykäyttöön. Tuhkat ovat peräisin kivihiilen ja biopolttoaineiden poltosta ja niistä on tehty seoksia erilaisten muiden teollisuuden sivutuotteiden kanssa.

Tutkimusten yhteydessä on kehitetty uusia NRC-materiaaleja (NRC on lyhennelmä sanoista New Recycling Construction) ja –rakennesovellutuksia alempiasteisille teille. Samassa yhteydessä on kehitetty ja testattu sekä laitteita että työmenetelmiä NRC-rakenteiden tekemiseksi. NRC-materiaaleja, -rakennesovellutuksia, laitteistoja ja työmenetelmiä, ts. NRC-teknologiaa on testattu yhteensä 33 koerakenteessa. Materiaalien sekoitus osoittautui erittäin tärkeäksi tekijäksi NRC-teknologian onnistumisen kannalta. Tutkimusprojektien yhteydessä onnistuttiinkin löytämään useita hyvin soveltuvia menetelmiä ja laitteistoja tähän tarkoitukseen.

Väitöskirjaan liittyvissä tutkimuksissa kehitettiin uusia lentotuhkapohjaisia materiaaleja, kuten; a) rakennekerrosmateriaaleja eri tyyppisistä tuhkista, kuitu-tuhkista, kipsi-tuhkasta ja kuona-tuhkasta, b) vanhan rakenteen stabilointiin soveltuvia lentotuhkapohjaisia sideaineseoksia, ja c) pehmeiden maiden, kuten turve-, lieju- ja savimaiden, massa- ja pilaristabilointiin soveltuvia lentotuhkapohjaisia sideaineseoksia. Nämä tutkimukset osoittavat, että biopolton tuhkat, joiden maarakennushyötykäyttöä on aiemmin tutkittu varsin vähän, ovat teknisesti ja ympäristöllisesti osittain jopa parempia kuin kivihiilen polton tuhkat. Tutkimuksilla on voitu osoittaa, että tuhkilla voidaan usein korvata perinteisiä sideaineita kerros-, pilari- ja massastabiloinnissa. Tämän lisäksi on onnistuttu kehittämään aivan uusia materiaaleja sekoittamalla tuhkiin kuitulietettä, prosessikipsiä tai terässulattokuonaa. Näiden seoksien ominaisuuksia voidaan muuttaa eri materiaalien seossuhteita muuttamalla. Alempiasteisilla teillä korostuvat lämmöneristävyys, muodonmuutoskestävyys ja kantavuus. Erityisesti kuitutuhkaseokset ovt myötölujenevia ja omaavat suuren muodonmuutoskestävyyden, mikä tekee ne lähes rikkoutumattomiksi.

NRC-materiaalien tutkimus- ja testausmenetelmät ovat kehittyneet tutkimuksen aikana. Tutkimuksissa on mm. pitkäaikaiskestävyyden tutkimukseen soveltuvia testaustapoja ja arviointikriteerejä. Tutkimuksien yhteydessä on voitu osoittaa, ettää NRC-materiaalien pitkäaikaiskestävyys on tutkittava erityisesti routa- ja jäätymissulamiskokeiden avulla. Pelkästään lujuus-muodonmuutos –tutkimuksilla ei vielä voida tehdä johtopäätöksiä materiaalien pitkäaikaiskestävyydestä.

Myös NRC-materiaalien ympäristökelpoisuutta on tutkittu sekä laboratoriossa että koerakenteissa. Useat pitkäaikaisliukoisuustestit antavat varmuutta näiden materiaalien erittäin vähäisestä riskistä ympäristölle. Tuhkien molybdeeni on aiheuttanut paljon keskustelua, minkä vuoksi molybdeenin liukenemista ja kulkeutumista tyyppirakenteissa on tutkittu dynaamisen kulkeutumismallin avulla. Tutkimus osoitti, että molybdeenista aiheutuva riski on erittäin vähäinen, ja että ko. mallia voisi soveltaa myös muiden aineiden kulkeutumisen tutkimiseen.

Tutkimusten perusteella on voitu osoittaa, että tuhkaan pohjautuvilla NRC-materiaaleilla voidaan rakentaa teknisesti hyvin toimivia ja perinteisiin kiviainesrakenteisiin verrattuna selvästi kestävämpiä rakenteita. NRC-teknologialla on saavutettavissa myös oleellista taloudellista säästöä, kun otetaan huomioon rakenteiden koko elinkaari. Lisäksi NRC-teknologia on osoittautunut kestävän kehityksen mukaiseksi menetelmäksi, sillä tutkittuja materiaaleja käyttämällä voitaisiin säästää jopa 24 % uusiutumattomista sora- ym. luonnonvaroja. Samalla vähenee tarve teollisuuden kaatopaikkoihin sekä soranottoon aroilla pohjavesialueilla.

Pentti Lahtinen: Inblandningar av flygaska som flexibla gravelvägars strukturer. Helsinki 2001. Vägförvaltningen, Nylands vägdistrikt. Finnra Reports 70/2001. 95 s. + bilagor 55 s. ISSN 1457-9871, ISBN 951-726-826-2, TIEH 3200716E.

Nyckelord: Återvinning, avfall, biprodukter, vägbyggmaterial, vägkonstruktioner, vägbyggnad, geoteknik, miljökonsekvenser, tillämpningar, gravelvägar

SAMMANFATTNING

På 1990-talet genomfördes flera undersökningar på användningen av industriella restprodukter i jordbyggandet. De mesta av dessa undersökningar gjordes av SCC Viatek Oy tillsammans med industrin, vägverket och kommuner. Denna doktorsavhandling fokuserar på de mångsidiga möjligheter att använda askor och deras inblandningar som jordbyggnadsmaterial. Askor kommer från brännandet av kol och biobränsle, och de har inblandats med olika andra industriella restprodukter. Det huvudsakliga syftet är att bevisa på vilka villkor olika NRC-material är åtminstone lika bra, t.o.m. bättre än naturligt sten material för grusvägarnas strukturlager (NRC = förkortning av ord New Recycling Construction).

I samband med undersökningarna har vi utvecklat nya NRC-material och strukturtyper för grusvägar. Därmed har man utvecklat, applicerat och testat både verktyg, maskiner och arbetsmetoder för byggandet av NRC-strukturer. NRC-teknologi med flygaska har testats tillsammans i 33 testbyggnader. En lyckad NRC-tillämpning är särskilt beroende på den inblandningsmetod som används. I samband med olika forskningsprojekt har man lyckat att finna flera passande metoder och maskiner för inblandningen.

I undersökningarna för min avhandling har man utvecklat nya material baserade på flygaskor, liksom a) askor, fiberaskor, gipsaskor och slaggaskor som byggnadsmaterial för olika strukturlager, b) bindemedel med flygaskor för stabiliseringen av gamla grusvägsstrukturer och c) bindemedel med flygaskor för mass- och pelarestabiliseringen av mjuka jordtyper liksom torv, lera och gyttja. Dessa undersökningar har givit prov på, att bioaskor, som tills vidare har undersökts endast i liten grad, är på tekniska och miljö grunder delvis t.o.m. bättre än kolaskor. Därtill har man bevisat, att askor kan ofta kompensera traditionella bindemedel för mass- och pelarestabiliseringen. Man har också lyckats att utveckla alldeles nya material genom att inblanda askor med fiberslam, processgips eller stålsmältningsslagg. Egenskaper av dessa inblandningar kan man modifiera med olika inblandningsproportioner. För grusvägar understryks sådana egenskaper som värmeisoleringsförmåga, deformationsbeständighet och bärförmåga. Fiberaskornas relativt stor deformationsbeständighet innebär, att dessa är nästan obruten.

Undersöknings- och testmetoder för NRC-material har också utvecklats under olika FoU-projekt. Detta gäller lämpliga metoder att optimera materialegenskaper samt testmetoder och kriterier för att bestämma materialens långtidsbeständighet. Det har varit möjligt att bevisa, att långtidsbeständigheten av NRC-material skulle undersökas med tester på tjäl- och frysning-smältningsbeständigheten. Spänning-deformationstester är inte tillräckliga för detta ändamål.

Även NRC-materialens miljöduglighet har undersökts både i laboratoriet och med fälttester. Resultat av tester på den långtidiga lakningen övertygar, att dessa material inte innebär någon miljörisk. Askorna innehåller t.ex. molybdenium, vilkas miljöskadlighet har mycket diskuterats i Finland. Därför har man undersökt molybdeniums lakning och transport från vägens strukturlager till omgivningen med en dynamisk transportsmodell. Enligt resultat är molybdenium en mycket liten risk för miljön. Transportsmodellen kan användas för dylika undersökningar också på andra element.

På grund av undersökningarna har vi blivit övertygade, att NRC-material kan användas för att bygga tekniskt funktionella och beständiga vägstrukturer i jämförelse med de traditionella grusvägsstrukturer. NRC-teknologin är också ekonomiskt konkurrensduglig på grund av de besparingar, som kan vinnas under en grusvägs hela livscykel. Därtill är NRC-teknologin en hållbar jordbyggnadsmetod, då genom att utnyttja de undersökta materialtyper är det möjligt att spara t.o.m. 24 % av oersättliga naturtillgångar som grus och annat stenmaterial, och behovet av deponier samt grustäkter på känsliga grundvattenområden blir mindre.

Pentti Lahtinen: Fly Ash Mixtures as Flexible Structure Materials for Low-Volume Roads. Helsinki 2001. Finnish Road Administration, Uusimaa Region. Finnra Reports 70/2001. 95 p. + app. 55 p. ISSN 0788-3722, ISBN 951-726-826-2, TIEH 3200716E.

Keywords: recycling, waste, residues, by-products, road materials, road structures, applications, construction, geotechnics, environmental effects, low-volume roads, gravel roads, fly ash

SUMMARY

Extensive research and several studies have been carried out on the recycling of industrial by-products in soil construction in Finland in the 1990's. The research and studies have been made mainly in the laboratory of SCC Viatek Ltd SGT in co-operation with the public research institutes. The main beneficiaries have been the industry, the national road administration and the municipalities.

The Doctoral Thesis focuses on the versatile usage opportunities of the fly ashes (FA) from the combustion of coal and biofuel like peat and wood and their mixtures with certain other industrial by-products in soil construction. The main objective of this thesis is to show the conditions and premises on which the NRC (New Recycled Construction) -materials are at least as viable or even more viable than the natural stone materials in the applications for low-volume roads. The research and studies have succeeded in the development of new materials and structure applications for low-volume roads, proper equipment and work methods to manufacture the NRC-structures and proper test methods for the quality assurance of the materials.

The new FA-based construction materials include; a) materials based on FA, fibre-ashes, gypsum-ashes and slag-ashes for NRC-solid structures; b) binder admixtures based on FA for the stabilisation of old road structure courses; c) binder admixtures based on FA for the mass-column stabilisation of soft soil. It has been shown that FA from biofuel that have been studied relatively little so far may have even better geotechnical properties than the FA from coal. Additionally it has been possible to attain a versatile array of materials by mixing the FA with fibre sludge (outcome: fibre-ashes), process gypsum (outcome: gypsum-ashes) or stainless steel slag (outcome: slag-ashes). The properties of the different mixtures can be regulated by changing the proportion of different components. Thus, it has been possible to find proper materials for low-volume roads that require high heat insulation, deformation durability and bearing capacity.

The studies on the test methods have been focused on the methods and criteria to optimise the properties and to assess the long-term durability of the NRC-materials. It has been possible to show that the most important methods to assess the long-term durability are the tests for frost susceptibility and the freeze-thaw durability. It is not possible to judge the long-term durability of NRC-materials with the mere stress-strain tests. Also the environmental impact of the NRC-materials has been studied both in the laboratory by leaching tests and in the full-scale test structures with samples of soil and groundwater. The studies include also the use of a mathematical dynamic transportation model to predict the distribution of molybdenum from the coal ash structures to the environment surrounding the structures. The environmental studies indicate that there is no environmental risk involved in the use of FA-based materials in soil construction, assuming that the materials are used in a proper way.

NRC-technology will make the sustainable road construction possible. The durable NRC-structures will be economically viable alternatives to the conventional stone structures. Additionally it will be possible to save even 24 % of the non-renewable gravel and other natural resources, and there will be less need to use land for deposits or for stone intake at sensitive groundwater areas.

LIST OF PAPERS

This thesis is based on the following papers, which are being referred to in the text by roman numerals:

I Lahtinen, P., Jyrävä, H., Suni, H. (1999): **New methods for the renovation of gravel roads**. Paper for IRF Regional Conference, European Transport and Roads, Lahti 24-26. May 1999. 7 pages.

II Lahtinen, P., Fagerhed, J.A., Ronkainen, M. (1998): **Paper Sludge in Road Construction**. Paper for the Proceedings of the 4th International Symposium on Environmental Geotechnology and Global Sustainable Development, 9. - 13. August 1998, Boston (Danvers). University of Masschusetts, Lowell, pp. 410-419. 9 pages.

III Lahtinen, P., Jyrävä, H., Kuusipuro, K. (2000): **Deep Stabilisation of Organic Soft Soils**. Paper for the Proceedings of the Grouting Soil Improvement Geosystems including Reinforcement of the 4th GIGS, the International Conference on Ground Improvement Geosystems, by the Finnish Geotechnical Society in Helsinki, 7-9. June 2000, pp. 89-98. 10 pages.

IV Lahtinen, P., Jyrävä, H., Suni, H. (2000): **New Methods for the Renovation of Gravel Roads**. Paper for the Proceedings of the NGM-2000, XIII Nordiska Geoteknikermötet, Helsinki 5. - 7. Juni 2000. Building Information Ltd., Helsinki, pp. 531-538. 8 pages.

V Lahtinen, P., Jyrävä, H., Suni, H. (2000): **Use of Industrial Wastes in the Construction of Low-Volume Roads**. Paper for the conference of Geo-Denver 2000, 5. - 8. August 2000. Proceedings pending. 11 pages.

VI Lahtinen, P., Palko, J., Karvonen, T. (2000): **Molybdenum transport in coal fly ash soil constructions**. Paper for Ecogeo-2000, International Conference on Practical Applications in Environmental Geotechnology, Helsinki 4. - 6. September 2000. Proceedings pending. 7 pages.

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My thesis is based on 12 years' research and development work, most of it in the geotechnical laboratory SGT of SCC Viatek Oy, and on the full-scale field tests of 33 different structures at different sites in Finland. Therefore, I am grateful to many people for assisting me, in several ways, during the work with the thesis.

First of all I would like to express my gratitude to SCC Viatek Oy, and especially to Jaakko Heikkilä, the managing director, and Mikko Leppänen, the director of geotechnics, for their support and encouragement to produce this thesis. Also, I would like to thank the personnel of SGT for their impact on the work; to Aino Maijala who has helped me to collect and edit the research material; to M.Sc. Harri Jyrävä with whom I have created ideas and developed many of the innovations for the work; to Marjo Ronkainen, Tero Jokinen, Elina Ahlqvist, and Marjatta Jaakkola for their important work and studies carried out in the laboratory and at the field test sites; and to Ms. Terttu Salmela for her help in editing this thesis for its publication.

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- Fortum Heat and Power Oy
- Helsinki Energy
- Pohjolan Voima, PVO
- Avesta Polarit Oy
- Kemira Phosphates Oy, Kemira Chemicals Oy and Kemira Pigments Oy

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I hope that all this work will have practical impact to increase the exploitation of the sustainable NRC-technology for the saving of our most valuable natural resources.

I am very grateful to Finnish Road Administration, Uusimaa Region and Pekka Kontiala for making it possible to publish this thesis.

Luopioinen 8.11.2001

Pentti Lahtinen

LIST OF SYMBOLS AND ABBREVIATIONS

5(F+L, 1:1) or 5(FL, 1:1)	Example of notation: Abbreviation for "5 % of an admixture of components F and lime. The proportion of the components is 1:1 in the admixture". Normally given in relation to the dry mass of the basic NRC-material
5Ce	Example of notation: Abbreviation for "5 % cement". Normally given in relation to the dry mass of the basic NRC-material
C or Ce	Cement in general
CaO or L	Lime
CC	Calcium chloride, $CaCl_2$; salt
D	Relative compaction; relative to the maximum Proctor density of the material [%]
dry FA	FA taken directly from the dust filters, from a silo or from another dry storage
F	Finnstabi® ; by-product gypsum from the production of TiO_2
FA	Fly ash, in general. The specific types of fly ash are expressed according to the type of fuel in the combustion: CFA = Coal fly ash MFA = Miscellaneous fly ash, i.e. fly ash from the combustion of mixed fuel like fibre sludge and wood PFA = Peat fly ash WFA = Wood fly ash
FGD or D	Flue gas desulphurization residue
FS	Fibre sludge
FW	Filterwaste or –cake from the production of CC
LoI	Loss of incineration [%]
M	Blast-furnace slag
n/a	not available data or information
NRC	i.e. "New Recycled Construction"; an abbreviation for "New construction based on recycled materials" (NRC materials, structures, construction, technology)
PG or G	Phosphogypsum
pile-FA	FA taken from an open-air storage (a pile, a lagoon), usually moist
S	Stainless steel slag
SGT	Geotechnical R&D unit of SCC Viatek Oy Ltd, the employer of the author, in Finland
SP_o	Segregation potential [mm^2/Kh]
T or THK2	Hydrated lime ($Ca(OH)_2$) or secondary hydrated lime with at least 50 % $Ca(OH)_2$
UCS	Unconfined compression strength
w	water content [%]; geotechnical
w_o	water content, optimum [%]

Table of Contents

1 INTRODUCTION

Fly ashes (FA) are being quite widely utilised in many countries. However, a significant part of these materials are still not recycled or are being deposited into landfills. Cement and concrete industries are the biggest users of FA having established standards for their use. Also in soil construction applications FA have significant usage potential but the efforts to develop other FA than CFA into construction materials have been minor and incomplete, to date. However, there are large soil construction markets for FA everywhere where the materials are being produced.

It has been found that it is possible to develop many new types of geotechnical applications based on FA with or without other industrial residues. However, every new type of material or application needs extensive technical and environmental studies, first at the laboratory level and finally at full scale. Expensive geotechnical instrumentation and long-term follow-up measurements at field test sites are required for the assurance of the technical and environmental acceptability of the new application.

The research for the doctoral thesis concentrated on FA from coal, peat, wood and mixed fuel combustion. Mixed fuels also include different types of sludge from the paper industry. The average annual production of FA in Finland is about 1,2 million tonnes (the annual variation of the production is relatively large).

The following FA applications have been studied for this research:

- FA as bearing and insulating courses in road construction [I, IV, V] [15]
- Mixtures of FA and paper sludge as bearing and insulating courses [II, V] [15]
- Mixtures of phospho-gypsum and FA as soil construction material [15]
- New FA-based binders for the stabilisation of low-volume roads [I, IV, V]
- New FA-based binders for soft soil stabilisation [III], [5]
- Mixtures of FA and stainless steel slag in road construction [15]
- Mixtures of FA and desulphurization residues (FGD) for geotechnical applications [5, 6, 15]

It is also necessary to study the total economical and environmental benefits of the new types of applications based on the use of FA in order to ascertain their advantages. The calculations have shown that the life-cycle costs of FA constructions will be about 30 % less than the life-cycle costs of competing (conventional) methods, even without considering the effect of residue taxes (I, IV, V). There are also factors that cannot easily be determined with any monetary value, like the savings of non-renewable natural resources and landscape, as FA compensate for natural stone materials. For example, gravel pits are normally situated in important groundwater areas, and the excavation of these pits involves grave risks to the groundwater. Recycling of FA and FA-mixes in soil construction would reduce the use of stone materials by about 20-30 % of the total annual amount needed for conventional soil construction at present. In individual cases the savings of stone materials could be even larger, 50-70 %.

Another important question is the total environmental impact of the FA applications in the long term. With environmental dynamic modelling it has been possible to show that FA applications are really minor risks to the environment. The dynamic modelling is a mathematical method that calculates the transport of critical substances from a construction course to the environment, by combining the results of long-term leaching tests of FA materials and the data on the properties of the surrounding soil material. [VI]. Also many full-scale test structures that have utilised soil and water sampling and analyses for many years have proved that FA applications are environmentally safe [15].

2 LITERATURE REVIEW

The utilisation of coal fly ash (CFA) in soil construction applications has been studied in many countries in Europe, Asia and North America. Many of the road construction applications have been based on stabilised or self-cementing CFA of different strength levels, and on different granulated ashes. [7]. CFA has been applied in all parts of road structures, from the embankment to the pavement. For example, in Indiana in the United States they have developed highway embankment materials based on a mixture of CFA of Class F and bottom ash. [4]. The applications of the basecourses have mainly been

a. stabilised, rigid CFA structures having high strength
b. with or without activator stabilised half-rigid CFA structures
c. stabilised old structural layers where reactive CFA have been used as binders or as components of a binder admixture

Bergeson and Barnes [35] reported that in rigid structures the unconfined compressive strength of the CFA basecourse was more than 5,6 MPa and in half-rigid structures the strength was 1,4 – 4,5 MPa.
Outside Finland there are only a few published studies on the soil construction utilisation of FA from the combustion of biofuels like peat and wood. However, these materials are equal and sometimes even better than CFA in their usage potential in soil construction applications. Another range of soil construction applications of relatively scarce research is the use of FA together with other industrial waste materials. There are some studies (unpublished studies of the European phosphate industry) on the upgrading of phospho-gypsum with FA, and several other studies on the use of FA mixed with desulphurization residues [8]. The use of steel melting slags in soil construction has been researched in the Ukraine [34]. However, mixtures of FA with different fibre sludges from the paper industry appear to have been studied only in Finland [15].

It has been proven that FA are adequate binder components for the stabilisation of soft soils. For this use FA have been studied and developed both in Japan [14] and in Finland [5] [III].

The properties of FA depend on the type of fuel and on the combustion technology. Therefore the properties of a certain FA may significantly differ from the properties of a FA from another source. In the United States the FA are being categorised into classes C and F. C-ashes are self-cementing and pozzolanic and contain more free lime (CaO) than F-ashes. The F-ashes are also pozzolanic and able to gain significant strength with the help of activators [9,10]. Based on the former categorisation most of the Finnish FA are F-ashes. The F-ashes primarily result from the burning of anthracite or bituminous coals, and the C-ashes from the burning of lignite or subbituminous coals. [4]. The Canadian Standards Association specification for FA (CSA A23.5) classifies FA according to the calcium content (CaO-content); low-calcium FA having less than 8 % CaO, medium class having 8-20 % CaO and high-calcium class having more than 20 % CaO. According to the former classification most of the Finnish FA falls in the low-calcium cathegory. There are many studies on the factors affecting the reactivity of ashes. The reactivity is especially affected by the relative quantity of LOI (loss of ignition), CaO, SiO_2 and Al_2O_3, and evidently the specific surface of the FA [e.g. 2, 11]. The pozzolanic activity of F-ashes increases as the grain size decreases.

The properties of a FA begin to change immediately as it is mixed with water or with water and activator. In practice this means that the longer a FA batch mixed with water and/or activator is waiting for compaction the lower its final strength will become. The use of dry FA has generally not been possible because of the absence of separate dry storage facilities. Therefore, there have been studies on the geotechnical properties of FA that have been stored in open air as moisturised piles before construction. In most cases, these pile ashes have to be used with activators, especially when adequate freeze-thaw durability is required. Also, when dry FA is used in practical construction processes there will be a delay before spreading and compaction of the material layers, after the FA material is moisturised into its optimum water content and mixed with activator(s). This delay has to be considered when performing laboratory tests. The studies indicate [12] that after mixing in the laboratory, a delay of 0,5 hours gives relatively correct results although the delay in practice might be much longer, as much as several hours during the same day. The studies of SGT (the geotechnical R&D unit of SCC Viatek Ltd in Finland) [15] have confirmed the former, and that more accurate results can be achieved with a delay from 1 to 2 hours after mixing in the laboratory.

The improvement of FA properties with binders or activators has been a widely studied topic. The most general activators have been different types of lime, cement, gypsum, desulphurisation residue (later FGD), slag and reactive dry FA. There are many studies that indicate that a small addition of lime can significantly improve the strength and durability of FA materials [2,6,12]. Majumbar, in a study conducted in India, indicated that lime addition up to 10 % could improve the strength, after which there is no further improvement [2].

The quality of a finished FA structure will be affected by the properties of the FA itself, the delay after mixing (see above), the water content, the activator(s), and also other factors. These other factors include the effectiveness of mixing, the precision of component proportions in mixing and especially the level of compacted density obtained in the mix. The strength of a well-compacted material layer can be many times higher than the strength of a poorly compacted material layer [2]. In addition, a poorly compacted material layer might not have the required durability properties.

Structures based on FA or mixes with FA have very good long-term cementing properties [12, 35]. In Berg and Bergeson's study [12] the strengths of four different lime-stabilised FA sharply increased during the first 3 months after stabilisation, after which the strength development continued more slowly for at least a year, and probably for much longer. The pozzolanic reactions probably continue as long as there is free lime and water available in the stabilised material [12]. Several studies have also shown that the long-term cementing property is the reason for the self-healing mechanism of a FA layer [7,12]. In some cases the strength development of the FA structure was adequate, and the structure was performing similar to a stabilised base of crushed aggregate, despite cracking [12].

The durability of stabilised FA against weather and external load have been studied with several types of methodology. It has been found that it is not sufficient to determine the strength by using the most general unconfined compression (UCS) test only. It is also necessary to test the stability of material properties in dry, wet and saturated conditions. The stability of material properties can be determined as the change in the compression strength and as the loss of mass. The studies indicate that most of the FA materials are relatively stable at different moisture conditions [12]. The frost susceptibility, and especially the freeze-thaw tests are more demanding of most of the FA materials. In frost susceptibility tests, the worst performing FA material lost all of its strength or proved to be too frost susceptible. There exist several standardised methods for freeze-thaw tests. Some of the standardised tests measure the loss of mass during the freeze-thaw cycles, for example until the loss of mass is 50 % [12]. The durability is determined on the basis of the number of freeze-thaw cycles. Other tests are performed with a constant quantity of freeze-thaw cycles, and the durability is determined on the basis of the loss of material strength during the test. Poor durability can usually be seen even at the start of the test. These tests have proven to be very important for materials that will be used in arctic climates with freezing soil in the winter. The freeze-thaw behaviour of a material cannot be forecasted on the basis of unconfined compression strength, although the standard ASTM C 593 test requires freeze-thaw durable material to have a minimum strength value (UCS) of 2,8 MPa. The studies of SGT [e.g. 15] have repeatedly shown that there are materials with lower strength and adequate freeze-thaw behaviour. Mixtures of fiber sludge with FA, which have strength much lower than 2,8 MPa, are especially durable against the strains of freeze-thaw cycles.

Usually different durability tests have been conducted as separate tests on a certain construction material. SGT has also studied the effects of combined durability in its laboratory. These studies have shown that the results of combined durability tests may clearly differ from the results of separate tests [15].

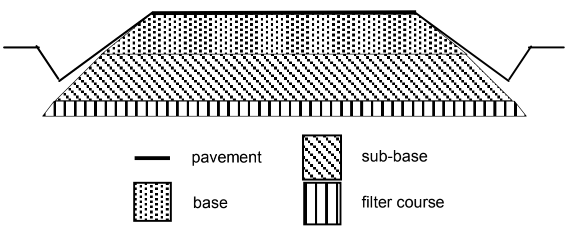
The environmental acceptability of FA applications has been widely studied in different countries. One extensive laboratory study has been done in the United States [33]. This study involved ashes from 20 different power plants. The ashes were tested with different types of leaching tests that simulated different conditions. The study concluded that according to the leaching behaviour none of the ashes can cause any harm to the environment. FA filling on a large construction area in Maryland also proved the environmental safety of FA. The average thickness of the fill was 5 meters and the total amount of FA was about 15 million tonnes. The environmental control at the site was multi-faceted for over 15 years. The results showed that the discrete FA filling did not affect the quality of the deep ground water. The substances of the leachates that were released from the fill have been bound into the soil or upper ground water in the close vicinity of the filling site [13]. Several test constructions based on FA and FA-mixes in Finland [e.g. 15] support the results of the research mentioned above, and conclude that properly processed and used FA materials are environmentally safe. Perhaps an important contributing factor limiting the use of FA is the lack of knowledge about the uses of FA in construction among professionals and environmental authorities. Educational programmes, demonstration projects, and technology transfer programmes would certainly help in that regard. However, the largest constraint to more extensive utilisation of FA might be the drawbacks of environmental legislation in different countries.

3 RESEARCH PHILOSOPHY AND METHODOLOGY

3.1 NRC-structures

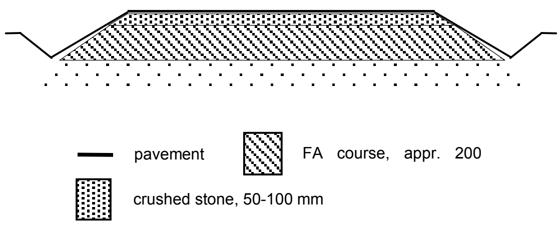
NRC ("New Recycled construction"; abbreviation for "New construction based on recycled materials") -technology aims at technically, economically and environmentally competitive solutions. Conventional road structures are based on natural stone materials and have to be made relatively thick in order to obtain adequate bearing capacity and frost resistance of the structures.
The use of FA mixes will make it possible to obtain properties that can be used to totally change the type and behaviour of a road structure. *Figure 3-1* describes the differences between conventional structures and NRC structures based on FA mixtures:

CONVENTIONAL STRUCTURE



- A thick structure → large consumption of natural stone materials and large settlements of clayey soils
- High embankment and deep excavation
- Water infiltrating through the pavement → the surface may be conveyed under the structure courses
- Stone material might become pulverized under the dynamic load on the structure
- The different structure courses might become mixed with each other
- Fines from the subsoil may be pumped up to the structure courses
- Poor deformation durability

NRC (FA) -STRUCTURE



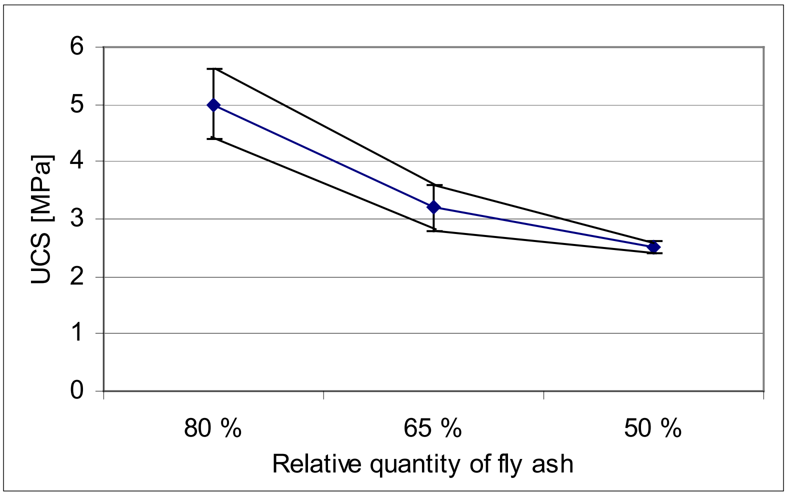
- Minor need for natural stone materials
- A frost insulating structure of light weight
- A thin structure → narrower area of land needed for construction → no additional clearing for renovation
- A thin structure → low embankment and excavation, and smaller settlements of clayey soils
- Low permeability of the FA course: the water infiltrating through the pavement and the crushed stone course will flow along the surface of the FA course → e.g. less water into the frost susceptible courses below the FA course in the autumn
- The different structural courses will not become mixed with each other
- High deformation and long-term durability
- Economical

Figure 3-1: Differences between the conventional structures and the NRC (FA) -structures

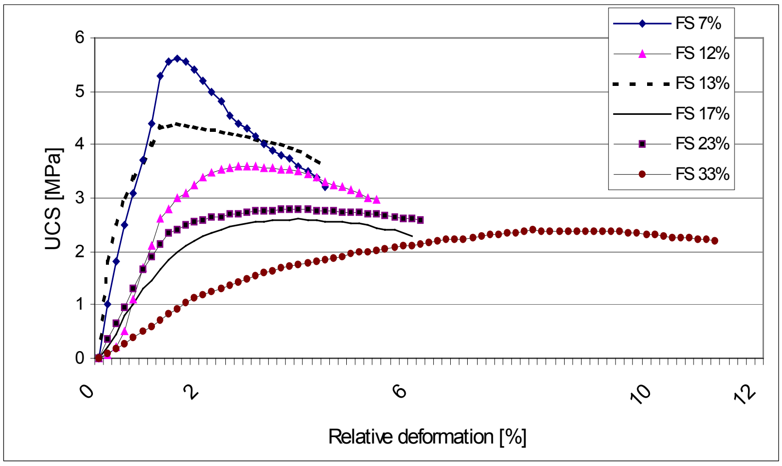
3.2 Upgrading material properties

3.2.1 Proportion of components in the material mixes

The requirements for the properties of a FA-mix depend on the requirements that have been specified for the structure; its bearing capacity, differential settlement etc. The combination of the mix properties can be modified relatively freely. Examples are given in *Figure 3-2;* by varying the proportion of the FA and the fibre sludge in the material mix properties like strength, deformation, durability and permeability can be changed. With an increasing proportion of fibre sludge the material decreases in ultimate strength and in modulus, but exhibits an increasing ultimate strain. With a sufficient proportion of fibre sludge the material becomes elasto-plastic, for example the material with 20 % of fibre sludge in *Figure 3-2b*. The former indicates that required properties for an application may be obtainable by changing the proportion of mixture components. For example, in order to obtain high bearing capacity (e.g. for highways), the amount of fibre sludge has to be relatively small. In case the road has to be frost resistant, and resistant against deformation caused by consolidation settlements (e.g. secondary roads), the amount of fibre sludge should be relatively large.



3-2 a.

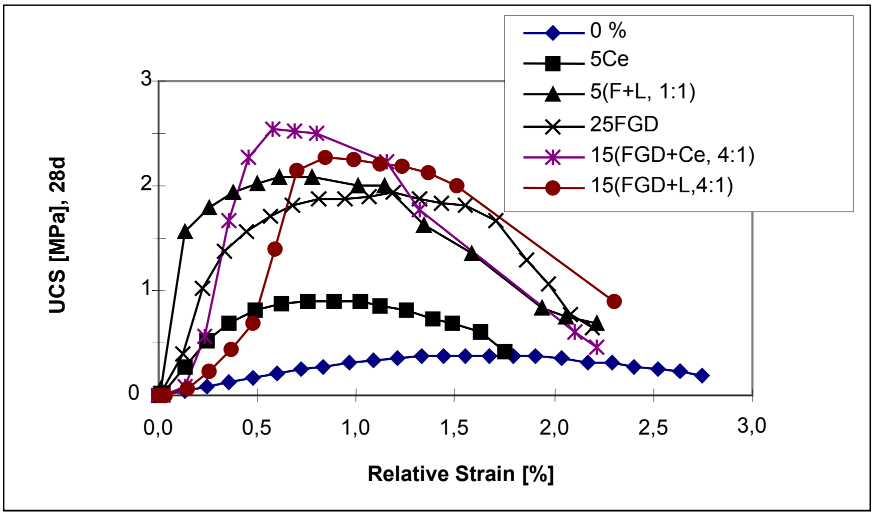


3-2 b.

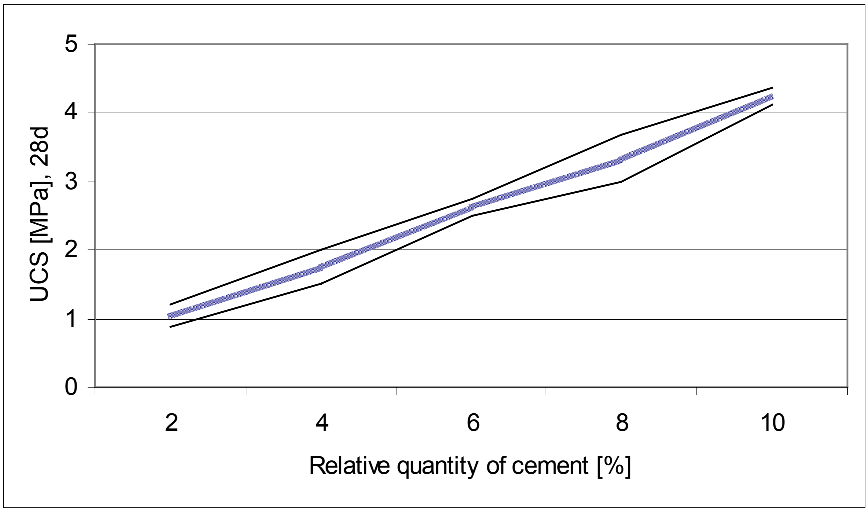
Figure 3-2: Modification of the properties of a FA-mix, i.e. a mix of FA and fibre sludge:
a) strength modified by changing the relative quantity of FA,
b) strength-strain modified by changing the relative quantity of the fibre sludge (FS). Strength development of test pieces for 28 days before testing [15]

3.2.2 Stabilisation

In addition to the variation in component proportions the properties of FA mixes can be improved and modified with different binders or stabilisers and with their proportion in the mixes. *Figure 3-3* shows an example of the stabilisation of a certain CFA with different binders, and the effect of the binder quantity on the stress-strain properties of the material:



3-3 a.

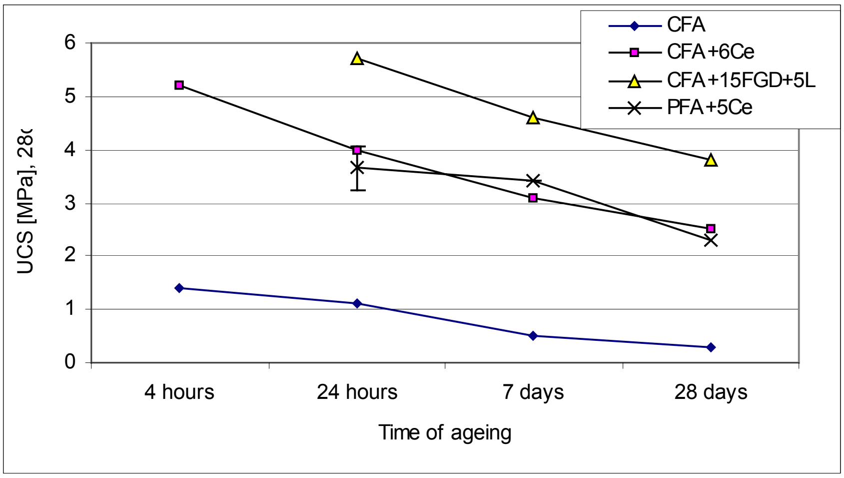


3-3 b.

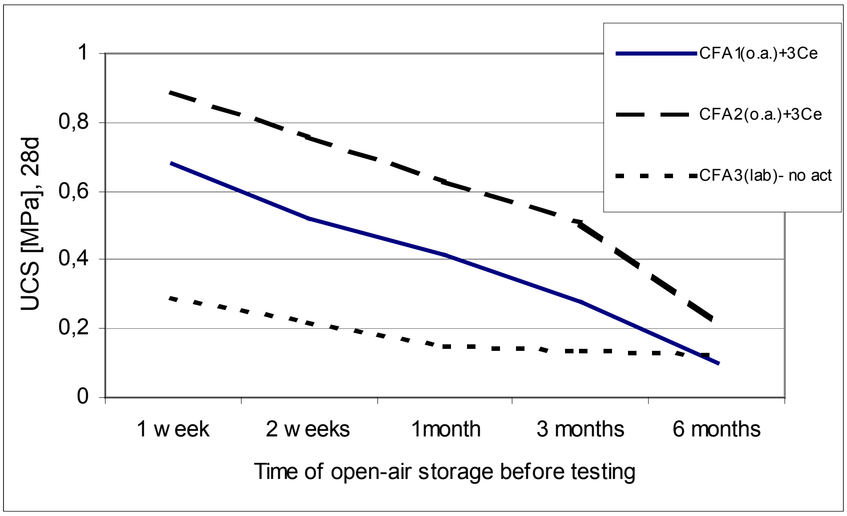
Figure 3-3: Examples of the effect of; a) different binders on the stress-strain properties of a CFA [6], b) the quantity of cement on the strength of a CFA [15]

3.2.3 Storage

The FA properties vary considerably depending on the type and properties of fuel, on the combustion technology and on the storage system. Dry storage (e.g. a silo) does not have any negative effect on the FA properties. If the FA will be stored in an open-air deposit the pile-FA will be moisturised, which affects its properties. This can be clearly seen in *Figures 3-4 a. and b.*, which show the weakening of the self-cementing properties as the compression strength of a certain CFA changes. For the laboratory ageing the CFA was at first moisturised and stored for a given time, relative to the open-air storage time. After storage the CFA was mixed with an activator when required. The test pieces were compacted to a Proctor density of D = 90-92 %. *Figure 3-4a* shows that the compression strength decreased during the first 28 days (1month) after moisturising, and Figure 3-4b shows that the cementing properties slowly became weaker as the open-air storage time became longer. Therefore, FA from dry storage (dry FA) has to be considered as an essentially different material than a pile-FA of the same origin.



3-4 a.

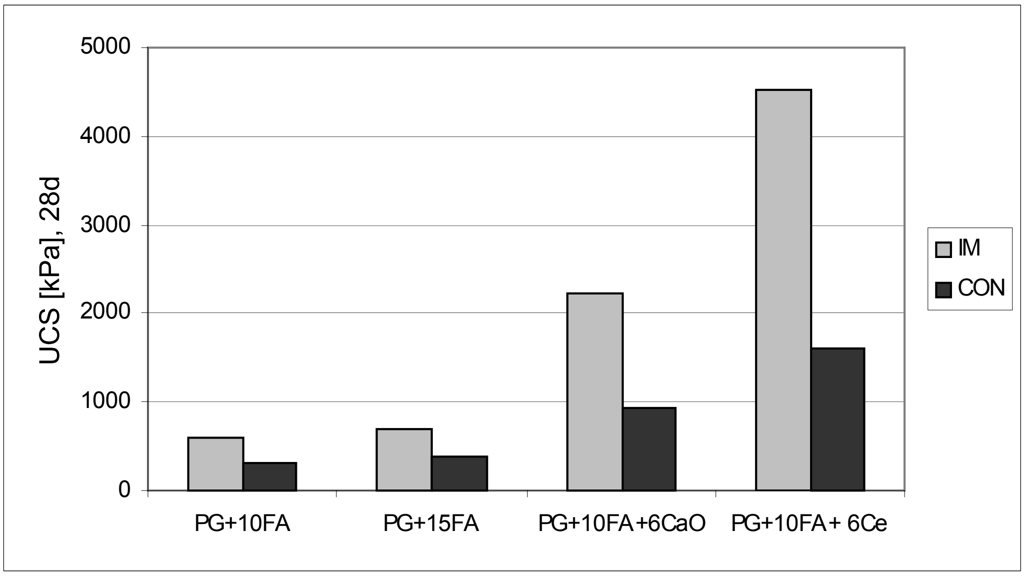


3-4 b.

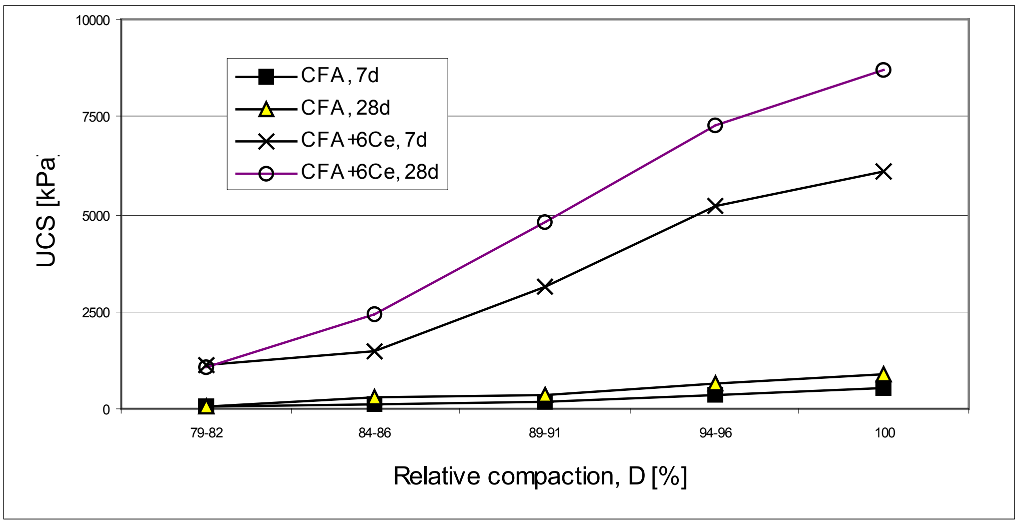
Figure 3-4: Effect of moisturising and storage on the stress-strain properties of some coal FA; a) Open-air storage from 4 hours up to 28 days. All materials were laboratory-aged. b) Open-air storage from 7 days to 6 months. CFA1 and CFA2 were samples from actual open-air storages. CFA3 was a laboratory-aged sample. [15]

3.2.4 Mixing and compaction

The properties of a NRC-material that is finally used in construction can be significantly affected by the mixing technology, its effectiveness and its dosage accuracy in the manufacturing of the material. The work methods during the actual construction process, especially the compaction method, might also have an important effect on the final outcome. *Figure 3-5a* shows the differences in the properties of a gypsum-ash mixture after a conventional batch mixer (CON) and a counterstroke or impact mixer (IM); see also *Figure 5-11*. The high-speed reverse motion of the drums of the impact mixer cause the material particles to heavily strike on each other and, consequently, the microstructure of the material to break. This can be seen in the SEM-photos of *Figure 3-6*. *Figure 3-5b* gives the results of a study on the effect of the relative compaction on the strength development of a CFA and a cement-stabilised CFA.



3-5 a.



3-5 b.

Figure 3-5: a) differences in the properties of a gypsum-ash mix after it has been mixed with a conventional (CON) and with an impact mixer (IM) and b) the effect of the relative compaction on the strength development of a CFA and a cement-stabilised CFA [15]

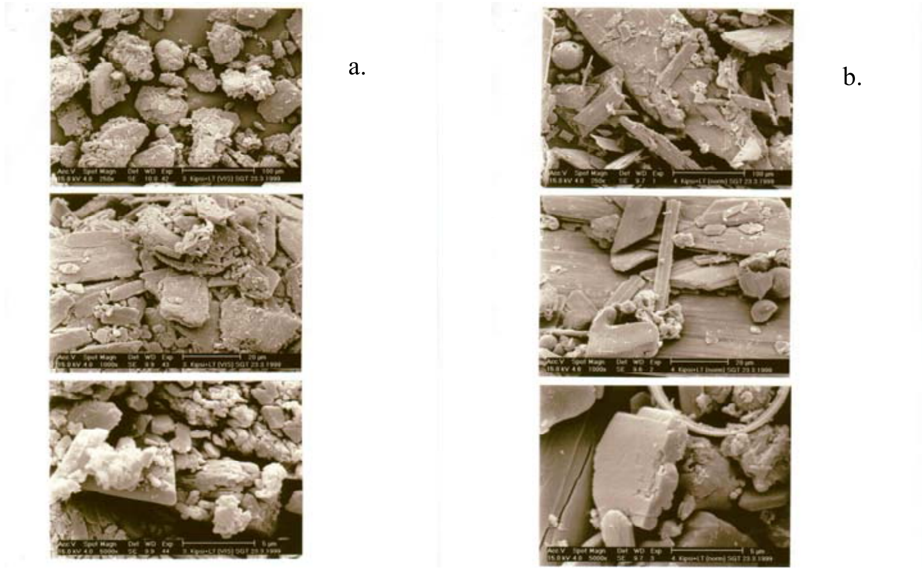


Figure 3-6: SEM-photos of gypsum-ash mixes by a) the impact mixer (IM) and b) the conventional batch mixer (CON)

3.3 Criteria and acceptability tests on materials

3.3.1 Criteria on materials

Geotechnical requirements

The geotechnical requirements that a NRC-material has to meet depend on the requirements set on the structure where the material will be used, and on the final design of the structure. The requirements for the structure include criteria on its bearing capacity, differential settlement, durability and life time. For this reason it is beneficial to optimise the material and the structure simultaneously.

Concerning NRC-structures for road and field applications there should be established geotechnical criteria for at least the following factors:

– Strength and rigidity
– Frost resistance and frost susceptibility
– Effect of saturation on the strength
– Freeze-thaw durability

Additional criteria could be the following:
– Bulk density
– Thermal conductivity
– Compressibility
– Dynamic load resistance
– Water permeability
– Resistance against acid infiltration or any other chemical load

Table 3-1 below gives several criteria that have been suggested in the published papers [I … V] and in reports [e.g. 5, 6, 15, 16].

Table 3-1: Suggested geotechnical criteria

Geotechnical Classification of NRC- materials		Unconfined compression strength [MPa], minimum	Frost susceptibility (segregation potential) SP_o [mm^2/Kh]	
			NRC in general	Fibre-ashes
A	Very strong	4,5	0,2	0,5
B	Strong	1,5	0,2	0,5
C	Fair	0,5	0,5	0,7
D	Weak	<0,5	0,5	1,2
E	No strength development	-	-	-

Assessment of the durability of NRC-materials		
Tests for the properties	Maximum decrease of the unconfined compression strength after the test [%]	Other recommendations
Freeze-thaw durability	40	Test pieces are solid and unbroken after test
Water retention capacity	30	
Frost heave	30	-
Infiltration of water	20	No visible erosion
Combined test	The result after the most severe test + 5%	

Environmental acceptability

A NRC-construction has to be environmentally sound; i.e. construction utilising recycled materials should not cause pollution of groundwater or soil. This is also strictly stated in the national legislation on waste and environmental protection [17,18]. One of the major problems in Finland is a missing set of criteria on the environmental acceptability of recycled materials for soil construction. The leaching and transport of different elements and substances from FA mixtures have been tested widely and for a long time, and both factors have been studied at the laboratory level and on different field test sites. The long-term impact can also be studied with dynamic transport models (see Section 6.3*)*.

3.3.2 Testing of materials

It has been found useful to carry out the development of a new FA mixture according to a step by step procedure suggested in *Figure 3-7*.

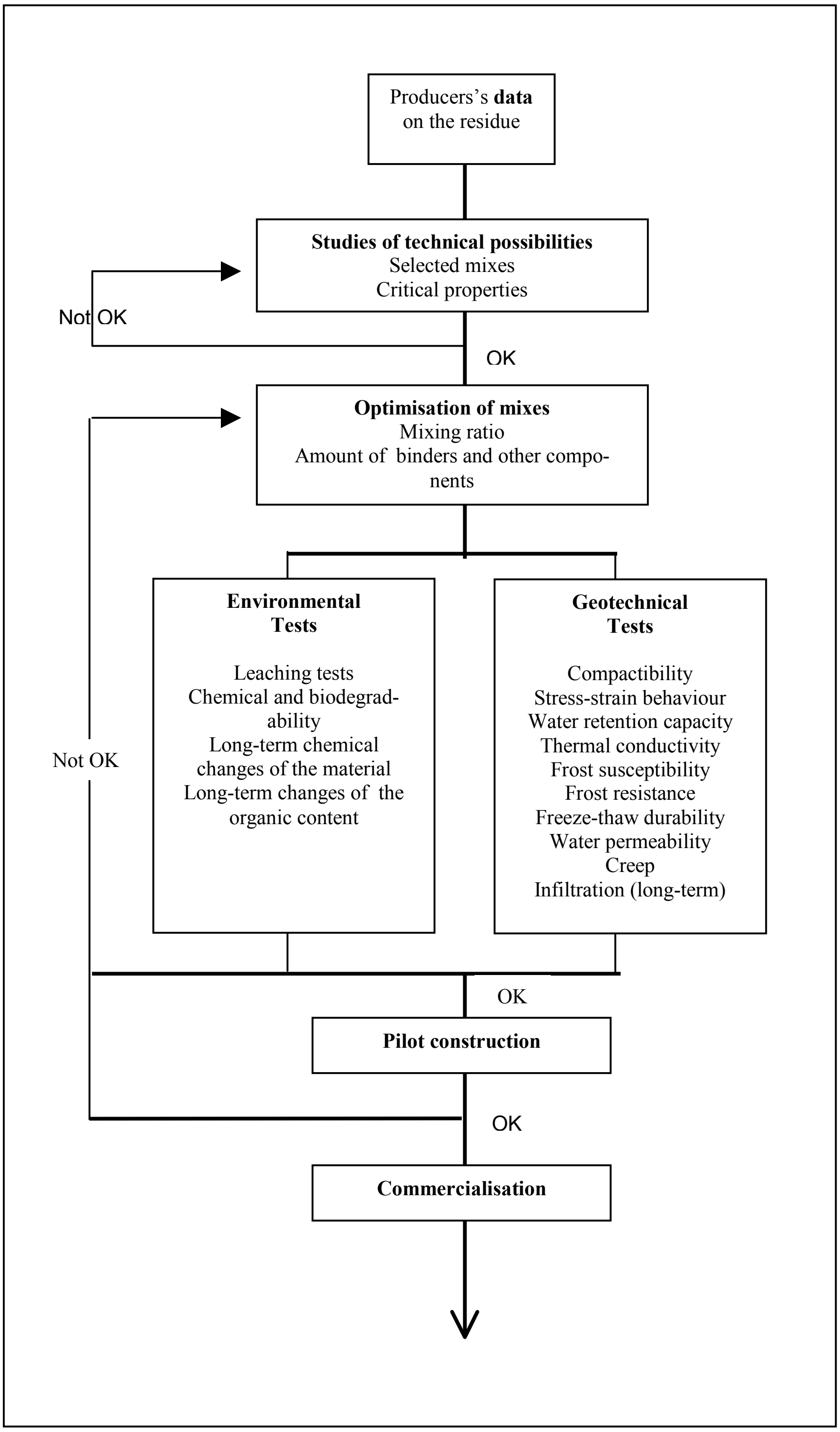


Figure 3-7: Development process of a recycled soil construction material (based on industrial residues) [15] [V]

At the first stage of the development procedure, basic geotechnical properties and the total content of a wide range of inorganic elements of the FA will be determined. The results will be used to make a preliminary assessment on the potential technical and environmental risks and the possibilities for risk management in connection with the FA.

The outcome of the first stage will be used to choose alternative mixtures, i.e. binders and other components, for the second stage of optimisation (optimisation of mixes). The optimisation aims at the determination of a mixture that meets the basic acceptance criteria and is an iterative process. At first, screening tests will be conducted on the selected mixes to determine certain critical geotechnical properties (e.g. stress-strain and freeze-thaw properties). The choices for the final and more detailed optimisation will be made on the basis of the results from the screening tests.

The third stage will involve final tests on one or a few of the best alternatives for their geotechnical and environmental properties and durability. The material mixes that do not meet the criteria can be improved e.g. by increasing the proportion of a binder and tested again - or rejected (e.g. in case there are several alternatives at this stage).

Finally, it is preferable that the best alternatives are tested in full scale (at pilot test sites) after the laboratory tests. Though these full-scale tests are expensive and of long duration, this is a necessary stage, particularly as there exist no officially established acceptance criteria for the NRC-materials and structures and/or national decrees that guide the use of industrial residues in soil construction.
Following is a concise survey of the test methods that the author recommends for the tests of *Figure 3-7*:

Compactibility

The compactibility of the NRC-material will be determined by using the modified Proctor test while simultaneously determining the maximum bulk density (dry), $\gamma_{d,max}$, and the optimum water content, w_{opt}, of the material. The resultant relative compaction D [%]= $(\gamma_d/\gamma_{d,max})*100$.

Stress-strain behaviour (UCS)

A cylindrical test piece is subjected to a steadily increasing axial load until failure occurs (standard unconfined compression test, see *Figure 3-8a*.). The axial load is the only force or stress applied. The rate of the load is 1 - 2 mm/min. If there is not any noticeable failure, the maximum value of the compressive strength is taken when the deformation (change of height) is 10 %.

Water retention capacity

The water retention capacity is determined by immersing the test piece in water for 7 days, after the test piece has been stabilised for at least 21 days. The condition of the test piece will be assessed during the immersion. After this the strength (UCS) of the test piece will be determined.

Thermal conductivity

Thermal conductivity is determined according to ASTM D 5334-92 (Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure).

Frost susceptibility

The test piece will be compacted in a plastic cylinder and the test will start after 28 days stabilisation and after the test piece has been saturated with water. The frost susceptibility will be tested with special test equipment that allows the upper side of the test piece to become frozen (- 3°C) and the under side to remain thawed (+ 1°C) and absorb water on a capillary carpet, see *Figure 3-8b*. At the start during water saturation the load on the test piece is around 20 kPa. The load on the test piece can be varied during the test, but normally it is around 3 kPa. The frost susceptibility will be determined by measuring the settlements or frost heave of the test piece over a certain time period. Segregation potential, SPo [mm^2/h], can be calculated on the basis of the frost heave.

Frost resistance will be determined by assessing the condition (eg. softening and lenses) and by determining the strength (UCS) of the test piece after the frost susceptibility test.

Freeze-thaw durability

Freeze-thaw tests are applications of a suggested test method of the Technical Research Centre of Finland (VTT:"Tien rakennekerroksissa käytettävän hydraulisesti sidotun materiaalin pakkas-sulamiskestävyyskokeen suoritus "): The test piece that has been stabilised for 28 days will be placed in a container on a capillary carpet. Water will be absorbed by the test piece through this capillary carpet. After 4 hours the test piece will be placed in a freezer, the temperature of which will be decreased from room temperature to freezing (-18 ^oC). The test piece will remain at this temperature for 8 – 16 hours. The test piece will then be rotated by 180^o and placed on the capillary carpet for thawing, after which the former stages will be repeated. These cycles will be repeated 12 times. The condition of the test piece will be controlled at all times during the test. After the test is completed, the strength (UCS) of the test piece will be determined

Water permeability

The permeability of a NRC-material is a measure of its capacity to allow a fluid (normally water) to filtrate or to flow through it.

The **rigid wall permeability** test with constant pressure can be carried out after the test pieces (inside plastic moulds) have been stabilised for at least 28 days. After this water will flow through the test pieces for the infiltration phase. The filtrates will be collected and weighed at certain time intervals. Darcy's coefficient of permeability (k) will be calculated.

Flexible wall permeability test with constant head is carried out according to the recommendations of the Environment Centre of Finland[1]. A test piece inside a rubber membrane will be subject to an all round confining pressure in a test cell. Water will be conducted through the test piece from a front container to a back container, and the water level differences of the containers will be measured. Water flows upward inside the test piece when there is higher pressure in the front water container than in the back container, see *Figure 3-8c*.

Infiltration (long-term acid permeability test)
A constant flow of acidified water (pH = 4 … 4,5) will be conducted through test pieces that have been stabilised for 28 days. Time for infiltration is 3 months (90 days). The leachate will be collected after infiltration for 30, 60 and 90 days. Water samples can be analysed and the results can be compared with column test results (in case environmental testing is necessary).

Changes of the strength characteristics of the test pieces will be determined with a unconfined compressive strength test after the infiltration, and the results will be compared with the results on stabilised test pieces without infiltration.

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[1] Tekes' National Programme on Environmental Construction / Geotechnics 1994-1999. TEKES = Technology Development Centre)

Creep test

The creep test provides information about the effect of pre-loading on the strength of the material by combining oedometer and long-term loading of the test pieces. Mixed materials are put inside plastic bags and placed into the moulds of Ø 68 mm. The moulds must be greased to allow free movement for the test pieces. Pieces are compressed with loads of 20, 40, 60 or 80 kPa for 180 days after which the unconfined compressive strengths will be determined.

Leaching tests

Leaching tests will determine potential environmental harm of soils stabilised with different binders after varying stabilisation times. Normally, the leaching test for stabilised NRC-material is the column test (Dutch standard NEN 7343, see *Figure 3-8d*). In a few cases the material density will become so high that it can be tested according to the diffusion test, e.g. the Dutch standard NEN 7345.

Biodegradeability

Biodegradability can be tested according to the OECD Method 301F (OECD Guideline 1992). This is discussed in Chapter 4.5.3.

Other environmental tests

Testing for chemical degradeability, and the long-term chemical changes or changes of the organic content do not have any specified methodology. These properties have not been studied in the projects that have been referred to in this Doctoral Thesis.

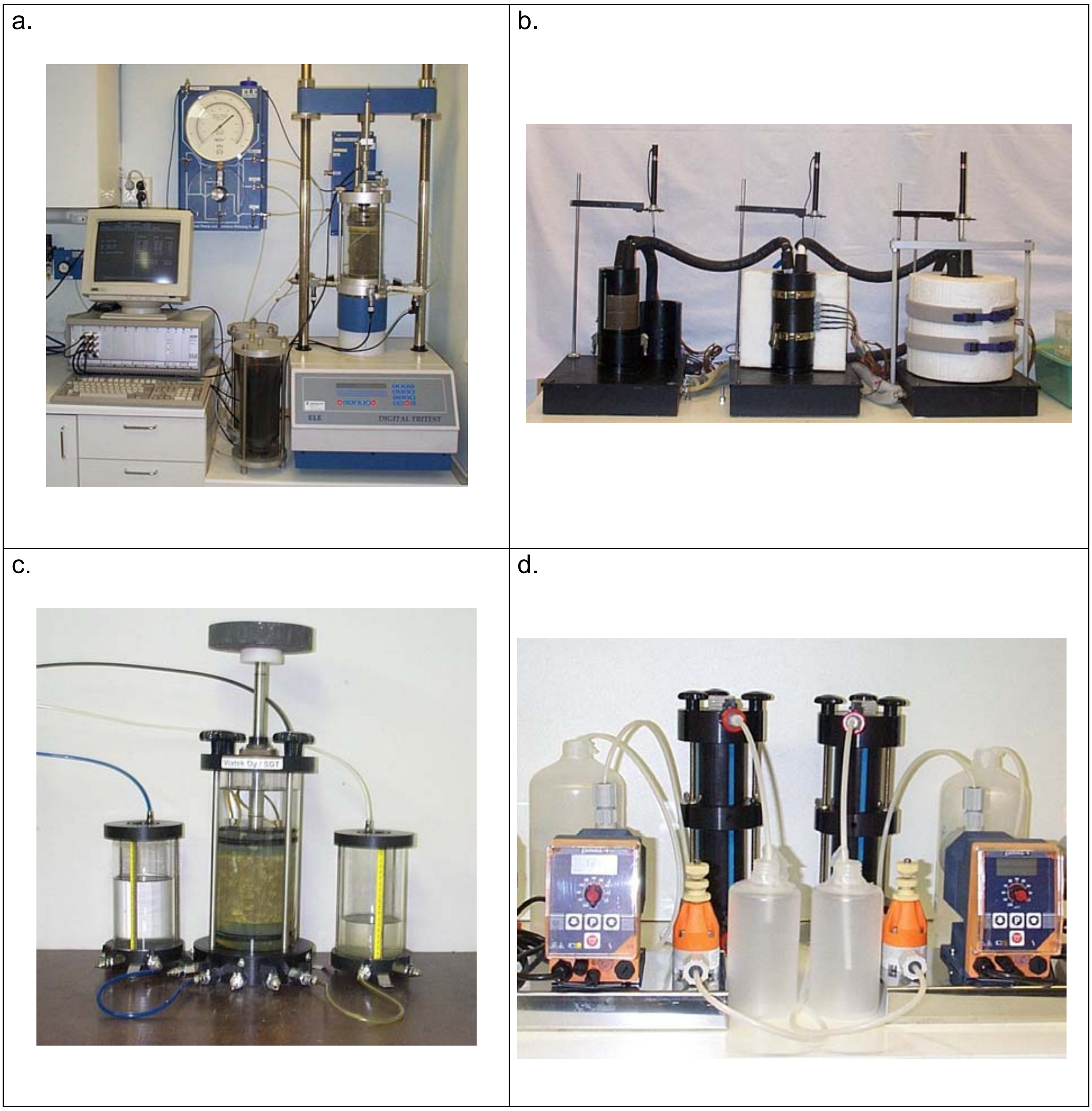


Figure 3-8: Equipment used for testing; a) Standard unconfined compresssion test, b) Frost susceptibility test; c) Flexible wall permeability test; d) Column test

4 MATERIALS AND APPLICATIONS

4.1 Fly Ashes (FA)

Out of the total annual production of FA in Finland half is CFA and half is from the incineration of fuels like peat (PFA), wood (WFA) and miscellaneous material (MFA). The miscellaneous materials include different types of sludge like fibre sludge (FS) from paper manufacturing, or sludge from the wastewater treatment processes of a paper mill.
A major part of the FA is not yet being utilised efficiently. However, soil construction is a field of high-volume applications that could easily and effectively recycle all available FA in Finland. CFA applications in soil construction have been developed and widely studied in the world, and for a long time. However, studies on FA based on other fuels are relatively scarse.
The studies and research for this doctoral thesis mainly concentrate on FA produced in Finland. The quality and properties of FA depend significantly on the type and properties of the fuel and on the incineration process itself. Also FA from individual power plants might vary from batch to batch. *Table 4-1* shows the variation in inorganic substances of the main FA categories in Finland.

Table 4-1: Inorganic substances of the main FA categories in Finland, mg/kg (Helenius 1992, Walsh 1997, Isännäinen 1997,SGT 1996-1998, Finncao 1998, Mäkelä et al 1999, SGT 1990-2000)

Inorganic substance / element		FA [mg/kg] based on different fuels			
		Coal	Peat	Wood	Misc.*)
Arsenic	As	19…57	2…284	…26	<10…120
Boron	B	…475	8…230	130…160	90…180
Barium	Ba	78…1600	55…790	115…1340	80…1700
Beryllium	Be	3…17	1…3	2	1…4
Cadmium	Cd	<0,5…16	0,5…19	0,8…11	<1…303
Cobalt	Co	21…49	13-33	7…23	6…30
Chromium	Cr	18…300	37…212	40…85	30…120
Copper	Cu	41…144	55…180	58…230	37…200
Quicksilver	Hg	0,1…1,1	0,01…0,6	0,2	<1
Manganese	Mn	430…792	-	-	-
Molybdenum	Mo	7…40	0,9…19	<5…14	<5…10
Nickel	Ni	23…1197	32…700	32…68	40…80
Lead	Pb	27…177	16…970	20…103	20…300
Antimony	Sb	0,2…15	…20	2…15	<13…130
Selenium	Se	2…6	2…7	…1,4	1…4
Vanadium	V	70…360	68…356	32…100	16…190
Zinc	Zn	38…1030	<20…900	300…1900	200…3200
Uranium	U	…12	-		

*) Miscellaneous fuel like peat/wood, peat/wood/sludge, peat/sludge, wood/sludge, coal/peat, coal/wood

Table 4-2 contains data on the most important chemical and geotechnical properties of FA. In general Finnish FA are F-ashes according to the classification in the United States, i.e. pozzolanic but only slightly self-cementing. In regard to the lime content (CaO) which might be larger than 20 %, some of the PFA, WFA and MFA could be classified as C-ashes [21]. The self-cementing behaviour varies significantly between different FA categories as can be seen in the data given in *Table 4-2*.

Since the pozzolan reactions immediately start after water addition it is clear that the cementing properties of a pile-FA are weaker the longer the storage time. This can be noted in *Figure 4-2*. Loss of Ignition (LoI), content of CaO, and the specific surface quite clearly correlate with the cementing behaviour of a FA [2,3].

Table 4-1 shows that PFA, WFA or MFA do not contain more environmentally harmful inorganic substances than CFA, and often even less.

Table 4-2 shows that in regard to pozzolanic reactions all types of FA have high contents of SiO_2 and Al_2O_3. Best self-cementing results, as high as 8-10 MPa after 28 days, have been obtained with PFA, WFA and MFA. In these cases the content of CaO was also high.

The optimum water content (w_o) also varies significantly. It is evident that the high content of CaO of PFA, WFA and MFA increases the optimum water content.

Table 4-2: Chemical and geotechnical properties of selected FA in Finland [6, 15, 22,23,24,25,26]. Figures given in parentheses are the mean values of the obtained data in case a range of data is given. Only one figure is the mean value of several measurements or test results

Fly ash	LOI	CaO	Fe_2O_3	SiO_2	Al_2O_3	MgO	C_q*)	Grain size, dry FA, d_{50}	Self-cementitious**) Dry FA	Self-cementitious**) Pile-FA, age-ing 28d	Bulk density (dry)	Water content, optimum/ w_o
	%	%	%	%	%	%	-	mm	kPa	kPa	kg/m³	%
CFA-A	5,6… 14,7 (9,0)	3,47… 9,4 (5,7)	7,7… 13,6 (8,8)	41,9… 53,4 (48,7)	16,6… 27,4 (22,9)	2,01… 5,9 (3,5)	0,54… 0,75 (0,66)	0,01…0,02	640…1310 (884) D = 100 % 380 D = 90 %	110 D = 90 %	720…850 (804) max dry den-sity 1220…1310 (1278)	22…27 (25)
CFA-B	1,5…3,4 (2,6)	3…3,9 (3,3)	6,1… 17,5 (9,6)	42,5	16,4… 22,7 (20,2)	n/a	0,58…0,62 (0,6)	0,015… 0,035	310…1660 (1030) D = 100 % 620 D = 90 %	200 D = 90 %	740…1090 (900) max dry den-sity 1290…1580 (1482)	13…26 (18)
CFA-C	6,1… 17,5 (10,0)	0,2…4,8 (2,3)	4,1… 17,0 (9,8)	42,9… 67,5 (54)	17,7… 25 (21,8)	0,5…3,3 (1,6)	0,33… 0,66 (0,49)	0,015… 0,04	330…1360 (692) D = 100 % 190 D = 90 %	180 D = 90 %	630…920 (804) max dry den-sity 1180…1360 (1292)	21…29 (24)
CFA	**1,5… 17,5 (7,2)**	**0,2…9,4 (3,6)**	**4,1… 17,5 (9,4)**	**41,9… 67,5 (48,4)**	**16,4… 27,4 (20,8)**	**0,5…5,9 (2,6)**	**0,33… 0,75 (0,6)**	**0,01…0,04**	**310…1660 (869)**	**163**	**630…1090 (836)**	**13…29 (22)**
Fly ash	LOI	CaO	Fe_2O_3	SiO_2	Al_2O_3	MgO	C_q*)	Grain size, dry FA, d_{50}	Self-cementitious **) Dry FA	Self-cementitious **) Pile-FA; age-ing 28d	Bulk density (dry)	Water content/ ω_o
	%	%	%	%	%	%	-	mm	kPa	kPa	kg/m³	%
PFA	**1…15**	**5…30**	**0…20**	**3…57**	**2…29**	**1…25**	**0,48**	**n/a**	**300… >9000**	**n/a**	**590…1500**	**20…79**
WFA	**5…34**	**40**	**3**	**30**	**7**	**5**	**1,7…1,8**	**n/a**	**1600… >8000**	**n/a**	**1000…1300**	**30…45**
MFA	**1…8**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**300… >10000**	**n/a**	**800…1600**	**18…57**

*) $Cq = coefficient\ of\ quality = \dfrac{CaO + Al_2O_3 + MgO}{SiO_2}$ [3]

**) *Self-cementitious is determined by the unconfined compression strength of a test piece after 28 days cementation.*

The strength development of a FA is less the larger the LoI value (i.e. the non-combustible part of the FA) and the smaller the percentage of CaO in the FA. *Figure 4-1* shows that even a very small (0,5-1,0 %) addition of active lime significantly improves the cementation. The figure shows, however, that there are differences between FA from different sources. Additionally, it has been shown that the larger the specific surface of a FA the better its strength development [2].

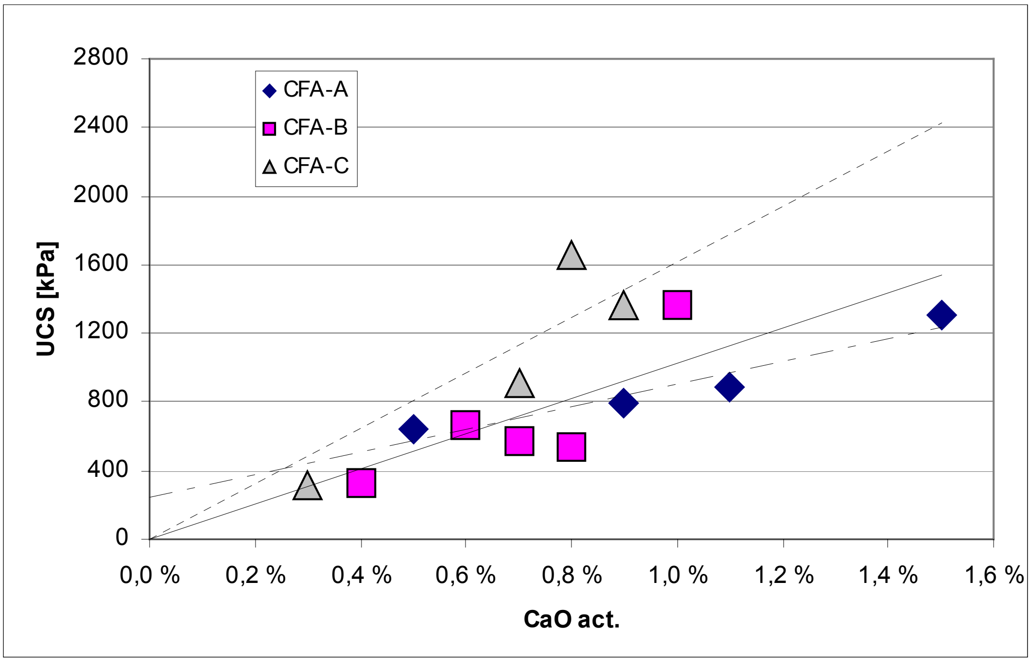


Figure 4-1: Unconfined compression strength as a function of the content of active CaO. The test was on CFA from three separate power stations [6]

The strength development of a FA will depend considerably on following factors as well:
- Binder or activator (quality, properties, quantity)
- Water content
- Compaction
- Homogeneity of the mixture
- Efficiency of mixing

The effect of the water content on the strength development and on the compaction of the FA is significant. Most importantly, the farther the water content of the FA is from the optimum water content the lower will be the resultant final strength. The following figures show test results on some FA: for the effects of water content, *Figure 4-2*, and compaction, *Figure 4-3*, on the strength. By using the tests showing the effect of different water contents it is possible to determine the tolerances for changes in water content in practice. Likewise, it is possible to determine the minimum relative compaction, D [%], by varying the relative compaction in the laboratory tests. Similarly, *Figure 4-3* shows the strength might fall significantly when relative compaction is less than 90-91 %. Therefore, the targeted relative compaction is 91-92 % for most of the FA structures.

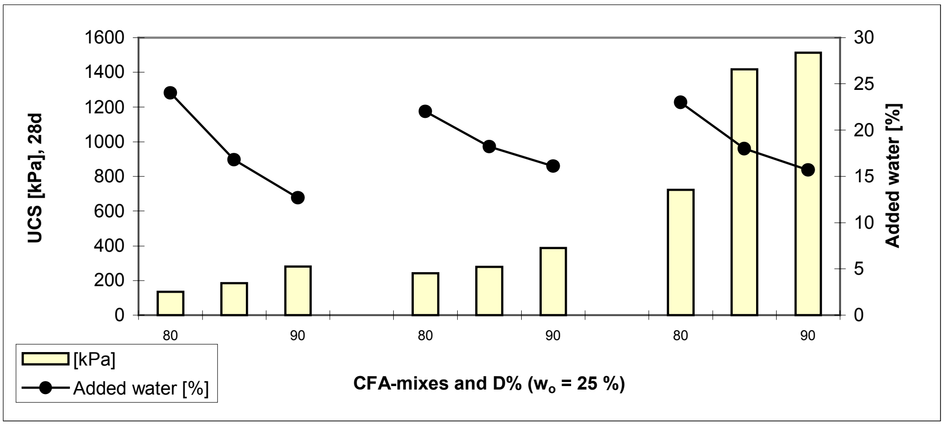


Figure 4-2: The effects of water content on the strength of some CFA-mixes **(examples)**

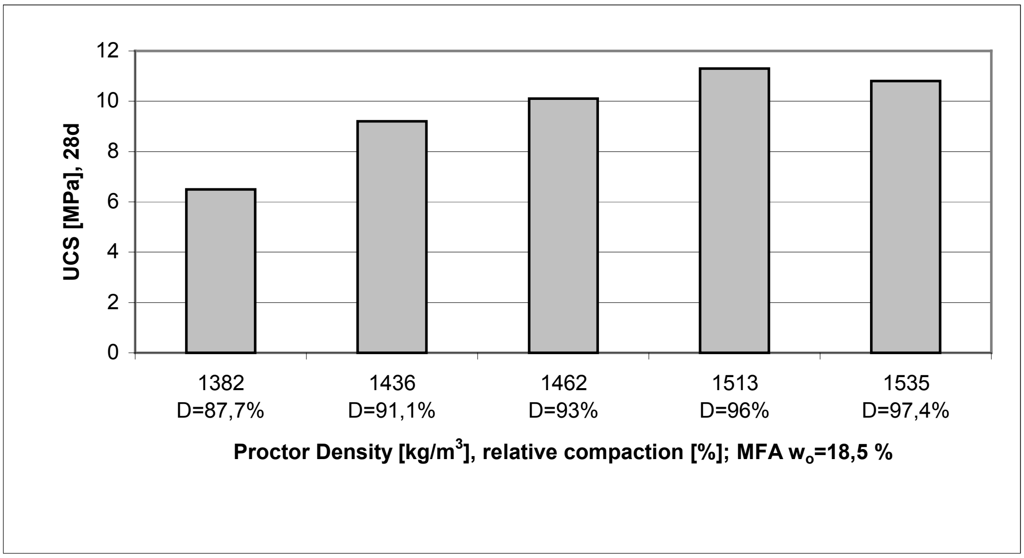


Figure 4-3: The effects of compaction on the strength of a MFA (example)

4.2 Improvement of FA properties with binders

Binders can be used to significantly improve the geotechnical and environmental properties of FA. Even a very small addition of binder as an activator for a dry FA may activate and accelerate the cementation reactions in the FA. Even 1 – 2 % of activator might multiply the strength of a FA material. To obtain sufficient strength of the material, the required binder quantity is considerably larger in the cases of pile-FA or other originally weakly cementing ashes [15].

There exist several binders or activators that can be used with FA. The most important binders are different types of lime and cement, as well as industrial residues like slag (especially the blast furnace slag), gypsum, reactive ashes and FGD (flue gas desulphurisation residues). Lime has proved to be a very efficient activator, and cement is very versatile. The use of industrial residues is reasonable because of the environmental and economic benefits, that can be obtained, and because it is also technically feasible. *Figure 4-4* shows the effect of cement quantity on the strength of three FA. The figure indicates that the strength of these three types of FA will be improved in an almost linear amount with an increasing amount of cement.

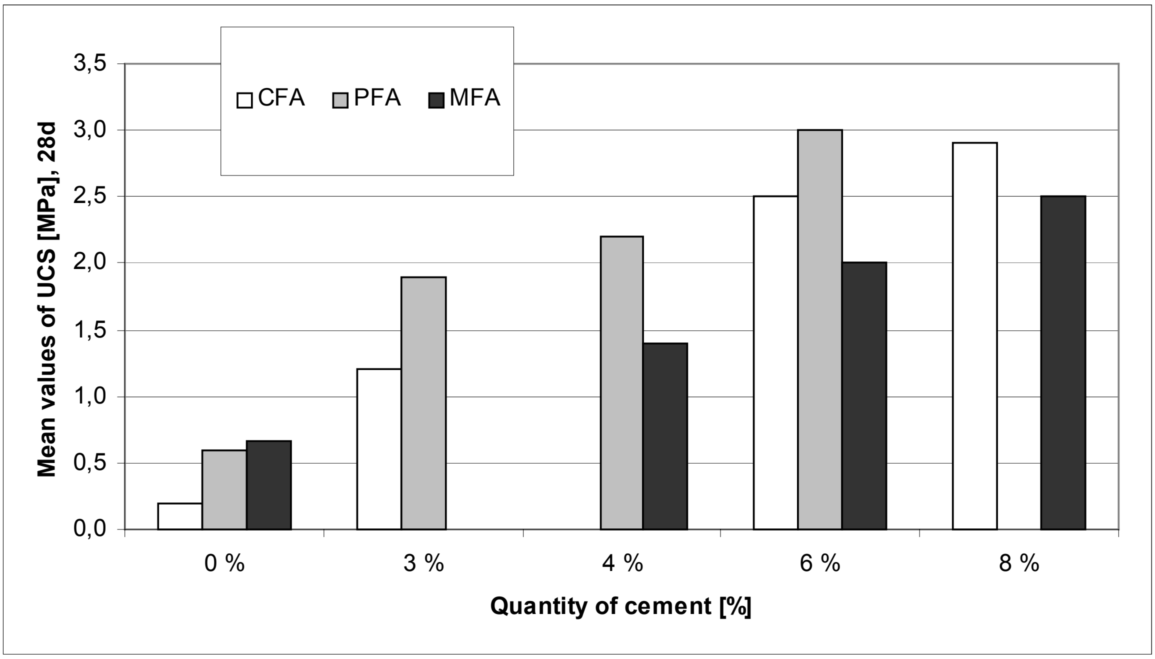


Figure 4-4: Effect of the quantity of cement on the unconfined compression strength of three different types of FA (examples of certain individual cases) [15]

It is obvious that the effects of binders and binder mixes are different for different FAs. *Figure 4-5* compares the effect of certain binders (all 6 % of dry weight) on different categories of FA samples of the different categories after 28 days of stabilisation.

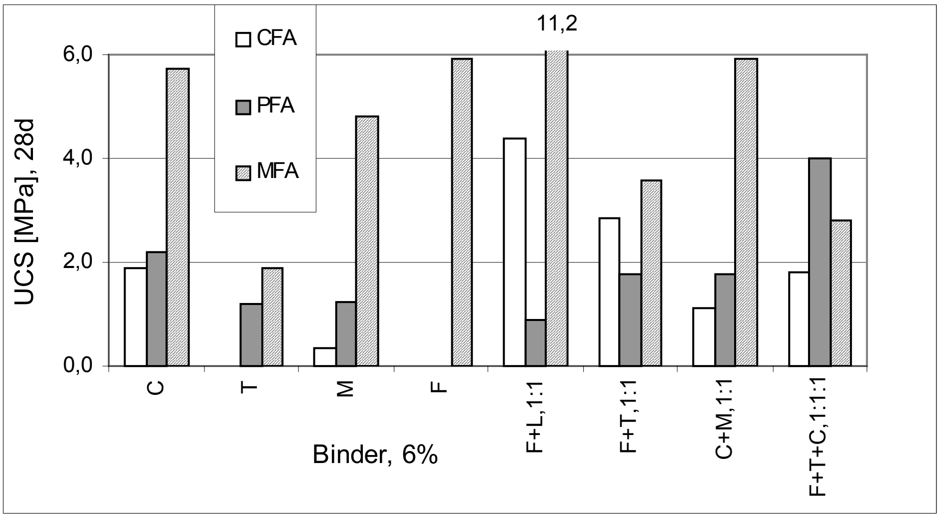
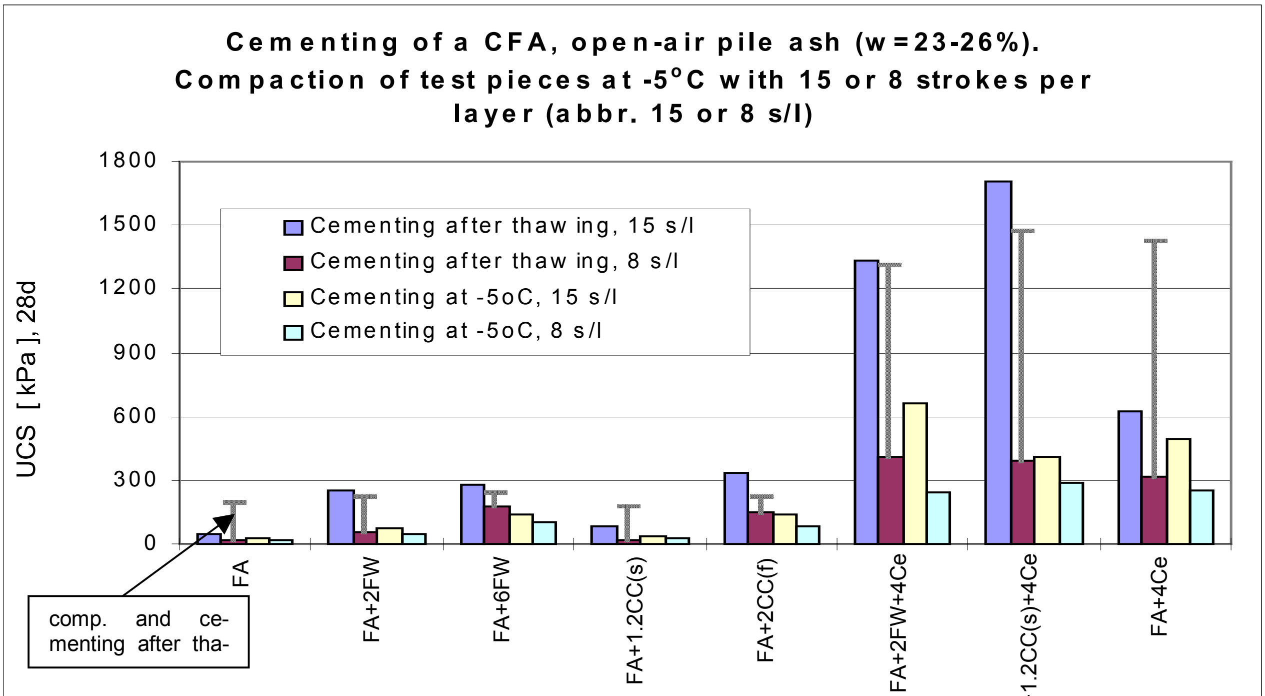


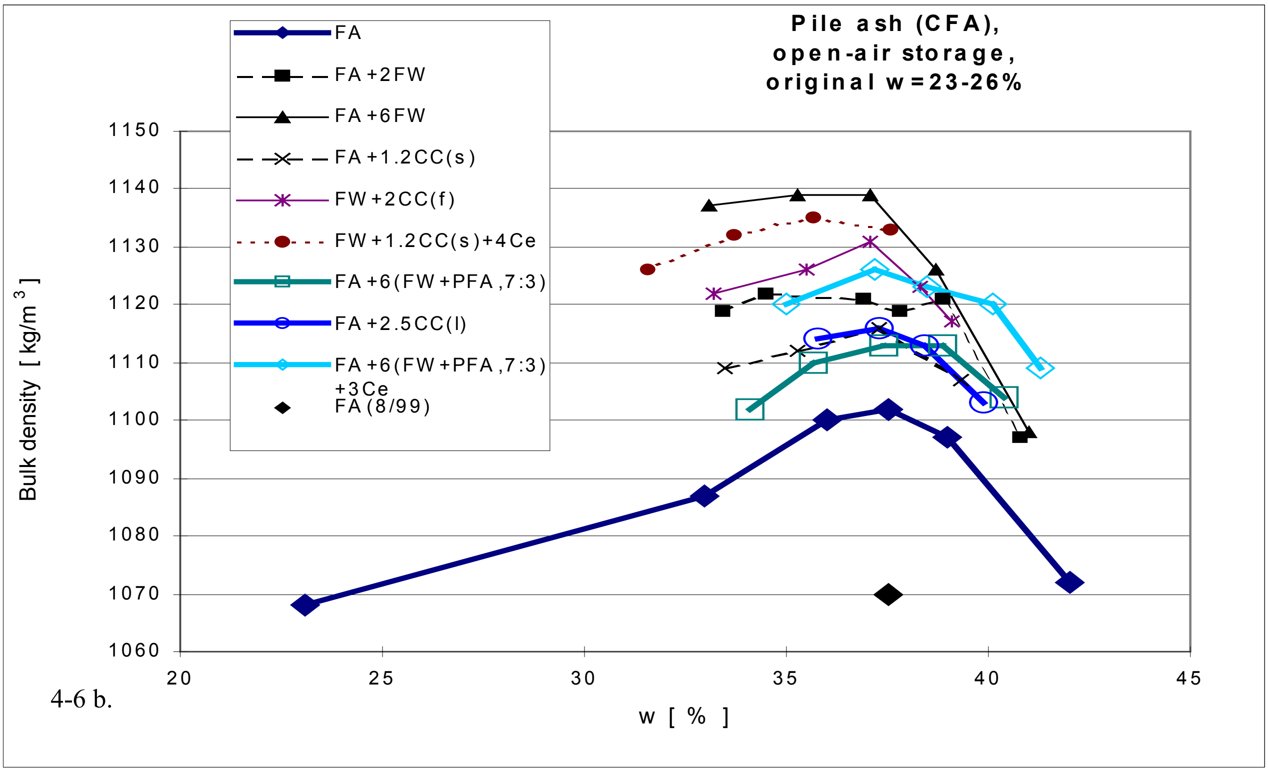
Figure 4-5: Effect of different binders (6%) on the strength of different FA (stabilisation for 28 days. C=cement, L=lime (CaO), T=hydrated lime, M= blast-furnace slag,, F=Finnstabi®; mean values of several cases) [15]

Each binder has its characteristic reactivity and stabilisation time. The results of *Figure 4-5* would be different with different binder quantities and times of stabilisation. The figure indicates that it is worthwhile to test the different binder alternatives because of their significantly different effects. The studies indicate that MFA-types of FA seem to have relatively good strength development with all types of binders.

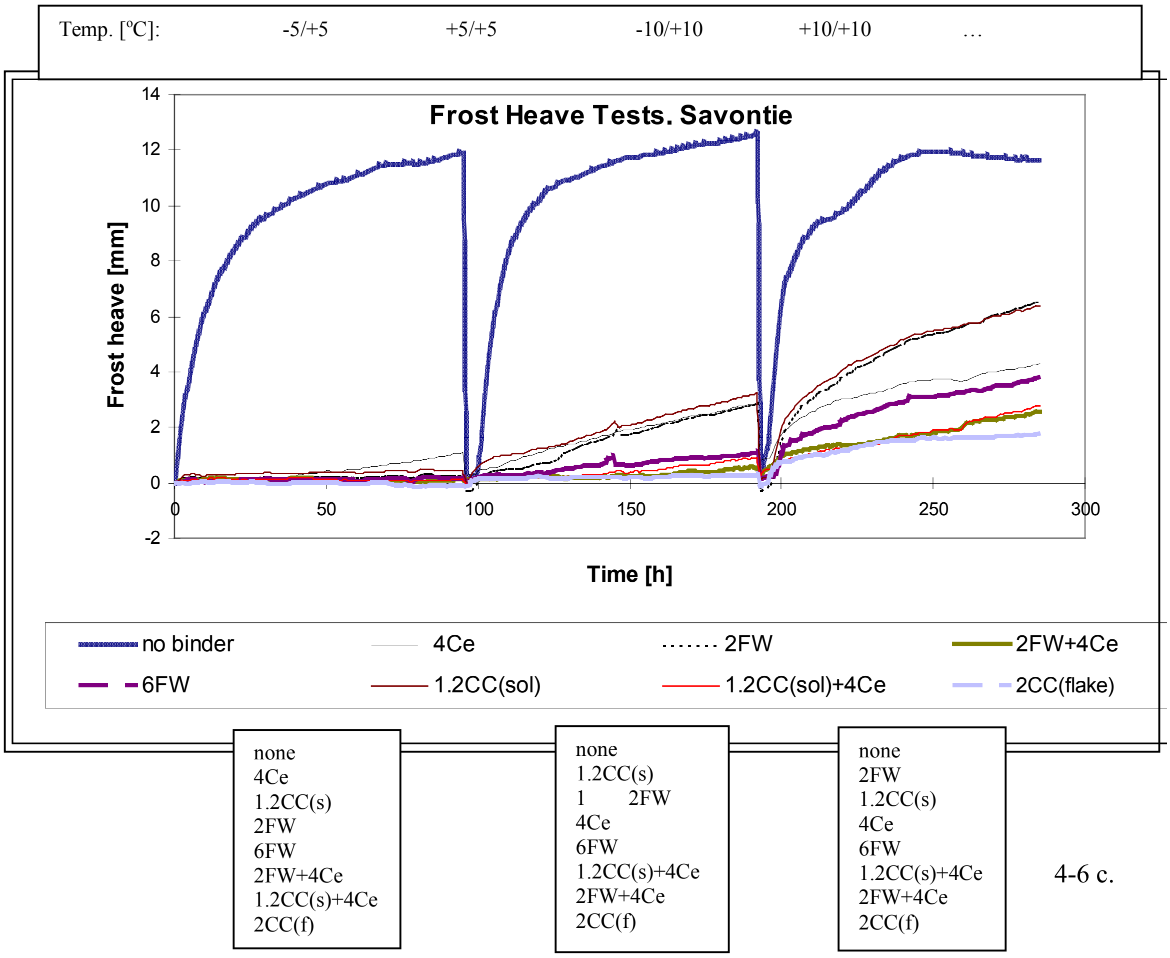
The winter-construction properties of FA can be improved with help of calcium chloride, $CaCl_2$ (CC). SGT studies have been conducted on the improvement of FA with salt products like CC-flakes or –solution and the filterwaste (FW). FW is a by-product of the production process of CC, and it consists of free lime, gypsum and 20-30 % calcium chloride. *Figure 4-6a* shows that the compaction and strength development of FA at -5^oC will be clearly more effective with an addition of only 2 % FW or 1,2 % CC-solution than without any CC. The actual cementing will start only after the FA structure has thawed, though the compaction has taken place during the frost period. *Figure 4-6b* shows the improvement of the compaction results of a certain FA (not frozen) when mixed with different salt products. The salt products also decrease the frost heave of frost susceptible NRC-materials. *Figure 4-6c* shows results from 3-cyclic frost heave tests on heavily frost susceptible materials that have been treated with the salt products. The results indicate that the frost heave is considerably decreased . The most effective additive was 2 % of CC-flakes. A study concluded that frost susceptible FA can be improved with a small addition of CC [20]. However, this finding has to be checked with additional research.


Cementing of a CFA, open-air pile ash (w=23-26%).
Compaction of test pieces at -5°C with 15 or 8 strokes per layer (abbr. 15 or 8 s/l)
UCS [kPa], 28d
1800
1500
1200
900
600
300
0
Cementing after thawing, 15 s/l
Cementing after thawing, 8 s/l
Cementing at -5oC, 15 s/l
Cementing at -5oC, 8 s/l
FA
FA+2FW
FA+6FW
FA+1.2CC(s)
FA+2CC(f)
FA+2FW+4Ce
FA+1.2CC(s)+4Ce
FA+4Ce
comp. and cementing after tha-

4-6 a.


Pile ash (CFA), open-air storage, original w=23-26%
FA
FA+2FW
FA+6FW
FA+1.2CC(s)
FW+2CC(f)
FW+1.2CC(s)+4Ce
FA+6(FW+PFA,7:3)
FA+2.5CC(l)
FA+6(FW+PFA,7:3) +3Ce
FA (8/99)
Bulk density [kg/m³]
1150
1140
1130
1120
1110
1100
1090
1080
1070
1060
20
25
30
35
40
45
w [%]

4-6 b.



4-6 c.

Figure 4-6: Improvement of FA and soil properties with calcium chloride salt (CC) and filterwaste (FW); a) Cementing behaviour of CFA; b) Bulk dencity of CFA ; c) Frost heave behaviour of crushed stone. CC as solution (s) or as flakes (f) [20]

Binders can also be used to improve the environmental behaviour of FA. *Figure 4-7* shows the effect of different binders on the solubility of heavy metals from a stabilised FA. For example, the figure indicates that the blast furnace slag significantly reduces the leaching of several heavy metals. This test was made in 1991 on a coal ash using the EP Tox Test [37] that is designed to simulate leaching under natural disposal conditions. The leaching medium was diluted acetic acid.

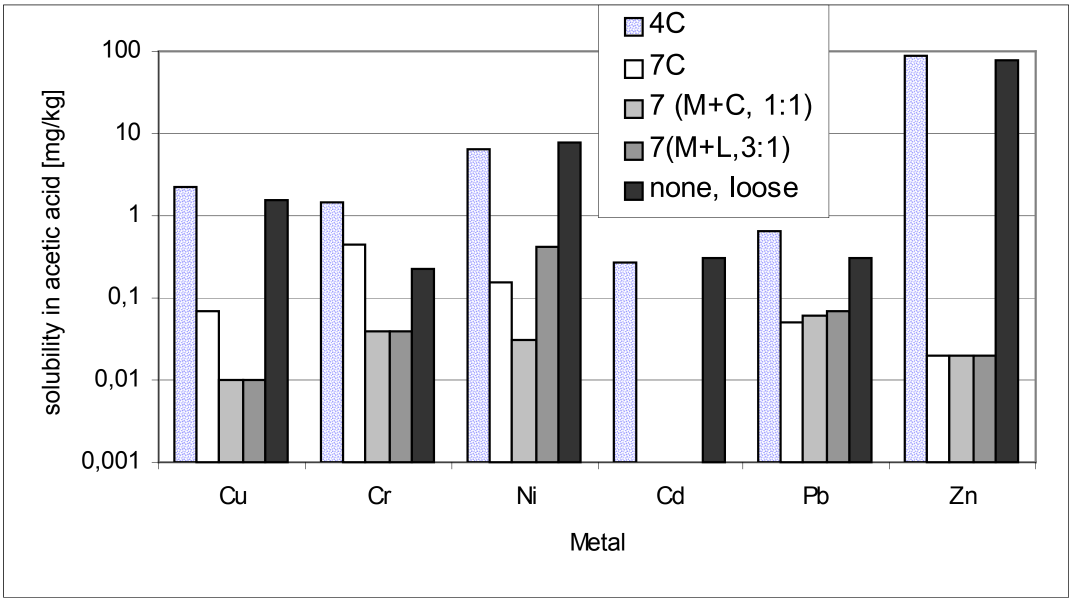


Figure 4-7: Effect of certain binders on the leaching of heavy metals from a FA. C=cement. M=blast furnace slag, L=lime. [15]

4.3 FA mixtures with other industrial residues

The mixing of FA with other industrial residues yields interesting possibilities for developing totally new types of materials and applications for road construction as well as for other areas of soil construction. The research for this doctoral thesis concentrated on the following NRC material mixtures:

- Fibre sludge (FS) + FA = Fibre-ash
- Phospho-gypsum (PG) + FA = Gypsum-ash
- Stainless steel slag (S) + FA = Slag-ash

Figure 4-8: Fibre-sludge or "fibre-clay" consists of organic fibres, kaolin and water.

4.3.1 Fibre-ash

The concept of fibre sludge involves pulp or wood based primary sludge and de-inking sludge from the paper industry. Principally the fibre sludge consists of organic fibres, kaolin (clay) and water. This is why it is frequently called 'fibre-clay', see *Figure 4-8*. *Table 4-3* characterises the Finnish fibre sludge types.

Table 4-3: Characteristics of Finnish fibre sludge [15]

	Mill Nr	w [%]	LoI [%]	Permeability, k [m/s] at D = 93-95 %
Deinking sludge	1	84…190	55…72	$1,2*10^{-9}…9*10^{-9}$
	2	138…233	52…59	$1*10^{-9}…3*10^{-9}$
	3	83…95	58…61	$1,5*10^{-7}…2*10^{-8}$
	4	95	56	$1*10^{-8}$
Pulp based sludge	5	176…213	70…81	$1*10^{-8}…1*10^{-9}$
	6	123…153	56…58	$3*10^{-9}$
	7	130	51	$5*10^{-10}$
	8	204	69	$2,5*10^{-9}$
Wood based sludge	9	120…180	55…67	$5*10^{-8}…5*10^{-9}$
	10	116…150	53…65	$1*10^{-8}…3*10^{-10}$
	11	147…154	59	$2,5*10^{-9}$
Pulp or wood based sludge	12	181…240	92	$2*10^{-8}$

To date fibre sludges have been reused or recycled relatively little in soil construction. Certain fibre sludges are being developed as construction materials for impermeable barrier structures of waste deposits or landfills, because of their relatively low water permeability. Fibre sludges cannot be used alone in road construction because of their rather low resistance to weather and physical load. On the other hand, a mixture of FA and fibre sludge, i.e. fibre-ash, might result in a NRC-material having quite new combinations of properties [II]:

a. resistant against large deformations, i.e. "unbreakable structures"

b. good frost insulation capacity

c. good water retention capacity

d. light weight

e. relatively good bearing capacity

f. workable and easy to construct

The excellent deformation resistance is due to the constituents of the fibre sludge, i.e. clay and fibres. The fibres may act as reinforcement in the sludge matrix [1]. The more fibre sludge a mixture contains the larger can be the deformations of the fibre-ash structure, as shown in *Figure 4-9* and *Figure 3-2*:

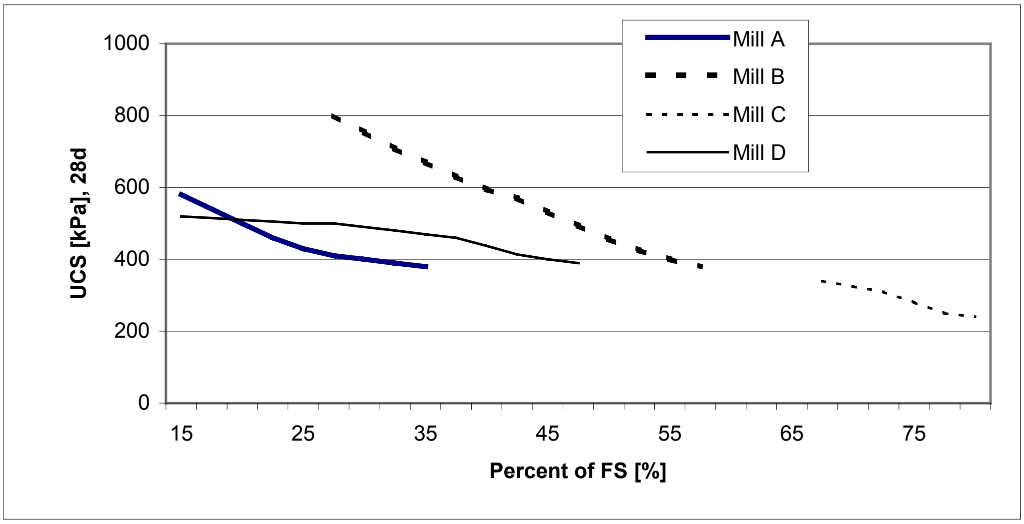


Figure 4-9: Effect of the percent of fibre sludge on the strength of fibre-ash mixtures ***[15]***

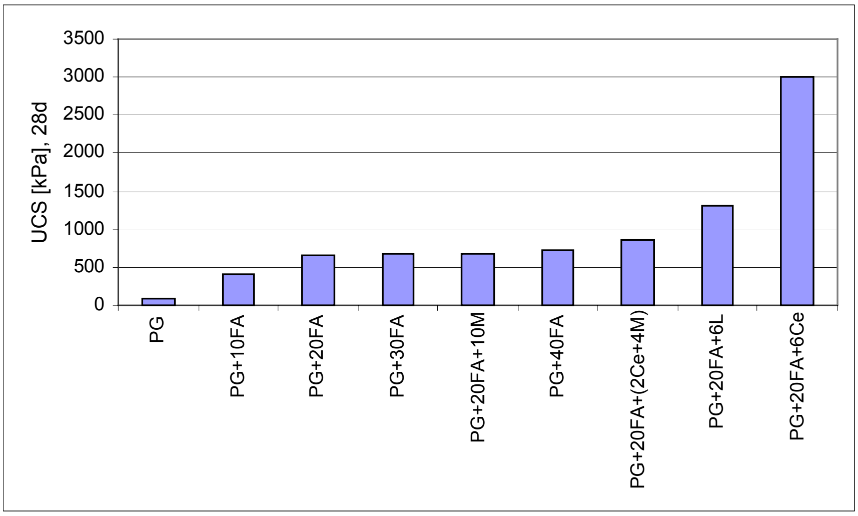
Usually it is necessary to add binder to fibre-ash mixtures in order to obtain NRC-materials that adequately withstand frost and freeze-thaw cycles. The most usual binder has been cement. Changing the binder quantity can significantly modify the properties of a fibre-ash mixture, but for economical reasons the quantity should be optimised to a level that allows only adequate long-term strength properties to be achieved. The quantity and quality of the FA in the mixture will remarkably affect the required binder quantity. It has been found that the larger the ash quantity the smaller is the required binder quantity. The type of fibre sludge in the mixture also affects the quantity of FA and binder. Studies indicate that the amount of de-inking sludge should not be higher than 70 % and the amount of other fibre sludge types not higher than 50 %. Additionally the studies have shown that even a small amount like 10 – 20 % of fibre sludge will significantly improve the deformation resistance of a fibre-ash [15].

Table 4-5 gives data on the properties of some fibre-ash mixtures that have been stabilised with cement.

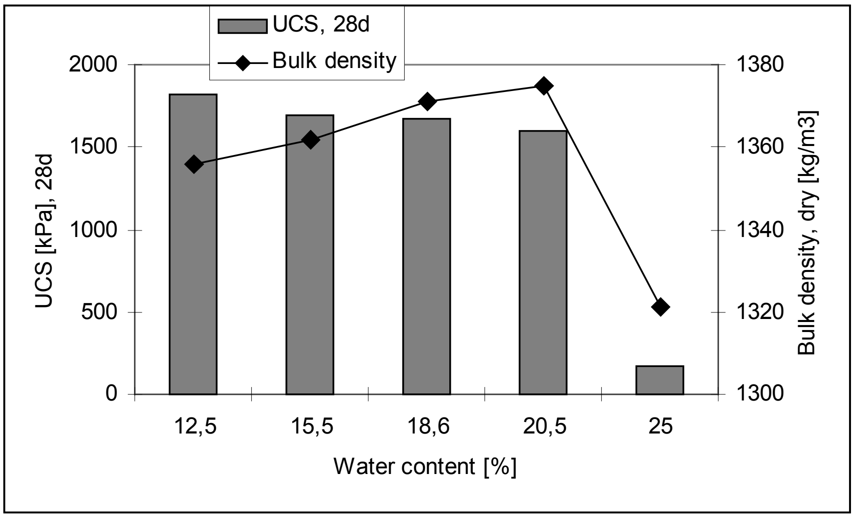
4.3.2 Gypsum-ash

Studies have been performed using phospho-gypsum or processgypsum (abbr. G or PG), a calcium sulphate dihydrate ($CaSO_4x2H_2O$) that is a residue from the manufacturing process of phosphoric acid. Some of the phospho-gypsums are being used by the construction industry for building materials but the main part is being dumped in deposits. Phospho-gypsum often contains small residual amounts of phosphoric acid and sulfuric acid and also some trace concentrations of other minerals [15, 19].

Thus phospho-gypsum alone cannot be recycled in road construction. However, mixtures of phospho-gypsum, FA and binders can yield materials that have adequate strength properties for road construction. The best types of binders for gypsum-ash mixtures are cement and lime, which can be seen from the test results shown in *Figure 4-10a*. The test results show the effect of binder type and quantity of PFA on the strength of gypsum-ash.



4-10 a.



4-10 b.

Figure 4-10: a) Compression strength of gypsum-ashes as function of binder type and quantity of PFA ; b) Effect of water content on the bulk density and strength of test pieces of (PG+PFA, 9:1)+5(M+Ce,7:3) [15]

The effect of water content on the strength of test pieces of gypsum-ash materials was tested with a mixture (PG+PFA, 9:1)+5(M+Ce, 7:3) that also has been used in full-scale test construction. *Figure 4-10b* shows that the maximum strength could be obtained with a water content that was significantly smaller than the optimum water content (w_o, which would yield the maximum bulk density). The results indicate that mixtures of gypsum-ashes have to be tested at different water contents, not only at the maximum bulk density.
Table 4-5 presents data on the geotechnical properties of some gypsum-ash mixtures.

4.3.3. Slag-ash

Stainless steel slag (hereafter referred to as slag) is produced in huge quantities as a residue of stainless steel production. Until now there have not been any feasible recycling applications utilising the stainless steel slag. In Finland the slag is deposited as piles in lagoons close to the sea.

For this doctoral thesis the author has studied the slag produced in Finland. The chemical composition of slag is given in *Table 4-4* and the grain size distribution in *Figure 4-11*.

The water content of slag is relatively high (30…60 % depending on the grain size distribution) because it is deposited in lagoons after the stainless steel production process. For recycling purposes the slag has to be drained, for example in piles that incorporate drainage pipes, to achieve a lower water content. After one month of drainage in the piles the water content of the slag is typically found to be around 15…25 % [15,27].

Table 4-4: Chemical composition of a stainless steel slag [27]

Constituent	% of weight
CaO	38,9
SiO_2	24,6
MgO	10,7
Fe_2O_3	8,9
Cr_2O_3	5,7
Al_2O_3	5,0
TiO_2	1,2
MnO_2	0,9
NiO	0,7
C	0,6
S	0,1
MoO_3	0,09
Cr^{6+}	0,0005

The slag alone cannot be recycled in any soil construction application. For example, the slag is not a cementing material as such, it is susceptible to large amounts of frost heaving and it contains relatively large quantities of soluble heavy metals. However, the technical and environmental properties of slag can be significantly improved with dry FA and binders [15]. From a geotechnical and environmental standpoint it has been shown that the best binder is a mixture of blast furnace slag with cement (MC, 1:1).
Various studies have shown that the best methods to improve the soil construction properties of slag are stabilisation with MC, dry FA or a mixture of these. *Figure 4-12* shows test results on the different alternatives after 28 days stabilisation. The strength development of the stabilised slag will be surprisingly high even after a month of stabilisation, as shown in *Figure 4-13*. After aging for about three months, the strength might still increase as much as an additional 50 % above the one-month strength. Thus, the properties of stabilised slag have proved to be quite promising. *Table 4-5* lists the results of geotechnical tests on some stabilised slag mixtures.

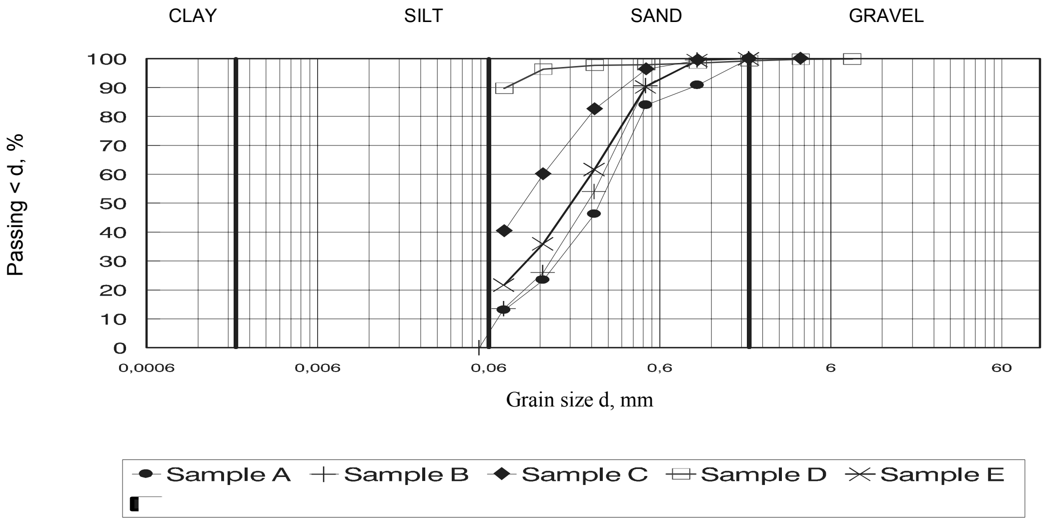


Figure 4-11: Grain size distribution of a stainless steel slag; 5 batches [15]

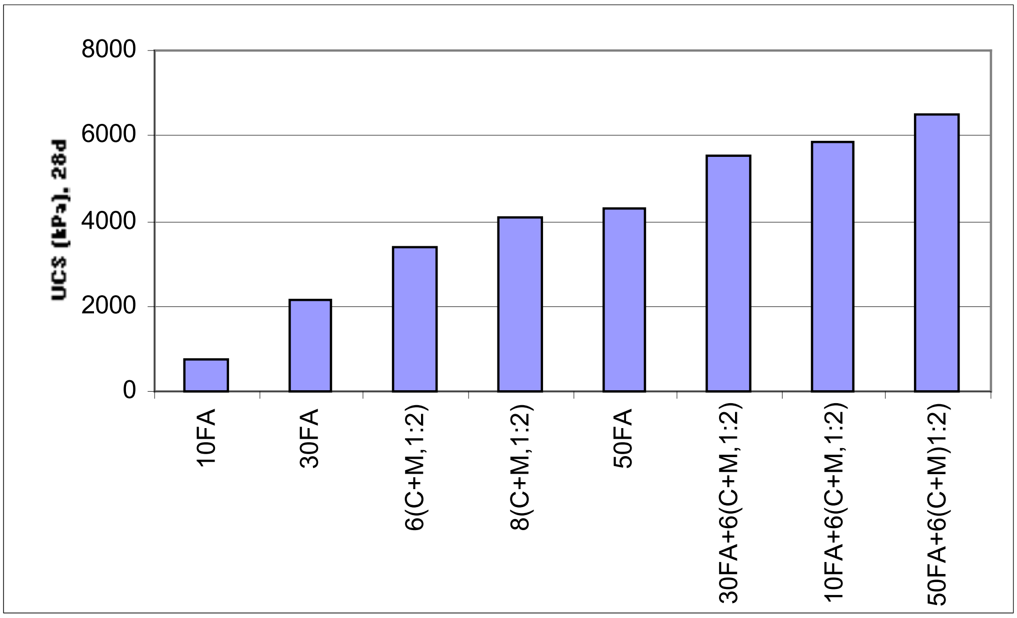


Figure 4-12: Improvement of slag with CM, FA and CM+FA. C=cement, M=blast furnace slag, FA=MFA [15]

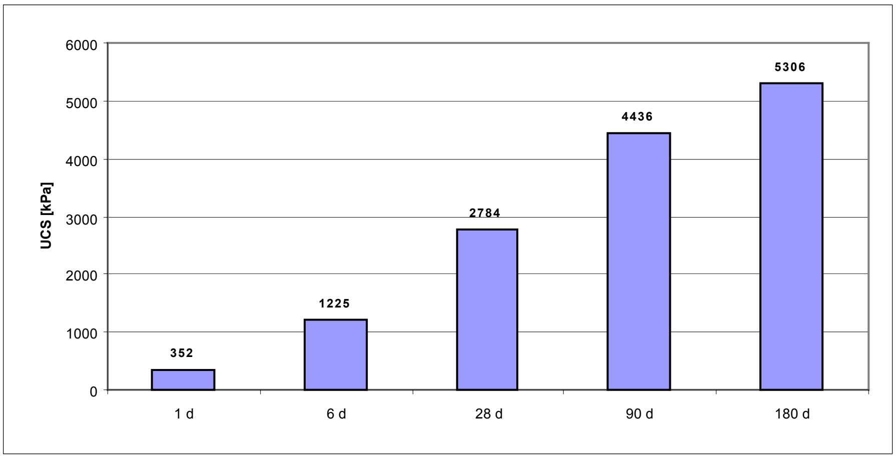


Figure 4-13: Strength development of a CM-stabilised slag (6 % CM, 1:2) [15]

Table 4-5: Properties of stabilised fibre-ash, gypsum-ash and slag-ash [15]

NRC mixture	Geotechnical properties							
	Water content	Bulk density	UCS and deformation				Thermal conduc-tivity	Segre-gation poten-tial
			28d		90d			
	w_o [%]	ρ [kg/m³]	σ_u [kPa]	ε_u [%]	σ_u [kPa]	ε_u [%]	λ [W/mK]	SP_o [mm²/Kh
(FS1+MFA ,2:10) + 6Ce	51	895	600-700*	>10	n/a	n/a	n/a	≈1
(FS2+MFA, 45:55) + 7Ce	65	855	600*	>10	n/a	n/a	n/a	> 1
(FS3+WFA, 10:3) + 5Ce	56	810	300-400*	>10	n/a	n/a	n/a	>> 2
(FS4+CFA, 10:4) + 14(FGD+Ce, 2:1)	42	1060	760-770	5,5	n/a	n/a	$0{,}58_{+22°C}$ $0{,}89_{-10°C}$	0.6-0.8
(G + 10MFA) + 3(M+Ce, 7:3)	18,6	1370	614	3,5	1120	2,5	n/a	n/a
(G + 10MFA) + 4(M+Ce, 7:3)	18,6	n/a	942	3,5	1880	1,8	n/a	1,2
(G + 10MFA) + 5(M+Ce, 7:3)	18,6	1366	1092	n/a	2760	1,6	n/a	n/a
(G + 10MFA 10%) + 6(M+Ce, 7:3)	n/a	n/a	1642	2,5	3088	1,5	$0{,}58_{22°C}$ $1{,}41_{-17°C}$	1,1
S + 10MFA	9,3	2200	726	2,3	n/a	n/a	n/a	n/a
S + 10MFA+ 6Ce	9,3	2158	6484	2,2	n/a	n/a	n/a	n/a
(S + 10MFA) + 2(M+Ce, 2:1)	8,9	n/a	1219	1,7	n/a	n/a	n/a	0,02-0,12
(S + 10MFA) + 3,5(M+Ce, 2:1)	8,9	n/a	1843	1,6	n/a	n/a	n/a	< 0,1
(S + 10MFA) + 5(M+Ce, 2:1)	8,9	n/a	2982	1,3	n/a	n/a	n/a	< 0,1
(S + 10MFA) + 6(M+Ce, 2:1)	9,3	n/a	5852	1,3	n/a	n/a	n/a	n/a
S + 30MFA	8,9	2160	2158	1,6	n/a	n/a	n/a	0,1-0,12
S + 30MFA + 6Ce	8,9	n/a	8215	1,0	n/a	n/a	n/a	n/a
S + 30MFA + 6(M+Ce, 2:1)	8,55	2070	5526	1,3	n/a	n/a	n/a	n/a
S + 30MFA + 6M	8,9	n/a	4613	1,4	n/a	n/a	n/a	n/a
S + 50MFA	11	2100	4291	1,3	n/a	n/a	n/a	n/a

Note:	
FS1	Pulp-based sludge
FS2	De-inking sludge
FS3	De-inking sludge
FS4	Wood-based sludge
*)	UCS at ε=10%

4.4 FA as binder

Dry and reactive FA can often be used as a component in binder mixtures. In the international project EuroSoilStab different FA types have been studied for the stabilisation of peat, gyttja and clay [5] [III]. In addition, it has been proven that it is feasible to use FA for the renovation of old gravel roads structural courses [15].

4.4.1 Stabilisation of soft soil

During the EuroSoilStab project there have been studies on the use of four different FA types for the stabilisation of soft soil. The properties of the FA are given in *Table 4-6*.

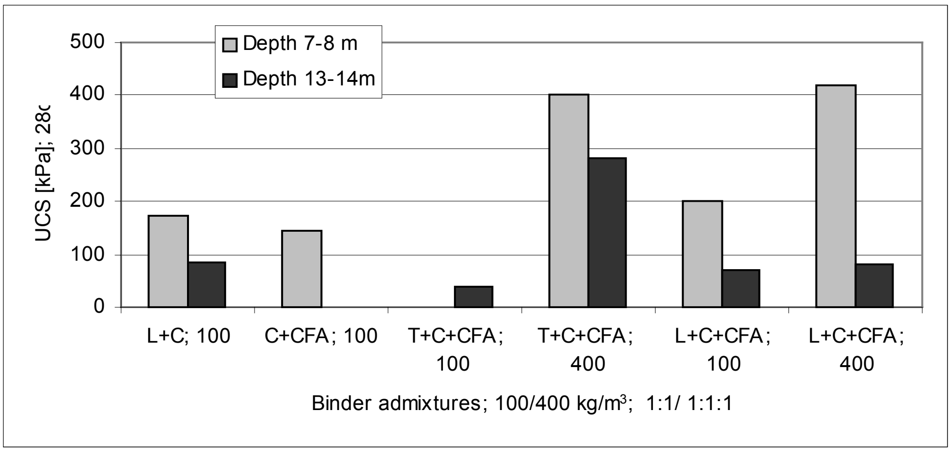
Table 4-6: FA in EuroSoilStab studies [5]

	Content [%]											
CFA from	CaO	SiO2	Al2O3	Fe2O3	MgO	K2O	Na2O	MnO	PsO5	LoI	Specific weight [kg/m^3]	Specific surface [m2/kg]
Finland	5,8	43,8	22,2	8,4	2,8	2,2	1,2	0,09	0,68	11,3	2390	459
Sweden	22,3	25,1	16,3	5,0	13,4	1,1	0,64	0,14	0,80	8,6	2740	339

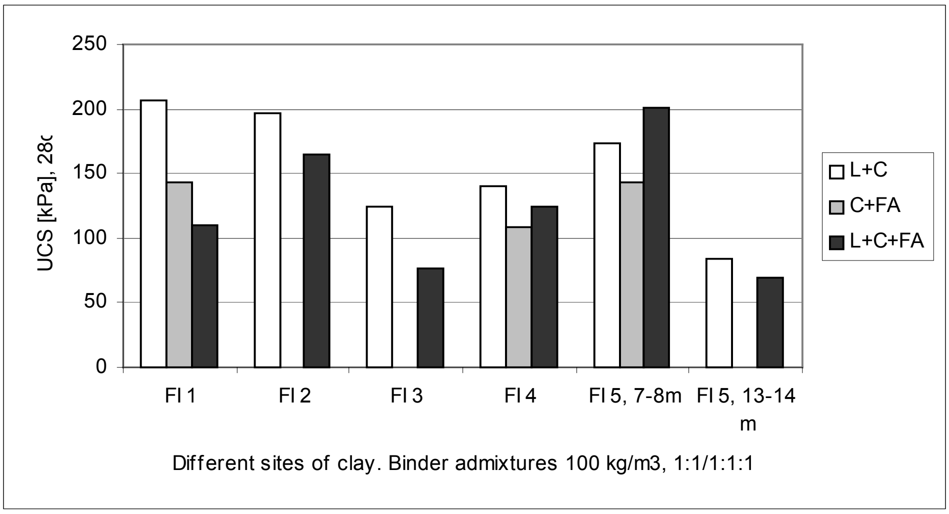
Figures 4-14…4-16 compare the effects of different CFA based binder mixes on different peat, gyttja and clay materials. Figure 4-14 shows that the effect of binders is different on the clay materials from different depths as the properties of clay are different. At this site, the clay from a deeper soil layer cannot be stabilised as effectively as the clay from the upper layer. This is often the opposite. *Figure 4-17* shows the results of a study on the effect of CFA quantity on soft soils [5].

The FA-based binders are not appropriate for all types of soft soils. The studies indicate that soft soils that can be cement-stabilised and yield good results also benefit from the use of FA based binders. For peat stabilisation, the largest economical benefits can be obtained by using mixtures that require relatively large quantities of binder. *Table 4-7* presents information about the properties of two different peat types that have been stabilised with a FA mixture [5].

The test results indicate that cement or a portion of lime can be compensated with FA in cases where the soil can be stabilised with FA. In general, however, with an equal amount of binder the strength of the FA-stabilised soil will be a little lower than the strength of the cement- or lime stabilised soil. Because of the lower price of FA, it is generally economical to increase its amount in the mixture. An increase in the amount of FA is technically advantageous, as can be seen in *Figure 4-17*, which shows an increase in strength with increasing amount of FA.



a.



b.

Figure 4-14: Comparison of the effect of different CFA-based binders on clay a) clay from one site at two depths, b) clay from different sites [5]

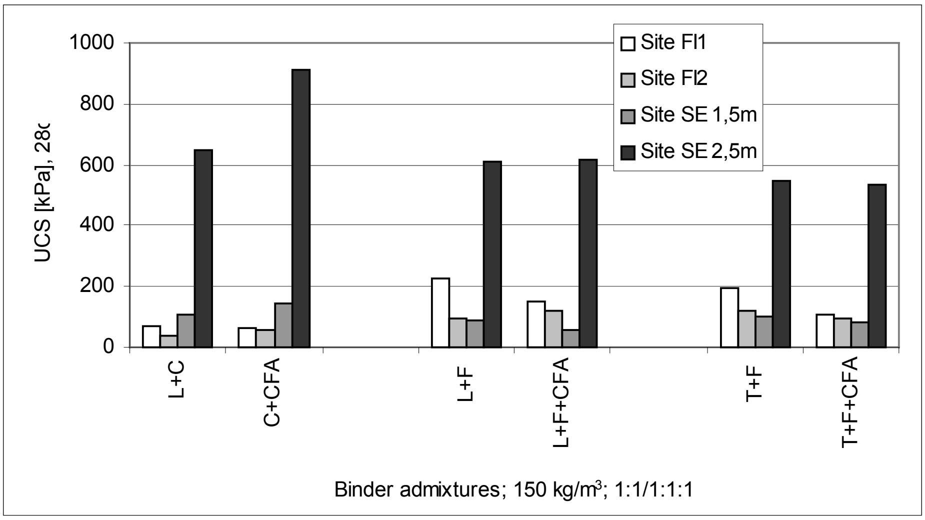


Figure 4-15: Comparison of the effect of different CFA-based binders on gyttja [5]

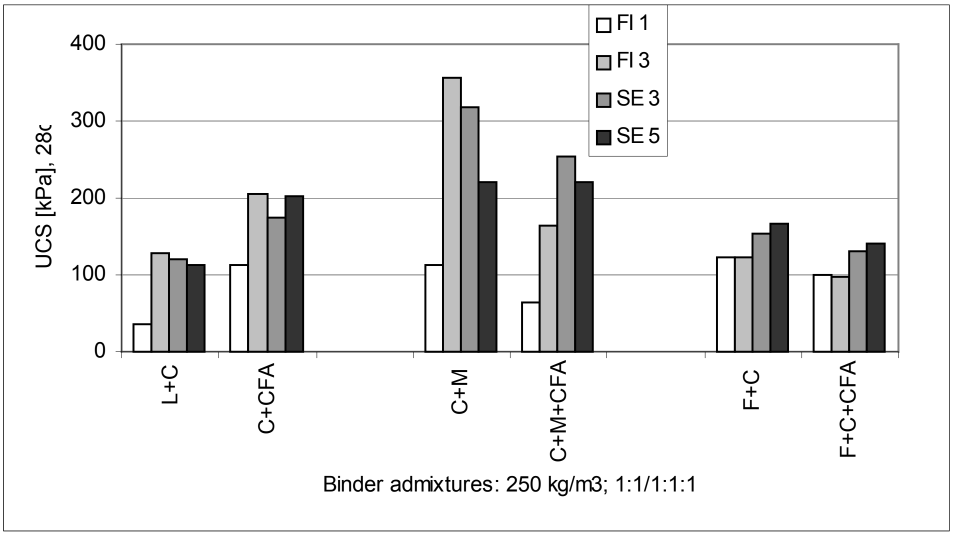
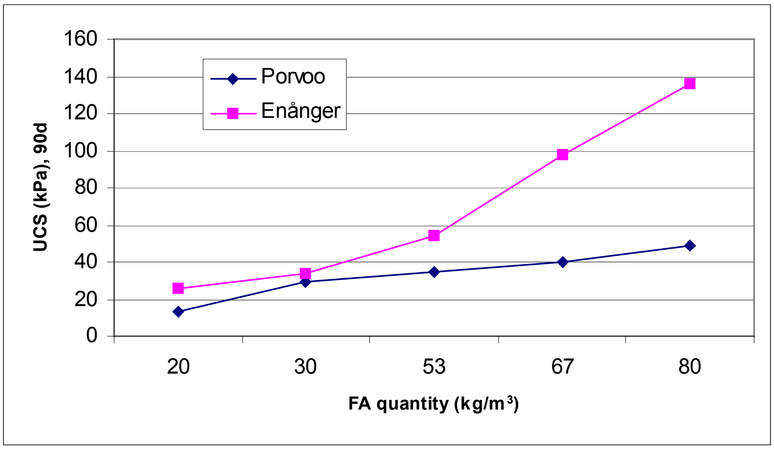
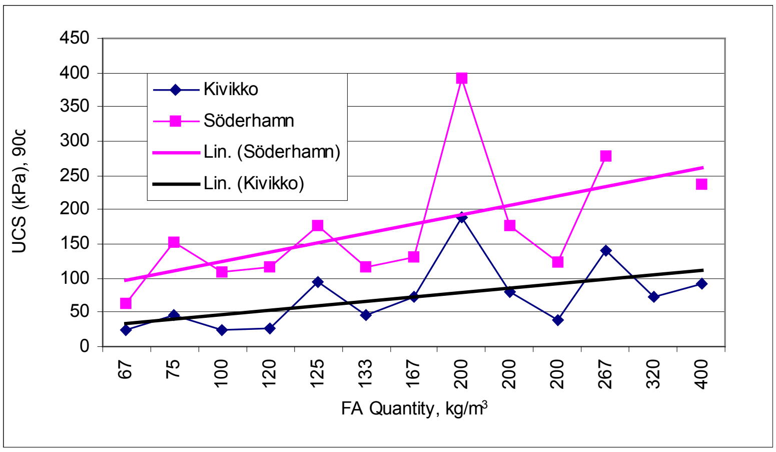


Figure 4-16: Comparison of the effect of different CFA-based binders on peat [5]



a) gyttja



b) peat

Figure 4-17 Effect of CFA quantity on the strength of soft soils, a) gyttja and b) peat (Lin. = linear regression) [5]

Table 4-7: Properties of two peats stabilised with CFA mixtures [5]

Source of peat	Binder mixture / quantity (kg/m^3) / stabilisation time (d)	Bulk density	Unconfined compression test		Water permeability Rigid wall test
		ρ [kg/m^3]	σ [kPa]	ε [%]	k [m/s]
Finland	Ce+FA/250/28	1001-1010	97,0	3,7	6,15E-08
	Ce+FA/250/90		94,3	3,6	7,20E-08
Sweden	Ce+FA/250/28	1023	143,9	3,5	n/a
	Ce+FA/250/90		177,3	3,0	n/a

4.4.2 Stabilisation of old road structures

The studies on the stabilisation of old road structures concentrated on badly frost-damaged sites that are a part of the low-volume road network in Finland. The damaged road sites have relatively thin structural courses that partly have been mixed with the subsoil. Because of frost heave and freezing-thawing cycles repeating each year, the courses of this type of road structure usually soften and weaken with time, as the fines of the subsoil will be pumped into the structural course, and the structural course sinks into the subsoil. Stabilisation of the structural course should effectively prevent this kind of damage of the road.

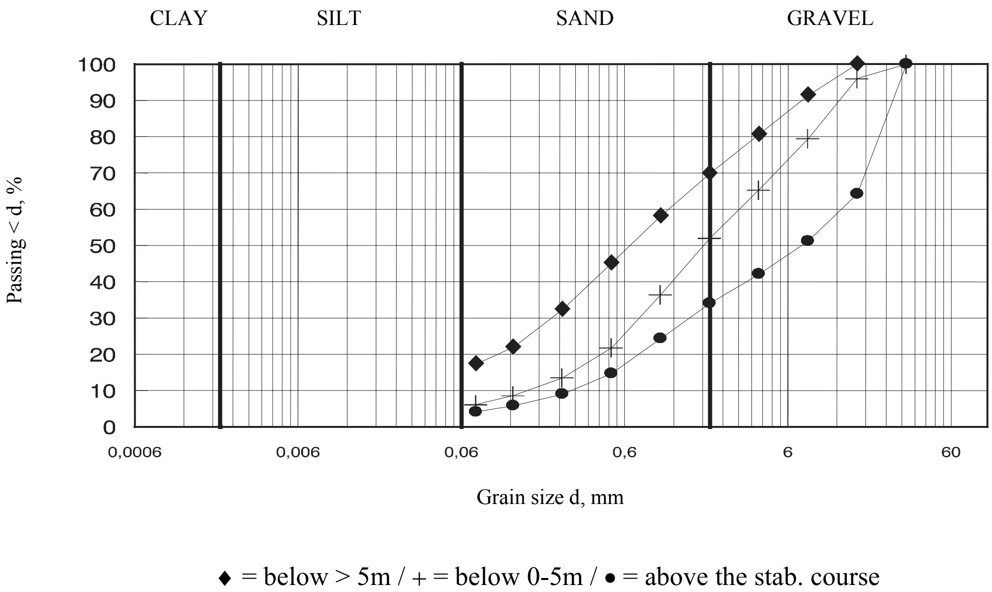


Figure 4-18: Grain size distribution of materials of an old road structure examined for NRC-stabilisation [15]

The NRC-materials for stabilisation should have a grain size distribution similar to moraine deposits, as the suitability of a NRC-binder mixture depends on the amount of fines in the moraine deposit, which has to be stabilised. For this doctoral thesis, NRC-stabilisation of old road structures have been studied only on materials having grain size distribution such as in *Figure 4-18* [15].

Figure 4-19 shows results that have been obtained with FA-based binders used in the stabilisation process. The best binder components for FA were cement, blast furnace slag (M) and gypsum. *Figure 4-19* shows the effect of binder quantity on the strength and *Figure 4-21* shows the effect of stabilisation time. *Table 4-8* gives information about the geotechnical properties of the old NRC-stabilised structures when using FA-based binders [15]

The test results have shown that the feasibility of FA-based binder mixes for moraine-type materials also depends on the properties of moraine itself, e.g. on its grain size distribution. In the best cases it is possible to obtain quite high strengths (5-7 MPa / 28d) with relatively small binder quantities (5-7 %). Also the strength development of FA-stabilised soils is significant during a longer time period. *Figure 4-21* shows that the strength may double or more between the 1st and 3rd months of stabilisation.

Primarily, the FA-based stabilisation of old road structures is used to improve the bearing capacity. FA-based stabilisation is not used to improve the frost susceptibility, although Table 4-8 indicates that the thermal conductivity of FA-stabilised structures might be a little smaller than the thermal conductivity of crushed stone in general, λ (crushed stone) > 0,89 W/Km.

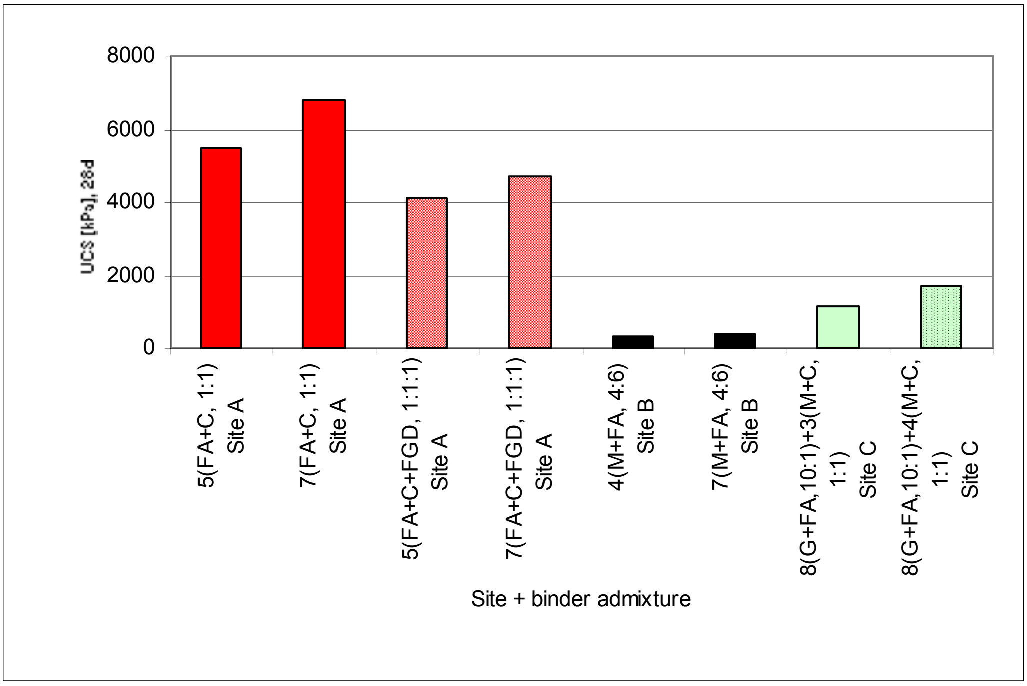


Figure 4-19: Strength of three different soil materials after stabilisation with FA-based binders: CFA for sites A and B and PFA for site C [15]

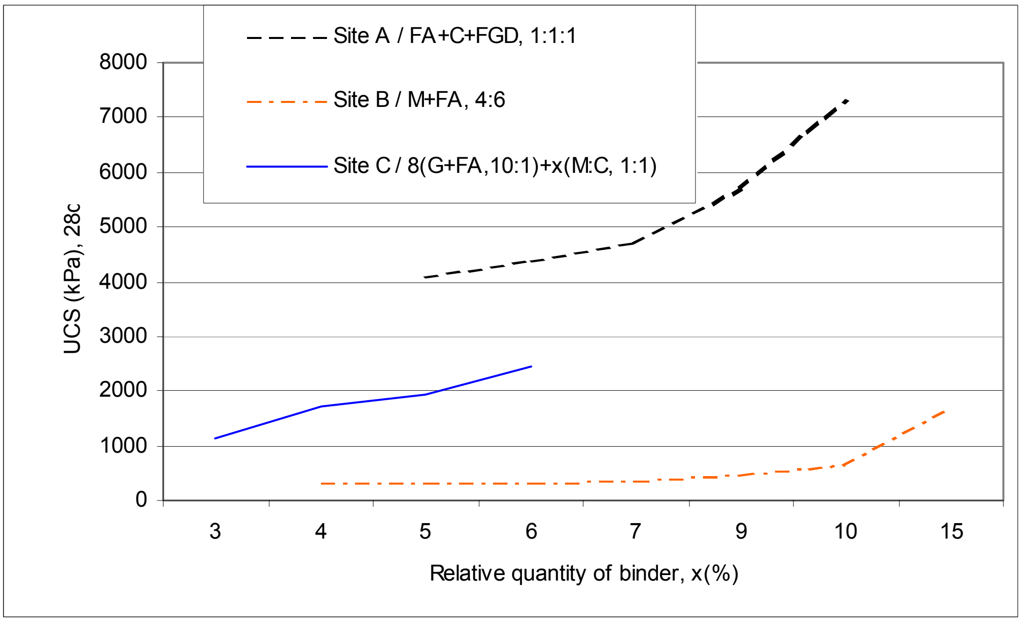


Figure 4-20: Effect of binder quantity on the strength [15]

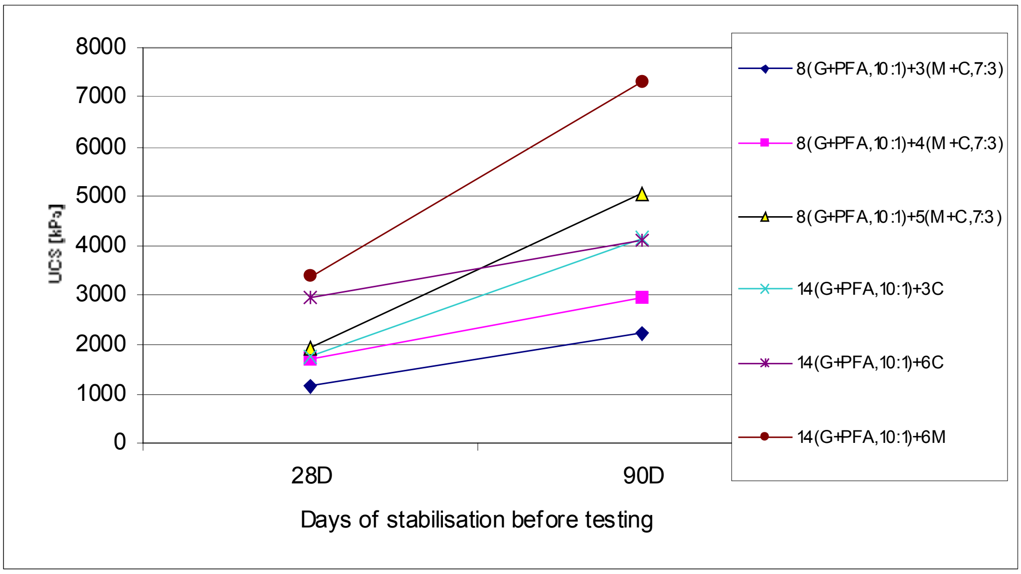


Figure 4-21: Effect of stabilisation time on the strength of crushed stone stabilised with mixes of gypsum (G), fly ash from peat combustion (PFA), blast furnace slag (M) and cement (C) [15]

Table 4-8: Geotechnical properties of old NRC-renovated (stabilised) road structures [15]

Stabilised structure material	Binder	Water content	Bulk density	UCS and deformation, 28d		Thermal conductivity
		w_o [%]	ρ [kg/m^3]	σ [kPa]	ε [%]	λ [W/Km]
CS A	15(CFA+M, 6:4)	6,2	2080	1700	1,2	n/a
CS A1	15(CFA+M, 6:4)	7,0	2180	400-1200	n/a	n/a
CS B	7 (CFA+FGD+Ce, 1:1:1)	5,5	2260	4400-4700	1,0…1,4	n/a
CS C	14(10G+PFA) + 6(M+Ce, 7:3)	7,1	2070	3367	2,0	0,72 $_{(+22°C)}$; 1,23 $_{(-17°C)}$
CS C	8(10G+PFA) + 6(M+Ce, 7:3)	6,9	2075	3292	1,3	n/a
CS C	8(G+PFA) + 4(M+C, 7:3)	6,7	2080	1708	1,6	n/a

Note

CS A, A1	Crushed stone structure from site A; A = laboratory tests, A1 = tests on samples from the full-scale test structure
CS B	Crushed stone structure from site B; laboratory tests
CS C	Crushed stone structure from site C; laboratory tests

4.5 Long-term stability of materials

The principles and methodologies described in Chapter 3 have been used to study the long-term durability of the materials. All materials have been tested for the following factors that are essential for road construction materials; water retention capacity, frost susceptibility, frost resistance and freeze-thaw durability. A few materials have also been tested to study the effects of infiltrating water or acid water. Additionally, materials containing fibre sludge have been tested to determine their biodegradability. Dynamic load durability has been studied only in test structures at full-scale test sites.

4.5.1 Water resistance, frost resistance and freeze-thaw durability

Different FA mixtures have been tested for water resistance, frost resistance and freeze-thaw durability, and the results have been compared with the strength of corresponding mixtures that have been stored at normal room temperature (18-21°C) without external fatigue load. *Figure 4-22* presents the results for FA, *Figure 4-23* the results for fibre-ashes, *Figure 4-24* the results for gypsum-ashes and *Figure 4-25* the results for slag-ashes [5,15].

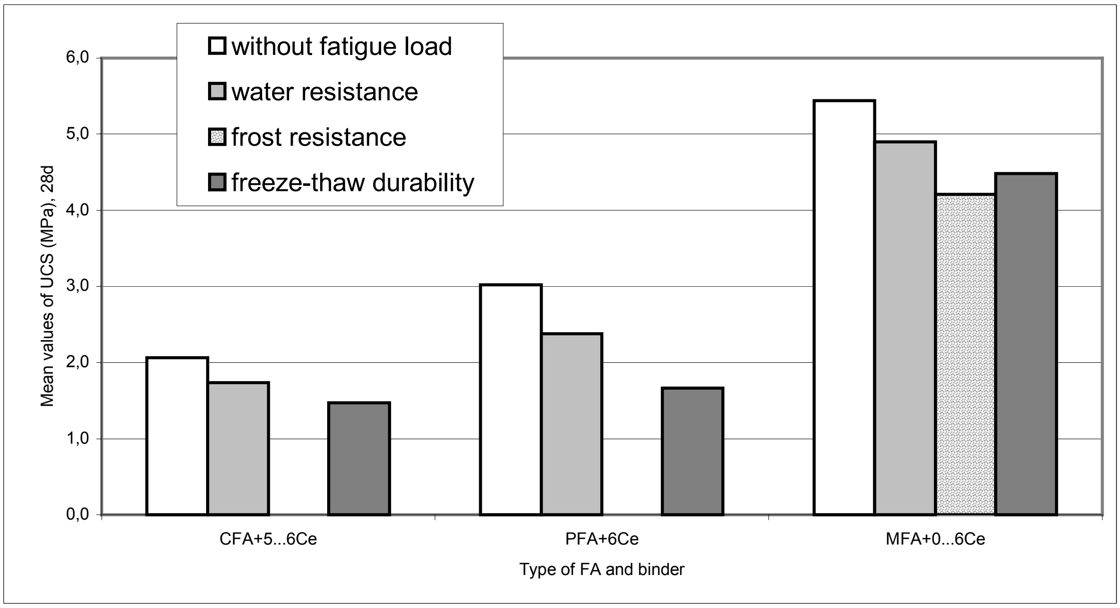


Figure 4-22: Water resistance, frost resistance and freeze-thaw durability of different FA-types. Mean values of test results. [5,15]

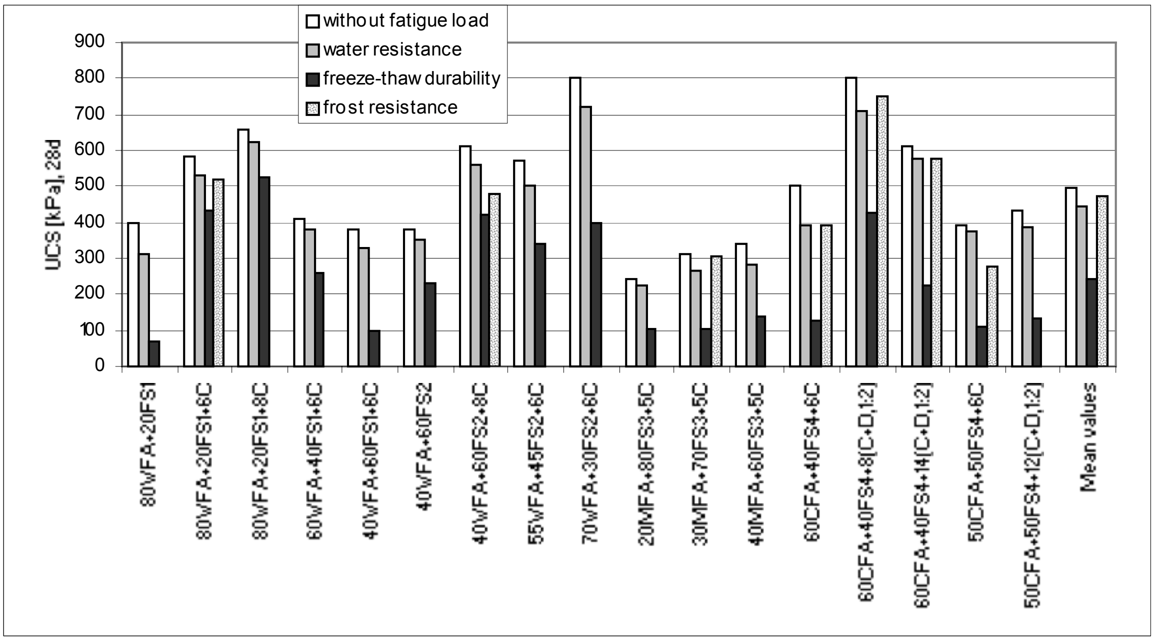


Figure 4-23: Water resistance, frost resistance and freeze-thaw durability of different fibre-ashes: FS = fibre sludge, WFA/MFA/CFA = different types of fly ash, C = cement, D = desulphurisation residue [15]

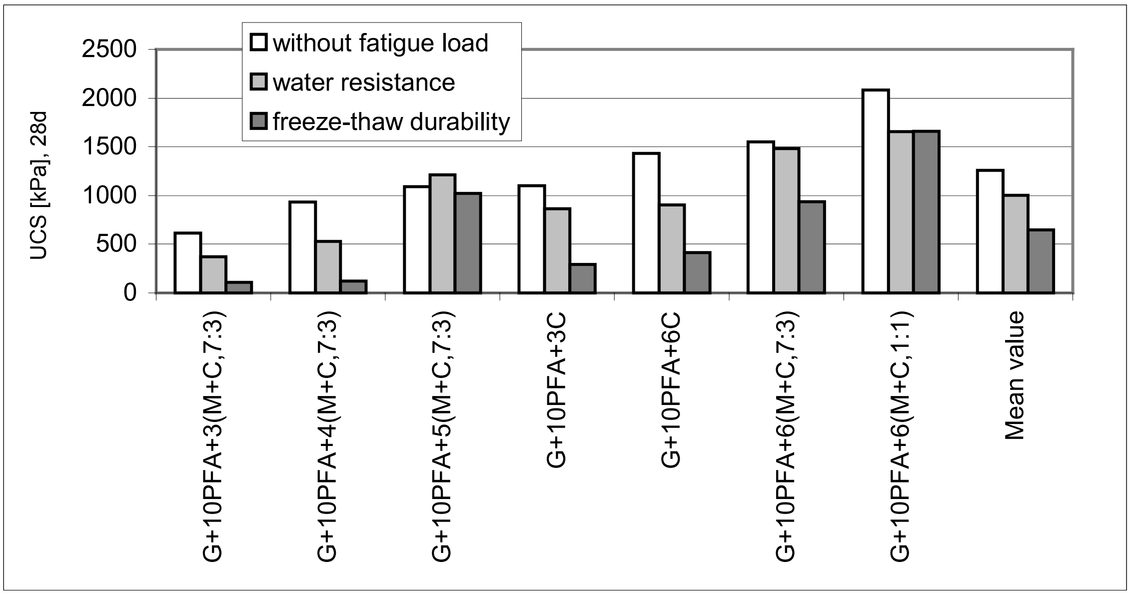


Figure 4-24: Water resistance, frost resistance and freeze-thaw durability of different gypsum-ashes: G = phospho-gypsum, PFA = fly ash from peat combustion, C = cement, M = blast furnace slag [15]

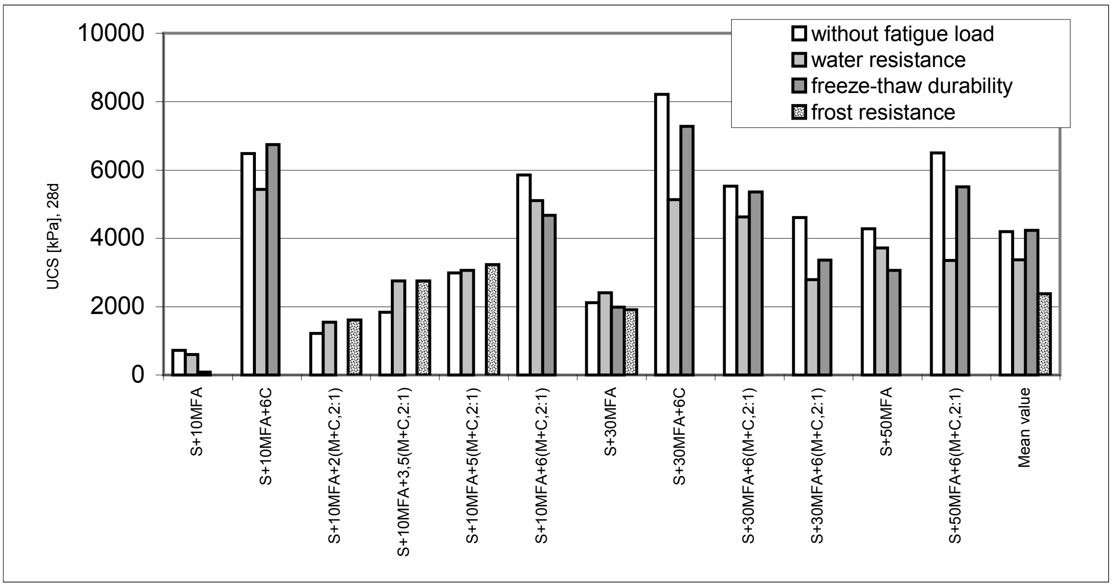


Figure 4-25: Water resistance, frost resistance and freeze-thaw durability of different slag-ashes [15]

The fatigue tests on NRC-materials are important for the determination of their suitability in geotechnical applications. According to *Figures 4-22 ... 4-25* the UCS of a material does not correlate well with the material's frost resistance or freeze-thaw durability. A material having a high UCS value might have inadequate freeze-thaw properties, and vice versa.

In general fatigue tests result in decreasing strength of the material with increased number of cycles; a slight decrease in the water retention test, slightly more in the frost susceptibility test and the largest decrease in the freeze-thaw test. The stabilised FA presented in *Figure 4-22* have exhibited quite good durability when subjected to different fatigue loads, and their strength decrease has been moderate. Many of the SGT's studies [15] have shown that moist pile-FA requires binder to obtain adequate freeze-thaw durability. When using dry FA the need for binder is less and in some cases no binder is required.

Fibre-ash mixes based on pile-FA always require some binder in order to obtain adequate freeze-thaw durability as shown in *Figure 4-23*. For example, UCS of the material mix 80WFA+20FS1 was 400 kPa, as the material was not subjected to any fatigue load, while its UCS was only 80 kPa after the freeze-thaw test. Increasing the relative amount of ash in fibre-ash mixtures will increase the material's strength (UCS). *Figure 4-23* also indicates, that fibre-ash materials from different producers may clearly differ from each other in strenght, despite the use of same binder and equivalent component proportions in the mixtures. For example, the mixtures 60 WFA+40FS1+6C, 55WFA+45FS2+6C and 60CFA+40FS4+6C all had 6 % cement as binder, but the UCS varied between 410 kPa and 570 kPa after no fatigue load, and even more, between 120 kPa and 330 kPa, after the freeze-thaw test. Additionally, the same figure indicates, that the larger the share of fibre sludge in the mixture, the more binder will be needed, in order to achieve adequate freeze-thaw durability for a fibre-ash material. For example, 6 % cement for the mixture 40WFA+60FS1 was not sufficient, as the UCS decreased from 380 kPa to 200 kPa (about 50 %) during the freeze-thaw test. On the other hand, 8 % cement for the same mixture was sufficient, as the UCS decreased only about 30 %, from 610 kPa to 420 kPa during the freeze-thaw test. Finally, the results shown in *Figure 4-23* indicate, that it might be feasible to compensate part of cement with some suitable industrial residue. For example, as 6 % cement in the mixture 60CFA+40FS4+6C was compensated with 8 % of a binder mixture C+D (one part of cement with 2 parts of flue gas desulphurisation residue), the UCS (after no fatigue load) improved from 500 kPa to 800 kPa, and the UCS (after freeze-thaw test) from 120 kPa to 420 kPa.

When using dry FA the need for binder is often non-existent or clearly smaller than when using FA alone. The fatigue durability of fibre-ash materials essentially depends on the quality and proportion of the components (FA and FS) and on the quality and quantity of the binder. Therefore, to obtain adequate geotechnical properties for fibre-ashes, the mix optimisation is significantly more demanding than in the cases of pure FA materials. As shown in *Figure 4-23* there is a poor correlation between the UCS and the freeze-thaw durability of fibre-ashes. This fact emphasizes the importance of freeze-thaw tests on fibre-ash mixtures.

Gypsum-ash mixtures, when mixed with pile-FA, require binder to obtain adequate freeze-thaw durability. In addition, with gypsum-ash mixtures a dry FA may decrease the need for a binder or even eliminate the need for a binder. *Figure 4-24* shows that adequate freeze-thaw durability can be achieved with the right choice of binder, and with a binder quantity that exceeds a threshold value. In these cases the best binder was a mixture of blast-furnace slag (M) with cement (C) in a proportion of 1:1. The threshold quantity of the binder in that case was 3-5 %, since with 3 % of binder the freeze-thaw durability was far too low, but with 5 % it was excellent.
Slag-ash mixtures have exhibited excellent durability values. *Figure 4-25* indicates that the durability of these materials will be very good even with 10 % of FA and 2 % of binder (MC, 2:1), or with only 30 % of FA. This indicates that there is no need for binders when using an adequate quantity of FA.

4.5.2 Frost susceptibility

Frost susceptibility can be determined by utilising segregation potential, a parameter that has been determined for each material (shown in *Table 4-9*). The table also presents existing guidelines for frost susceptibility [5,15,28].

Table 4-9 refers to studies that have been conducted using pre-moisturised or imitated pile-FA, and dry FA. It has been observed that the segregation potential SP_o is smaller in materials based on dry FA than in pile-FA materials. There is also correlation between SP_o and frost resistance [15]. It can also be observed that if the $SP_o < 0,2$ the frost resistance of the material will be very good, and if the $SP_o \geq 0,5$ the frost resistance of FA materials (except fibre-ashes) can be critical. In the case of fibre-ashes the critical limit can be as high as $SP_o = 1,0$. As a rule, the higher the SP_o the weaker the frost resistance of a material. SP_o can be decreased (improved) with the use of binders. In fibre-ashes the SP_o can be improved by increasing the quantity of FA and binder. The SP_o of gypsum-ashes can be improved by increasing the quantity of binder. The SP_o of slag-ashes will be very small even when small quantities of binder and FA are utilised.

Table 4-9: Frost susceptibility (segregation potential) of different materials

Materials tested		Segregation potential, SP_o [mm^2/Kh]	Evaluation
FA	FA + 15 %D + 3…5 % BI	< 0,1	not susceptible
	FA + 3…7% BI	0,1 – 0,6	slightly susceptible
Fibre-ashes	FS + 20…40%FA + 3…9 %BI	0,11 – 0,59	slightly susceptible
	FA + 20…100% FS + 6…14%BI	0,5 – 2,0	slightly susceptible / susceptible
Gypsum ashes	G +10%FA + 4…6%BI	1,0-1,2	slightly susceptible / susceptible
Slag – ashes	S +10…50%FA + 6% BI	< 0,1	not susceptible
Abbreviations		Guidelines [28]	
FA	Fly ash (CFA, MFA, PFA)	< 0,18	not susceptible
BI	Binder (cement, lime and their mixes)	0,18 – 0,72	slightly susceptible
D	Desulphurisation residue	0,72 – 3,6	susceptible
		> 3,6	strongly susceptible

4.5.3 Biodegradability

Fibre-ashes contain organic material, i.e. fibres. No previous studies were found dealing with the biodegradeability of these mixes, e.g. for road applications. Full-scale test structures yield information about this aspect, but there is a need for laboratory testing as well.

The biodegradability of fibre sludge has been studied utilising OECD Method 301F (OECD Guideline 1992). Method 301F is a Manometric Respirometry Test that is being applied in the laboratory of Envitop Oy in Oulu. Degradation is followed by the determination of BOD (Biological Oxygen Demand) as a portion of the COD (Chemical Oxygen Demand). Thus, biodegradation is expressed as BOD/COD (%). The acceptable level for characterising readily biodegradable material (rapid biodegradation in an aquatic environment under aerobic conditions) is 60 % in 28 days. Values less than 60 % indicate that the materials cannot be considered readily biodegradable. In general, the biodegradability of fibre sludge or its mixes with FA has been less than 60%, i.e. typically 18 … 58 %. (Envitop Oy, Oulu).

4.6 Environmental impacts

The environmental impact of FA and FA mixes in soil structures can probably be best determined by the release of environmentally harmful and soluble constituents from the material into the soil and groundwater over long periods of time. For this doctoral thesis environmental impacts have been determined from tests using the methodology described in Chapter 3, i.e. the leaching tests performed according to the Dutch standards NEN 7343 (column test). *Table 4-10* presents the test results on the materials [5,15].

Table 4-10:Results of column test (NEN 7343) on FA materials. [5,15]

Materials	Constituent [mg/kg (L/S10)]											
	As	Cd	Co	Cr	Cu	Mo	Ni	Pb	Sb	Se	V	Zn
CFA1						**3,96**						
CFA2	0,015	0	0,355	0,553	0,04	**4,895**	0,03	0,151	0,021	**1,125**	0,355	**1,549**
PFA1	0,021	0,008	0,001	0,113	0,001	**4,96**	0,002	0,001	0,006	**0,183**	1,28	0,08
PFA2	0,04	0,004			0,01		0,11					0,76
PFA3	**0,159**	<0,001		0,185	<0,005	**0,362**	0,016	0,005			1,095	
MFA1	0,11	0,006	0,003	0,102	0,22	**0,407**	0,01	0,022	0,002	**0,5**	0,02	0,84
MFA2	**0,24**	**0,02**	0,02	1,446	0,214	**1,952**	0,059	0,048	0,021	**4,927**	0,058	0,60
WFA1+3Ce	**0,145**	**0,025**	0,02	1,182	0,236	**4,358**	0,06	0,093	0,021	**5,0**	0,216	0,447
Slag (without ash)	0,002	**0,029**	<0,003	**3,2-8,9**	0,04-0,1	**23-43**	0,02-0,1	0,08	0,002	0,05	0,003	0,03
Slag-ash (30 % MFA)	<0,02	0,010	<0,01	0,63	<0,02	**5,66**	<0,04	0,08	<0,02	<0,5	<0,02	0,33
Fibre-ash	0,06	0,001	0,016	0,005	0,002	0,001	0,28	0,001	0,001	0,008	0,026	0,007
Guide values [31]												
Group 1	0,14	0,011	1,1	2,0	1,1	0,31	1,2	1,0	0,12	0,06	2,2	1,5
Group 2	0,85	0,015	2,5	5,1	2,0	0,50	2,1	1,8	0,40	0,098	10	2,7

Group 1: Recycled material layers have to be covered (e.g. with crushed stone) to prevent the transport of material particles into the environment, or any human or animal to come into direct contact with the material. Figures exceeding these values are marked with bold letters

Group 2: Water infiltration through the recycled material layer must be prevented by asphalt or other impermeable pavement. Figures exceeding these values are marked with bold letters + underlines. In this case a specific risk analysis is required.

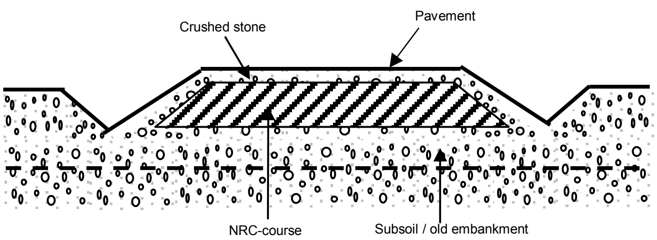
Table 4-10 includes the guide values that have been suggested by the Finnish Environment Centre [31]. Many of the suggested guide values are stricter than the Dutch guide values on which the suggested ones are based. The guide values for molybdenum (Mo) and selenium (Se) are extremely strict in comparison with the practise in other countries. In general, according to several international sources, the leaching of Mo and Se from ashes is not considered an environmental risk. However, when comparing the leaching of materials in Table 4-10 with the suggested guide values it can be noted that the leaching of Mo and Se will usually exceed the guide values, except in the case of fibre-ash. The environmental impact of FA and FA-mixes will be discussed in greater detail in section 5.5.

5 FULL-SCALE TESTS ON NRC-STRUCTURES

5.1 Different types of NRC-structures

NRC-constructions differ from conventional constructions both in materials and in structures. The differences in materials and material properties were described in Chapter 3. *Figures 5-1… 5-3* show the basic types and the principles of implementation for one type of NRC-solid structure (Figure 5-1), the stabilisation of old road structures (Figure 5-2) and the mass-column stabilisation (Figure 5-3) based on recycled materials.

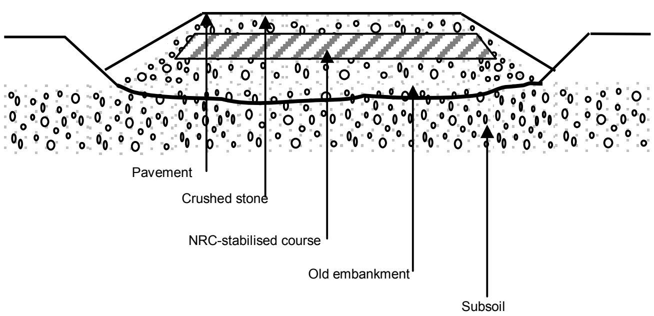
Dozens of former structure types based on different industrial residue mixes have been tested in full scale in Finland, mainly in co-operation with SGT and the Finnish Road Administration (FinnRa). Most of the test structures involve different applications of fly ashes. Laboratory tests on fly ash mixtures for mass – column stabilisation have given promising results but, until now, all full-scale tests have been carried out with other types of industrial residues. Therefore, a more detailed discussion on mass – column stabilised structures will be excluded and Chapter 5 will concentrate on the experience and test results of NRC-solid structures and the stabilisation of old road structures.



Principles of Implementation

1. Removal of the old pavement and, probably, its subsequent reuse in the new structure
2. Planing of the surface to support the road edges
3. Compaction of the subsoil/old embankment
4. Production of the NRC material course (≈ 200 mm): mixing,transport, spreading and compaction
5. Spreading and compaction of the crushed stone layer (50-100 mm)
6. Paving

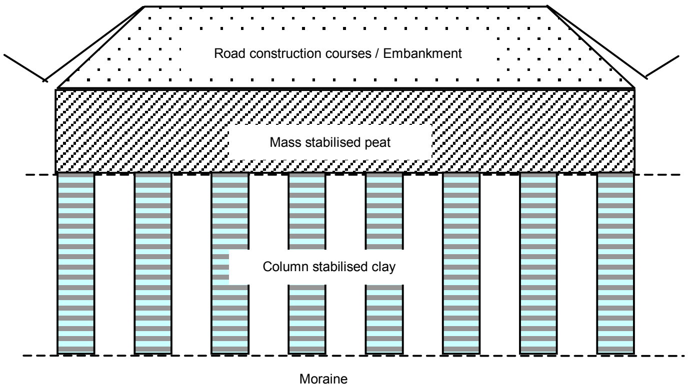
Figure 5-1: The basic type of NRC-solid structure



Principles of Implementation

1. Removal of the old pavement / surface and, probably, its subsequent reuse in the renovated structure
2. Stabilisation of the old course with a NRC - binder mixture (200-250 mm)
3. Compaction after stabilisation
4. Spreading and compaction of a crushed stone course (50-100 mm)
5. Paving

Figure 5-2: The basic type of renovation by NRC-stabilisation



Principles of Implementation

1. Removal of trees, stumps, stones etc. (at a new construction site) or removal of an old embankment (at an existing construction site)
2. Column stabilisation
3. Mass stabilisation
4. Construction of the embankment and other upper structures

Figure 5-3: The basic type of mass-column stabilisation

5.2 Test sites

Table 5-1 describes the structures, materials, time of construction and equipment tested for NRC-construction at 18 full-scale test sites that consisted of 32 different test structures [I, II, VI, V]. The NRC- materials that have been used in the test structures include different types of FA from the incineration of coal, peat, wood and miscellanous fuel, different types of fibre sludge and one type of gypsum. The test structure types are different NRC-solid structures (23 FA – structures, 6 fibre-ash structures, 1 gypsum-ash structure) and NRC-stabilisation for the renovation of old roads at three sites. Mixtures of stainless steel slag and FA have not yet been constructed nor tested at full scale in spite of promising laboratory test results.

Table 5-1: Full-scale test sites for recycled construction [15]

TEST	SITE	YEAR	STRUC-TURE	MATERIALS	TESTED EQUIP-MENT
FA (solid)	Pirkkala, Savontie	1992	A	MFA + 4(M + Ce, 1:2)	II
	Luopioinen, Rajalantie	1996	A	MFA + 4(M + Ce, 7:3)	II
	Sipoo, Knuters (I-III)	1997	A	CFA	I
			A	CFA + 25FGD	I
			A	CFA +5Ce	I
	Koria	1998	A	MFA1 + 3Ce	I
			A	CFA + 6T	I
			A	MFA2	I
	Jämsä	1998	A	MFA1 + 4Ce	III
			A	MFA2 + 6,2Ce	III
	Laitila	1998	A	CFA + 3T	I
			A	MFA + 5T	I
	Juankoski, Vehkalahti	1999	A	MFA + 6Ce	I
			A	PFA1 + 6Ce	I
			A	PFA2 + 9Ce	I
	Mustasaari	1999	A	CFA + 6Ce	III
			A	CFA + 2CC + 4,5Ce	III
	Tornio	1999	A	MFA + 4Ce	III
			A	MFA	III
	Inkoo	2000	A	CFA + 15FGD + 5L	IV
	Oulu	2000	A	PFA1 + 6,5Ce	IV
			A	PFA2 + 7Ce	IV
FA as Binder	Laitila	1998	B	Binder 15(CFA + M, 4:6)	V
	Maaninka	1999	B	Binder [8(FG+10FA)+4(M+Ce, 7:3)	VI
	Inkoo	2000	B	Binder 7(CFA + FGD + Ce, 1:1:1)	V
Fibre-Ash	Luopioinen, Rajalantie	1996	A	FS + 40MFA + 5Ce	VII
			A	FS + 20MFA + 9Ce	VII
	Jämsä	1998	A	(FS1 + MFA1, 10:3) + 7Ce	III
			A	(FS2 + MFA2, 45:55) + 7Ce	III
			A	(FS3 + MFA3, 2:10) + 6,2Ce	III
	Inkoo	2000	A	(CFA + FS, 10:4) + 14(FGD +Ce, 2:1)	IV
Gypsum-Ash	Maaninka	1999	A	PG + 10PFA + 4(M + Ce, 7:3)	VI

Note

TYPE OF STRUCTURE	**TYPE OF EQUIPMENT**	Test sections in Luopioinen and Tornio have asphalt pavement. Other test sections have been covered with crushed stone.
See Figure 5-1 and 5-2 A = Solid NRC-structure B = Renovation of old road structures by NRC stabilisation	I = Stationary mixing plant II = Concrete mixer III = “Sami”-mixer IV = “Maamyyra” V = Milling mixer VI = Stack mixer VII = Screening scoop	Abbreviations of materials: see List of Symbols

5.3 Tests on recycled structures

The NRC-structures have been tested to ascertain their geotechnical behaviour and environmental impacts. The studies have involved measurements using instruments that have been installed at the test sites, tests on material samples and direct measurements of the structures.

The properties of NRC-materials have been measured as accurately as possible during construction, especially the following properties; water content; compactibility; binder quantity; proportion of components in the mixture; and the density of the final structural layer. These measurements are very important for assessing quality management during construction. They also have significance when assessing the quality of the NRC-structure and when investigating the reasons for a structure that achieved a lower quality level than originally targeted.

The test structures have been equipped with geotechnical instruments that electrically measure frost heaves, settlements, temperature and water content. Frost heaves and settlements are determined with potentiometers that have been wire-anchored below the maximum frost penetration depth. Measurements of temperature are made with thermo-elements (poles) at different depths of the structure and the subbase. Water contents in the structure are determined with a calibrated moisture gauge measuring dielectricity. The geotechnical instruments have been installed in the test structures in a similar manner as shown in *Figure 5-4*.

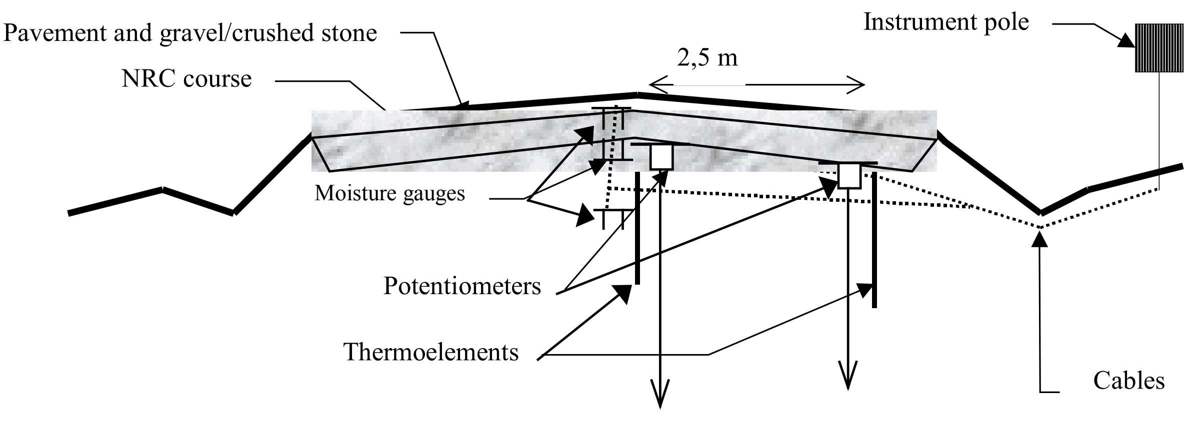


Figure 5-4: Geotechnical instruments in the test structures

Almost all test structures have also been equipped with groundwater pipes. The groundwater pipes have been installed a few meters off to the sides of the test structures, below the depth of groundwater flow, in order to observe the groundwater quality. Additionally, the test sites in Sipoo have been installed with lysimeters under the test structures for CFA and CFA + 25 FGD and, for comparison, under the reference structure. The lysimeters are used to determine water quality that is infiltrating through the structures. A schema of the groundwater measuring system is shown in *Figure 5-5*.

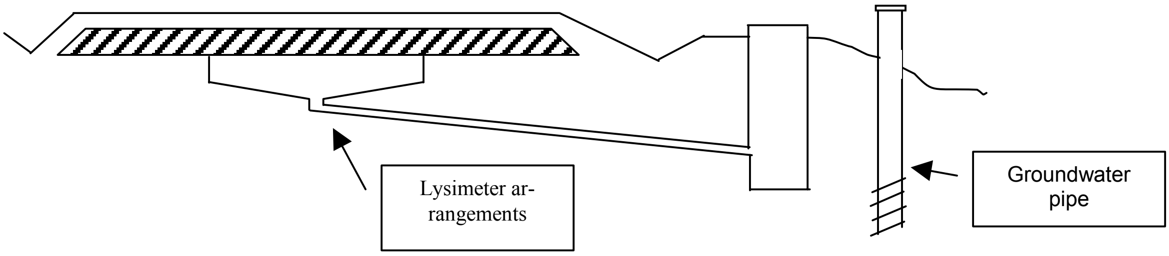


Figure 5-5: A lysimeter and a groundwater pipe. The principle of test arrangements in Sipoo

In addition to the measurements with geotechnical instruments, follow-up tests at the test sites included measurements of bearing capacity, damage observations, and studies and sampling of test pits at certain intervals. The tests on test pit samples have yielded significant additional information about the long-term behaviour and durability of materials and structures.

5.4 Storage, equipment and work methods

The quality of a NRC-structure will be significantly affected by the storage of materials and by the equipment and work methods used in the construction process. In NRC-construction the following factors are the most important ones that affect the quality of the construction:

1. Storage of materials
2. Mixing of the recycled material mass
3. Mixing in the stabilisation of the old structure for renovation
4. Compaction of the NRC-structure that is preceded by properly finished subbase and edge supports.

Storage

The storage method has a particularly significant effect on the quality of FA. The best recycling properties can be obtained when a FA has been stored dry. The longer a moisturised material is stored the greater the amount of its reactivity that will be lost. This has been shown in the laboratory tests (see Chapter 3). At present, power stations have very little dry storage space for FA in Finland. The fact that the major part of the FA is produced during the cold winter season is an additional problem, as the FA should be stored dry for successful NRC-constructions during the warmer season (late spring – summer – early autumn). Therefore, large dry storage facilities with capacities of 10 000 m^3 to 100 000 m^3 are a most important precondition for the implementation of extensive recycling of FA in soil construction applications. Steel silos are expensive solutions, but there also exist less expensive alternatives in the world, though less known and implemented. The storage of FA is a problem because it loses its fluidity when stored (it loses its fluid powder structure and becomes compact when stored).

The full-scale research projects that have been referred to in this doctoral thesis have primarily dealt with FA that have been stored in open-air piles for differing time periods. This is because of the shortage of dry FA. Only a few test structures have been constructed with dry FA that have been transported directly from power station's production or silo to the construction site (e.g. the NRC-stabilisation sites for the renovation of old roads). Otherwise the FA have been transported slightly pre-moisturised in truck platforms to open-air piles at temporary storage sites. The FA piles have been formed without compaction i.e. as loose as possible in order to avoid any strength development during the storage. The water content of the FA in piles would depend on wind and rain conditions. Therefore the piles have to be moisturised or covered. The length of storage varied with the capacity of the FA producer and the size of the construction project.

Storage of other residues, like fibre sludge and phospho-gypsum did not involve as many problems as the FA, because these materials inherently have high water contents. Also wetting and drying conditions do not have much effect on the properties of these materials during short-term storage.

Mixing of the NRC-mass

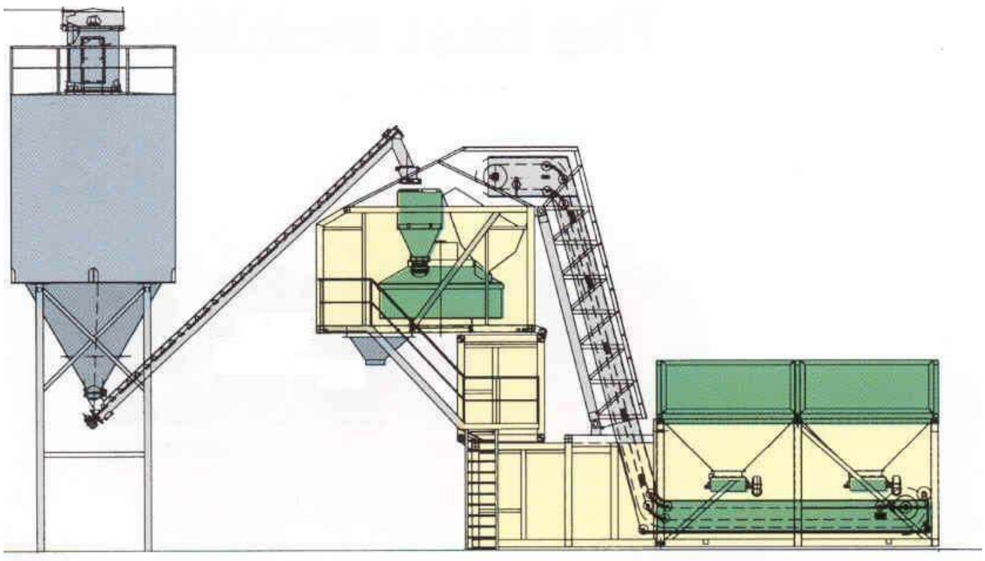
The efficiency of the mixing equipment largely affects the quality of materials such as fibre-ash and the gypsum-ash. Other factors that significantly control the quality of NRC-materials are the precision of the component proportions and the binder quantity. Different mixing equipment have been tested during the projects involved with test construction. The equipment, as well as their weaknesses and strengths, have been described in *Figures 5-6… 5-11*.
The tests on the equipment have shown that the development of special mixing equipment for NRC-materials is a formidable challenge for the equipment manufacturers. The mixing equipment has to be economical and have a high production capacity in addition to producing high mixing quality. A stationary mixing plant will be justified only in cases where the manufacture (mixing) of NRC-material masses will take place close to the storage point. Otherwise the mixing equipment should be easily movable from one construction site to another.

Mixing in the stabilisation of old road structures for renovation

The following equipment has been tested at the test sites: the Spring Harrow together with farming tractors, the Road Scraper and a special Milling Mixer for stabilisation. "Maamyyra" could also be used in the stabilisation of road courses, but this has not been sufficiently tested to date.

The Spring Harrow was used in order to find a cost effective mixing method. This equipment has clear deficiencies although the properties obtained for the test structures were fairly good. A road course that will be stabilised must be well loosened with a Road Scraper before mixing. There will be dust problems before mixing because the binder has to be spread on the surface beforehand. Stabilisation will be relatively slow because the Spring Harrow must be run over the length of the construction several times to achieve a moderate outcome. Additionally it is not possible to mix the binder into the total depth of the layer (e.g. 20 cm). The maximum depth of stabilation was 10 – 15 cm.

Also mixing results were relatively poor with the Road Scraper. The Milling Mixer operated efficiently throughout the total depth of the course, and had a fairly high production capacity. The Milling Mixer will be economical for large construction projects.

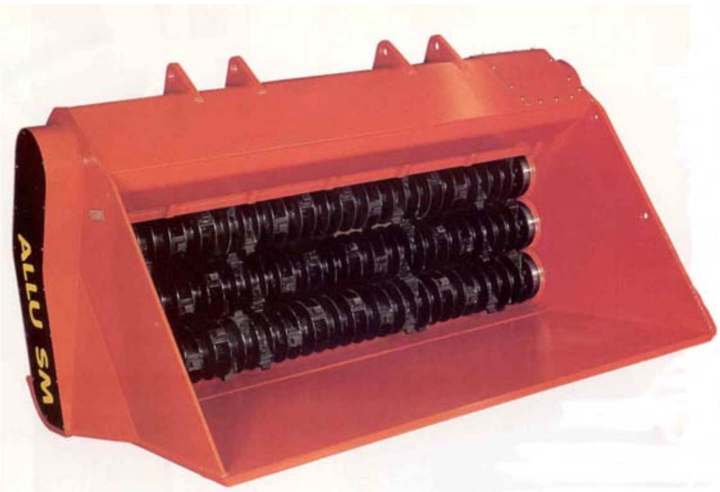


MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
Stabilised FA FA + FGD	Precise proportioning High production capacity	Expensive: high transfer and construction costs Incompatible with fibre materials Immobile

Figure 5-6: Stationary Mixing Plant

MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
- Fibre-ash - Stabilised FA	- Low costs - Moderate production capacity - Fair mixing results with fibre sludge	- Inaccurate proportioning - Dust problem

Figure 5-7: "SAMI"-Mixer



MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
- Fibre-ash	- Low costs - Moderate production capacity - Mobile	- Inaccurate proportioning - Dust problem - Poor results with fibre sludge

Figure 5-8: Screening Scoop

MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
- Gypsum-ash	- High production capacity - Cost effective in large construction projects	- No tests with fibre sludge or other than gypsum-ash - Moisturising - Dust problem

Figure 5-9: Stack Mixer

MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
- Fibre-ash - Stabilised FA	- Good mixing results with fibre sludge - Mobile	- Small producti-oncapacity - Dust problem - Inaccurate pro-portioning

Figure 5-10: "Maamyyrä"

MATERIALS AT THE TEST SITE	STRENGTHS	WEAKNESSES
Tests in laboratory with - Gypsum-ash - Fibre-ash	- Very good results in laboratory tests - Accurate proportioning	- Low production capacity - Energy intensive - Expensive

Figure 5-11: Impact Mixer (prototype)

Compaction of the NRC-structures

Various aspects of the compaction of FA courses have been studied, i.e. in relation to the water content, thickness of the course, and the compaction equipment and methods, during the "Tuhkat Hyötykäyttöön" – project [6]. The studies have shown that a layer having a depth of at least 20 cm can be compacted to 92 % - 95 % of the maximum Proctor density value. This can be achieved if the water content of the FA is within certain ranges around the optimum water content, and if the compaction is performed with proper equipment and work methods. The FA course can be efficiently compacted with a 5 tonne Smooth Drum Vibratory Soil Compactor with a proper stroke length. Only the surface will remain loose and it must be compacted later, e.g. using a Rubber Roller or through a thin (approximately 5 cm) layer of crushed stone or gravel. This can be seen in *Figure 5-12*.

Figure 5-12: Testing of the FA compacting methods [6]; a) A Smooth Drum Vibratory Soil Compactor is compacting deep but leaving a scalelike surface which b) can be compacted through a thin course of crushed stone.

At the test sites the compaction was carried out after spreading and pre-compaction. The pre-compaction was done using a spreading machine, a truck or a Road Scraper running over the construction length for several passes.

The compaction of the sides of a NRC-structure requires special measures in order to prevent excess looseness and inadequate cementation. *Figure 5-13* shows the principles of two simple but successful methods that have been tested at the full-scale test sites.

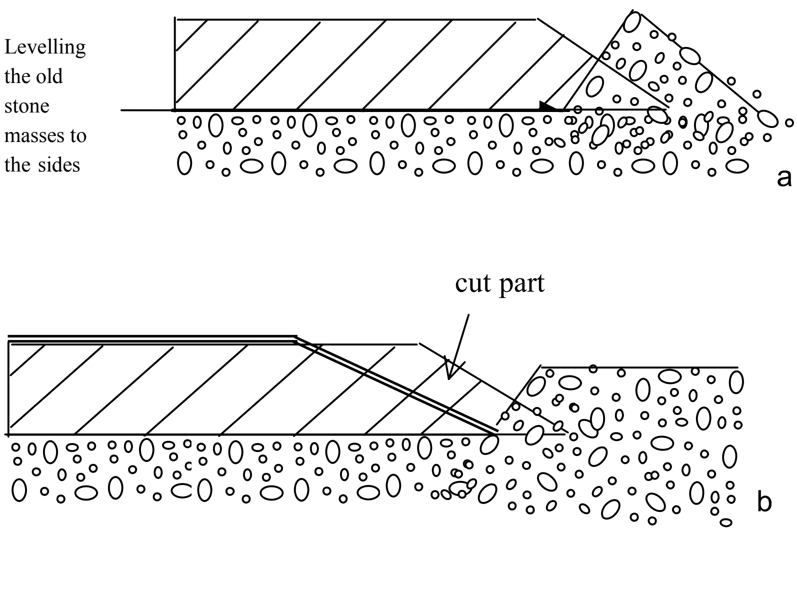


Figure 5-13: Principles to ascertain the compaction of the road side in NRC-construction; a) Side support; b) an extra wide structure where a part can be cut away.

5.5 Follow-up studies

Homogeneity, compactibility and strength development

Follow-up studies at the test sites have been carried out for 0 – 8 years. *Table 5-2* summarises the results of tests and measurements during the construction and follow-up periods.

Table 5-2 indicates the relatively wide variation of the water content in the material masses. As a rule the water content has been less than the optimum, which is safe in regard to the success of the compaction. At the site of Knuters it was possible to achieve very high precision with the help of the stationary mixing plant. However, the targeted relative compaction has been achieved at almost all of the test sites. At the MFA-section of Laitila considerably high water contents were measured that resulted in a low degree of compaction and softening during the thawing period of the first spring following the construction.

At the first fibre-ash site (Luopioinen) the mixing of FS with FA was not quite satisfactory with the use of a screening scoop. For this reason it was not possible to achieve the targeted relative compaction. Despite this the structures have been performing as expected, which indicates that the fibre-ash structures allow wider tolerances than only FA structures. At the site of Jämsä the fibre-ash structures were constructed using the "Sami"-mixer, and the better mixing quality resulted in a higher relative compaction.

In Maaninka, the gypsum-ash section where the subsoil is mainly silt was constructed in the early spring. During the construction a part of the road's subsoil was very wet and its bearing capacity was very low. Consequently, the compaction of the gypsum-ash layer above the soft and wet subsoil was not totally successful. However, the road has been performing quite well.

At most of the test sites samples have been taken by drilling or from a sampling pit at different time periods. The samples have been tested, e.g. for strength (UCS), that indicates the minimum strength achieved at the test section. The UCS results of FA and FA-mixes have to be considered with some reservations because these materials are often relatively brittle. In general the materials become more brittle as the strength develops with time. This can be seen in the results from Knuters: after 330 days the UCS of the samples taken from the sampling pits were larger than after 690 days. Penetrometer results measured in the sampling pits showed opposite results.

The results from samples of certain test sites showed significant strength development between the ages of 1 month and 12 months, for example the MFA-sections of Tornio and the CFA-sections of Mustasaari. The oldest site (8 years old) at Pirkkala shows that despite a thin structure and heavy (timber) truck traffic the strength of the FA structure of this gravel road has remained close to the target strength.

The targeted bearing capacity has been well achieved and the condition of the roads have remained essentially excellent at all of the FA sites and renovated FA-stabilised sites. The bearing capacity of fibre-ash and gypsum-ash structures has not become as high as the FA sites. However, the fibre-ash structures (with their excellent stress-strain properties) have been often observed to withstand the fatigue loads and settlements better (without breaking) than the structures utilising only FA.

Table 5-2: A selection of results of follow-up studies at the test sites

NRC	Site	Year of const.	Material mix	Water content [%]		Relative compaction (Proctor) [%]		UCS [MPa], 28 d		UCS from samples from the test site at a certain age of the structure [days / MPa]		Bearing capacity, mean, road midline E_2 [MPa]			Noted condition during follow-up	
				optimum	Measured variation	Target	Measured variation/ mean	Lab.	from materials mixed at site	I sampling	II sampling	Before constr.	After constr.	Year after constr.	Age of the structure [years]	
FA (solid)	Pirkkala	1992	MFA + 4(M + Ce, 1:2)	18,5	46-51	95	90-97	1,3	1,4-1,8	360/ 1,1-1,3	1800/ 0,9-1,5	30	90	1997	8	Good
	Luopioinen	1996	MFA + 4(M + Ce, 7:3)	17,5	19-23	90-95	79-82	2,48	n/a	28/0,27	n/a	69	118	1999	4	Good
	Sipoo, Knuters	1997	CFA	27	16-31	92	89-95/92	0,5	0,45	330/0,47	690/0,17	42	171	2000	3	Good
			CFA + 25FGD	24-26	22-25		75-98/93	2,2	1,78	330/1,85	690/0,74	61	376			
			CFA +5Ce	33	24-36		91-97/96	1,2	1,07	330/1,13	690/0,48	90	167			
	Koria	1998	MFA1 + 3Ce	19,5	15-23	94	92-94	4,1	2-3	360/1,7-3,4	-	44	140	2000	2	Good
			CFA + 6T	28	23-28	92	92	8-9	3	360/1-2,9		47	113			
			MFA2	18,5	19-22	92	90	6,9	3	360/1,7-4,5		98	120			
	Jämsä	1998	MFA1 + 4Ce	38,5	34-38	92	91-93	3,9	1,5-2	360/0,8-0,9	-	65	109	2000	2	Good
			MFA2 + 6,2Ce	46	30-42	93	91-94	2,3	1,5	360/0,6-0,8		55	102			
	Laitila	1998	CFA + 3T	23	20-25	92	91-92	2,2	2	360/2,7-3	-	55	170	2000	2	Good
			MFA + 5T	45	31-60		85-88	2,1	<1	360/0,4-0,6		45	105			
	Juankoski, V	1999	MFA + 6Ce	42	30-36	92	90-92	>7,3	2,5-6,9	360/3,9-5,3	-	75	n/a		1	Good
			PFA1 + 6Ce	36	31-36			1,3	0,8-1,2	360/1,1-1,4		44				Fair
			PFA2 + 9Ce	38	35-40			2	1,1-1,2	360/0,6-1,3		48				Good
	Mustasaari	1999	CFA + 6Ce	37	19-25	91	89-92	2,3	1,5	360/3,9-5,5	-	94	163	2000	1	Good
			CFA + 2CC + 4,5Ce	37	22-25		90-92	1,5	1,5	360/1,5-3,1		81	114			
	Tornio	1999	MFA + 4Ce	31	20-24	91	88-89	4-5	2,5	360/7,7-8,5	-	76	132	2000	1	Good
			MFA	31,5	20-24	92	91-93	3	2,5-3	360/4,7		118	221			
FA as Binder	Laitila	1998	Binder 15(CFA + M, 4:6)	6,2	4,2-6,6	95	91-95	1,7	0,4-0,6	360/0,2-1,2	-	56	82	2000	2	Good
Fibre-Ash	Luopioinen	1996	FS + 40MFA + 5Ce	40,9	40-46	90-95	85-86	0,7	n/a	30/0,45[1]	360/0,11	94-134	46-69	1999	4	Good
			FS + 20MFA + 9Ce	51,2	52-56		87-88	0,4	n/a	30/0,22[1]	360/0,22	38-68	23-39			
	Jämsä	1998	(FS1 + MFA1, 10:3) + 7Ce	56	60-68	96	97-100[2]	0,3-0,4	0,4	360/0,2-0,5	-	71	67	2000	2	Good
			(FS2 + MFA2, 45:55) + 7Ce	65	59-73	97	≈ 100[2]	0,6	0,4	360/0,3-0,4		77	98			
			(FS3 + MFA3, 2:10) + 6,2Ce	51	39-50	92	90-92	0,6-0,7	0,5-0,6	360/0,2-0,4		40	87			
Gypsum-Ash	Maaninka	1999	PG + 10PFA + 4(M + Ce, 7:3)	18	14-22	95	83-90	1	1-2	90/0,5-1,5	360/0,7-1,2	60	92	2000	1	Good

1) ε = 10 % ; 2) in relation to the maximum density, **not** the maximum **dry** density

Freezing and frost heave

Freezing of the test structures has been controlled with Thermoelement Poles. As there are major variations in the annual thermal loads the freezing at a given NRC-test structure should be compared to the freezing of a conventional reference structure at the site. *Figure 5-14* shows the results of frost heave measurements at a test site (Luopioinen) and *Figure 5-15* the maximum frost depth at the same site from 1997 to 2000. The results were obtained from the fibre-ash sections (KT1 and KT2) and from the reference crushed stone section (MK). *Figure 5-14* shows that the frost heave has been on average 80 % (KT1) and 57 % (KT2) less than the frost heave of the reference structure (REF). Tests on other FA and fibre-ash structures of 200 mm thickness have shown similar results. Tests on gypsum-ash and slag-ash materials have not shown as low frost heave results as fibre-ash materials.

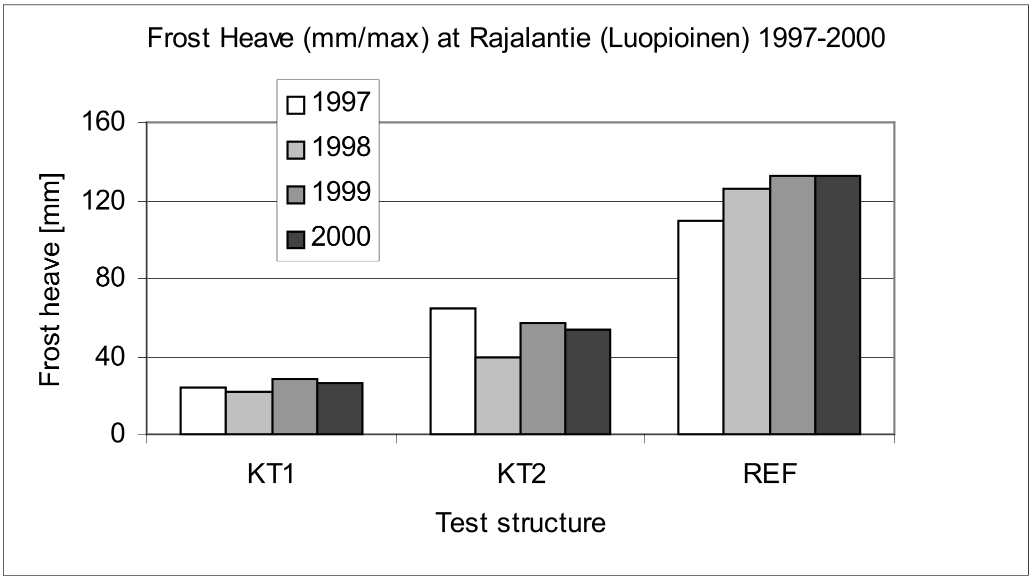


Figure 5-14: Frost heave at the Rajalantie test site in Luopioinen 1997 – 2000. KT1 = FS + 40MFA + 5Ce; KT2 = FS + 20MFA + 9Ce; REF = conventional crushed stone structure

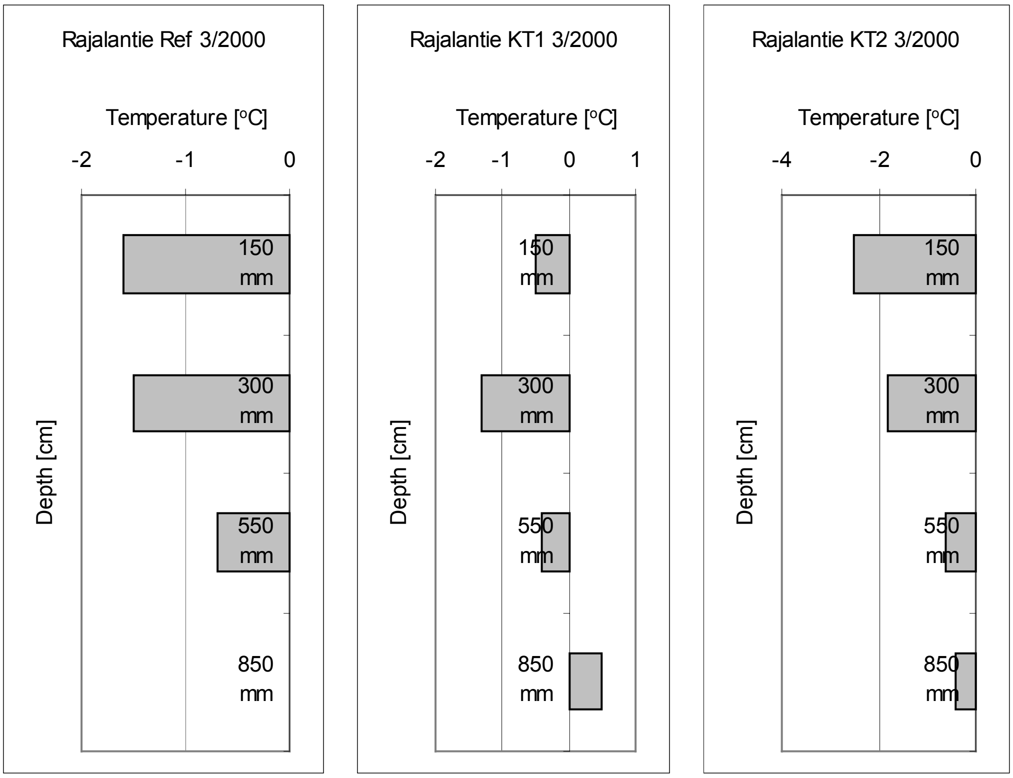


Figure 5-15: Frost depth at the Rajalantie test site in Luopioinen 1997 – 2000. KT1 = FS + 40MFA + 5Ce; KT2 = FS + 20MFA + 9Ce; REF = conventional crushed stone structure

Temperature during cementation

When using FA or FA-mixes the prevailing temperature during and after construction has a significant effect on the start of cementation. The cementation will start only at temperatures above 4,0 °C. The pozzolanic reactions do not initiate at temperatures lower than + 4,0 °C and the strength of the FA-material will be very low. Also, at temperatures below 10 °C cementation will occur very slowly. This was evident at a test site in Inkoo in 2000 where the slow cementation of FA-materials kept the structures soft for a long time period and caused problems during the construction process. The mean temperature at the test site (+ 7 °C) was simulated during laboratory tests, and in comparison with tests at +20 °C the results were:

– the strength of CFA+15FGD+5CaO increased from 0,2 MPa to 0,4 MPa at 7 °C during the first 28 days and to 0,8 MPa during 60 days of cementation
– the corresponding strength development of this mixture was 3,6 MPa and 3,7 MPa at 20°C

For comparison, the same tests were made on a mixture of CFA+15FGD+5Ce. These tests indicate that the addition of cement tends to slightly improve the mix performance compared to lime at lower temperatures. The strength increased to 1,2 MPa, using cement, which is three times higher than with lime, during the first 28 days at 7 °C. *Figure 5-16* shows the results of the laboratory tests performed on laboratory-remolded test specimens as well as the results that were obtained with 1 – 1,5 months old samples taken from the test structure by drilling. A part of the drilled samples were stored at 20°C temperature for 30 days before testing. This storage period indicated that the cementation reactions started properly and the test specimens achieved the appropriate 20°C strength (> 3MPa) very quickly.

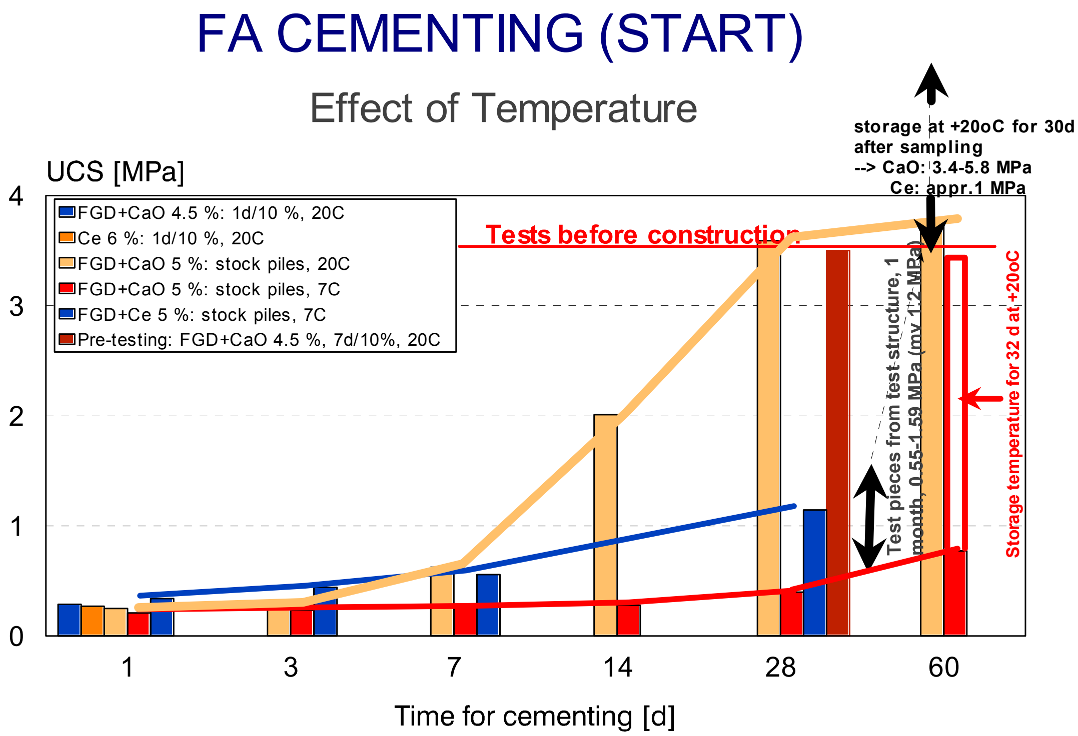


Figure 5-16: Strength development of FA-structures at different temperatures

Environmental impacts

The environmental impacts of the test structures have been studied primarily by analysing samples from groundwater pipes. To date, the results from all test sites have been very positive. The concentrations of potentially harmful substances in all groundwater samples have been either below detection limits or below the Finnish guide values for drinking water.

The analyses of lysimeter water beneath the test structures in Sipoo (see *Figure 5-5*) showed that there was some leaching of substances from the NRC-material courses directly to the environment. The concentrations of potentially harmful substances in the lysimeter waters below the FA-structure and the reference structure are presented in *Tables 5-3 and 5-4*. The results show, for example, that the readily soluble molybdenum leached from the FA-structure during the first year after construction.

After this the leaching of molybdenum is significantly less during the second and third year as shown in *Figure 5-17*. The FA+FGD -structure was quite permeable only during the first year after construction. Thereafter the lysimeters beneath the FA+FGD –structure have been totally dry, which indicates that the permeability of the structure clearly has decreased. The most probable reason for this was the development of ettringites in the FA+FGD -material.

The lysimeter waters obtained from the FA- structure (*Table 5-3*) also have high a chlorine content, but this is also the case with the lysimeter water obtained from the reference structure (*Table 5-4*). The reason for high chlorine values is the spreading of salt on the road during summer to prevent dust spreading from the road surface. The impact of salt spreading is so great that the impact of any chlorine leaching from the structure because of fly ash or FGD is only marginal. However, the leaching of sulphate from the test structure is sligthtly higher than that from the reference structure.

Lysimeters have also been installed at some fibre sludge test sites. However, the hydraulic conductivity of these structures has been so low that the lysimeters have remained dry for several control years. In these cases it is evident that infiltrating water will not infiltrate through the NRC-course, but will flow on the surface of the NRC-course, through the crushed stone course to the sides of the road.

Table 5-3: Substances analysed from lysimeter waters obtained from FA test structure (Sipoo, Knuters). At the same site and control period the lysimeter well of a FA+FGD structure has been dry, and no sampling has been possible for comparison.

Analysed item	Method	Unit	Drinking water guide-lines	Date of sampling				
				29.7.98	1.7.99	5.11.99	3.8.00	6.11.00
pH	SFS3021	-	6,5-9,5	11,58	11,2	8,8	7,6	9,3
Electric conductivity	SFS3022	mS/m	*<250*	990	406	800	730	900
Arsenic, As	AH102	mg/l	0,01	0,2	0,064	0,012	0,007	0,01
Boron, B	ISO9390	mg/l	0,3-*1*	1,8	<1	-	0,84	1,68
Chromium, Cr	SFS5074, 5502	mg/l	0,05	1,4	0,35	0,24	0,2	0,23
Molybdenum, Mo	AAS	mg/l	0,07	8	2	1,5	0,9	1,52
Selenium, Se	AH102	mg/l	0,01	0,2	0,065	0,020	0,07	0,033
Vanadium, V	AH102	mg/l	-	1,4	0,68	0,085	0,16	0,099
Sulphate ,SO_4	ISO/DIS 10304-2	mg/l	150-*250*	240	100	60	68	88
Chloride, Cl	ISO/DIS 10304-2	mg/l	100-*250*	2300	950	2400	2900	2900
Nitric-nitrogen, NO_2-N	SFS3029	mg/l	0,03-*0,15*	1,2	2,7	0,43	1,7	0,2
Nitrate-nitrogen, NO_3-N	ISO/DIS 10304-2	mg/l	6-*11*	10	4,5	1,7	16	1,2

Table 5-4: Substances analysed from lysimeter waters obtained from the reference structure (Sipoo, Knuters). The results can be compared with the results in Table 5-3

Analysed item	Method	Unit	Drinking water guide-lines	Date of sampling				
				29.7.98	1.7.99	5.11.99	3.8.00	6.11.00
pH	SFS3021	-	6,5-9,5	7,92	8,0	7,4	7,6	7,4
Electric conductivity	SFS3022	mS/m	*<250*	253	492	1850	2600	3100
Arsenic, As	AH102	mg/l	0,01	<0,01	0,0072	0,032	0,006	<0,01
Boron, B	ISO9390	mg/l	0,3-*1*	0,09	<1	-	0,04	0,14
Chromium, Cr	SFS5074, 5502	mg/l	0,05	0,006	0,006	0,062	0,008	0,003
Molybdenum, Mo	AAS	mg/l	0,07	0,017	0,021	0,036	0,02	0,013
Selenium, Se	AH102	mg/l	0,01	<0,02	0,0036	0,033	0,09	0,076
Vanadium, V	AH102	mg/l	-	<0,05	<0,001	0,001	0,003	0,002
Sulphate, SO_4	ISO/DIS 10304-2	mg/l	150-*250*	71	57	89	95	110
Chloride, Cl	ISO/DIS 10304-2	mg/l	100-*250*	670	1500	3900	2800	12000
Nitric-nitrogen, NO_2-N	SFS3029	mg/l	0,03-*0,15*	0,004	0,005	0,035	0,042	0,018
Nitrate-nitrogen, NO_3-N	ISO/DIS 10304-2	mg/l	6-*11*	0,9	0,75	0,77	15	2,9

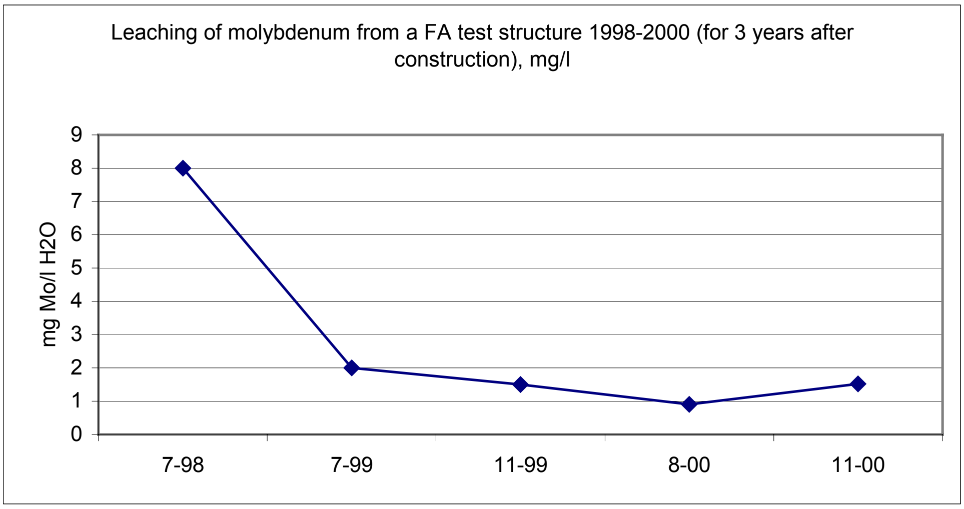


Figure 5-17: Leaching of molybdenum from the test structures in Sipoo (analysis of lysimeter waters)

6 EVALUATION OF NRC-TECHNOLOGY

6.1 Life Cycle

Full-scale tests on fly ash and its mixtures with other residues and binders have shown that these NRC-structures essentially differ from conventional structures based on natural stone materials. The mass of material required for recycled structures could be as low as 25 % of the mass required for conventional structures (see Ch. 6.2). Thus, there will be environmental benefits such as less transport of materials and, consequently, less consumption of energy and less emission of CO_2 and other pollutants. Furthermore, the NRC technology will reduce the disposal of valuable materials and consequently reduce private and public costs of waste disposal. Thus, less transport, less landfills as well as lower waste charges and taxes.

The lifetime of a structure and the long-term duration of its quality are factors that essentially contribute to its economy and other benefits. The data and information obtained from the full-scale test structures are indispensable for the evaluation of these factors associated with NRC-technology. On the basis of the follow-up studies and measurements it has been possible to prove that the lifetime of NRC-structures is longer, and the quality of NRC-structures will remain high for a longer period than conventional structures. Accordingly, the investment costs of NRC-construction can be distributed over a considerably longer time period and the maintenance costs are smaller, compared to conventional structures. Based on data and information from test structures *Table 6-1* presents estimates of the lifetimes of different NRC- structures in low-volume roads [15].

Table 6-1: Estimates of lifetimes of NRC-structures in low-volume roads. Lifetime is here the period between the construction and the renovation. [15]

STRUCTURE	LIFETIME [YEARS]
FA (solid)	30
FA as binder	30
Fibre-ash	40
Gypsum-ash	40
Slag-ash	40-50 (difficult to predict)
Crushed stone (conv.)	6-8
Crushed stone + filter cloth (conv.)	10-15

The studies noted above have given the following reasons for the excellent durability of NRC-structures:

- NRC-structures are based on the utilisation of cementatious materials that do not mix with subsoil or embankment materials as do the granular stone materials used in conventional structures.
- Flexible road structures with a 200 mm NRC-course can be well compacted in one course.
- The NRC-materials that have shown high long-term durability in laboratory tests have performed in a similar manner in test structures.

- In general, the NRC-materials have high (and fibre ashes have excellent) deformation durability that prevents failure when subjected to smaller frost heaves or settlements.
- Properties of FA such as strength development over a longer time period and self-healing behaviour are advantageous, compared to conventional structures.
- FA and fibre-ash structures become relatively impermeable ($k = 10^{-7}\ldots10^{-9}$ m/s). Therefore, water infiltrating through the structural layers above the NRC-layer will eventually be transported horizontally along the NRC-surface and not through it. As a result, the amount of water accumulating beneath the road structure will be minimal, minimising frost heave and loss of bearing capacity during freeze-thaw cycles.
- Paper sludge will first freeze below -5^{o}C [1] - according to the tests of SGT the freezing temperature is $-1 \ldots -3$ ^{o}C. This freezing point depression probably decreases the amount of frost heave in a structure.

6.2 Economic and Environmental Benefits

One of the most valuable environmental benefits obtained from using NRC-technology includes the preservation of non-renewable natural resources, since the use of gravel and crushed stone will be reduced. Accordingly, NRC-technology will protect the landscape, including beautiful and valuable areas of groundwater sources. Additional important benefits will be obtained by decreasing the amount of waste handling of industrial residues (see section 6.1).

NRC-technology will contribute to significant reductions in the use of natural stone materials. For example, by using NRC-materials (FA, fibre-ash, gypsum-ash, slag-ash) it is possible to achieve a bearing capacity of a road structure that is four times higher than a road constructed with crushed stone. Thus, a NRC-solid structure course of only 20 cm may substitute for a crushed stone course of 80 cm. Also, when reusing low-quality stone material from an old structure that is being stabilised with NRC-materials, it is possible to obtain a bearing capacity that is at least as high as the bearing capacity of NRC-solid structures (i.e. structures that consist of NRC-material only). The studies also indicate that there is almost no loss of bearing capacity of NRC-structures during freeze-thaw cycles in early spring. Reductions in the use of stone material will also be achieved because of longer lifetimes and the decreasing need for maintenance of NRC-structures. Also, NRC-materials and -structures are clearly lower in weight than stone materials.

Approximately 70 million tonnes of stone materials are consumed in soil construction in Finland every year. About 60 % of this amount is gravel and sand. An effective use of NRC-technology could contribute to the savings of stone material of about 24 %, or 16,5 million tonnes/year, i.e. almost the total amount of the yearly gravel consumption. The author has calculated the amount of hypothetically potential savings of stone material in Table 6-2. The calculations presented in *Table 6-2* exclude potential savings during maintenance.

The calculations are based on the following premises:

- The lifetime of NRC-structures is on the average two times longer than the life of conventional stone structures.
- The total amount of FA produced in Finland is approximately 1,2 million tonnes annually. The total amount of FA available for soil construction is approximately 0,85 million tonnes (roughly 70 %) each year.
- In comparison with conventional gravel structures the bearing capacity of NRC-structures will be (on average) four times larger for stabilised structures and slag-ash structures, three times larger for FA structures and two times larger for fibre-ash structures.

Table 6-2: Savings with NRC-technology. Calculations.

NRC- STRUCTURE	Use of residue [Mt/year]		Total length of a low-volume road [km][1)]	Savings of stone material [Mt/year]
	FA	Others		
FA structures	0,4	-	275	4,0
Fibre-ash structures; mixture 1:1	0,2	0,2 [2)]	140	2,6
Gypsum-ash structures having 15 % FA	0,1	0,67 [3)]	390	3,2
Slag-ash structures having 15 % FA	0,05	0,28 [4)]	150	2,7
Stabilisation of old road structures with 10 % binder	0,05	-	210	4,0
			1165	16,5

1) The amount of material (see: use of residue) can be used to construct a low-volume road, the width of which is 6 meters and the length of which is calculated in the column (total length of low-volume road)
2) Fibre sludge
3) Phosphogypsum
4) Stainless steel slag

One can conclude from the calculations shown in *Table 6-2* that the theoretical savings could be about 16,5 million tonnes annually in Finland. The assumed amounts of different residues used in *Table 6-2* are only part of the total amounts produced. *Table 6-3* shows estimates of the total amounts that could be used as NRC-materials in Finland, the amounts available for NRC-usage, and the primary areas of usage for each residue.

According to *Table 6-3* there should be sufficient material available when NRC-technology will become significant in the construction sector. The estimated amount of available FA (assuming a 70 % recycling rate) is relatively high. Therefore it is not likely that this figure will be higher, as there are also other uses for FA (e.g. for cement, as a filler in asphalt, and as forest fertiliser). Additionally, there is a relatively large variation in the seasonal and annual production of FA, depending on the prices of feedstock and energy as well as on energy consumption. Thus, the total amount of FA might occasionally be lower than the estimates shown in *Table 6-3*, and then the availability of FA could restrict the development and use of NRC-technology.

Table 6-3: Estimated availability of residues in Finland

RESIDUE	TOTAL AMOUNT FOR NRC-APPLICATIONS	AVAILABLE AMOUNT FOR NRC- APPLICATIONS		USAGE IN FINLAND
	Tonnes / year	Tonnes / year	% of total amount	
FA	1 200 000[1]	850 000	70	Southern and Central Finland
Fibre sludge	450 000[2]	200 000	45	Up to Southern Lapland
Phosphogypsum	1 200 000[2]	570 000	48	Eastern Finland
Stainless steel slag	300 000[1] (in 2000); appr. 500 000[1] (in 2002)	280 000 (in 2000)	90 (in 2000) 56 (in 2002)	Southern Lapland and Oulu region

1) dry weight
2) total weight

The former calculations used to quantify the potential for NRC-construction have significant implications for the development of the Finland's road network. In *Table 6-2* the calculations were used to estimate the total length of 6,0 meters wide low-volume roads that can be improved with NRC-technology annually. The average total would be about 1165 km / year. Although the former calculations were only applied to low-volume roads, the relative benefits of NRC-technology might be similar for other types of roads and field structures as well.

The total amount of industrial residues that is available for NRC-technology is estimated to be 1,9 million tonnes each year (estimated by the author). Presently, all of these residues are disposed of in landfills or used as secondary fillers. The disposal of this amount of industrial residues requires 30 landfill hectares each year (supposing the average heigth of the course is six meters and the average bulk density about one tonne/m^3). The construction costs of a landfill can be relatively high, largely depending on the prevailing requirements for the construction of landfill liners and covers. For a common municipal waste landfill, the costs of a bottom lining system is about 250 FIM/m^2, and the costs of a surface cover structure about 150 FIM/m^2 (based on calculations of different projects by SCC Viatek Oy). Thus, the construction costs of 30 landfill hectares will be approximately 120 million FIM. In addition to construction costs there will also be costs for transport, waste handling and waste taxes. Additional factors to be considered are the loss of land value in and around landfills, and environmental damage. It can be estimated that the total waste costs for disposal of industrial residues will be between 100 and 250 FIM/tonne. Thus, total waste costs to industry for disposal of the 1,9 million tonnes would be between 190 and 475 million FIM annually (without waste taxes).

The economy of NRC-technology has been summarised and discussed in a report dealing with a long-term study of different structures used for low-volume roads [29, 30]. Different low-volume road applications were compared relative to their differing geotechnical and environmental properties, and their relative economics were also compared. When calculating the costs of different applications total life cycle costs were considered. The construction costs are based on the data and information obtained from the test structures included in the study, and maintenance costs were based on the data supplied by FinnRa. *Figure 6-1* shows the total costs of different structures (FIM/road meter): the costs are calculated from the time of renovation until the time of the first minor repair at the site. The estimates for the life times of the different structures shown in *Table 6-1* have been based on the observations and measurements at the test sites. It should be noted that follow-up studies at different test sites will continue and estimates of the life-cycle costs and lifetimes should become more precise.

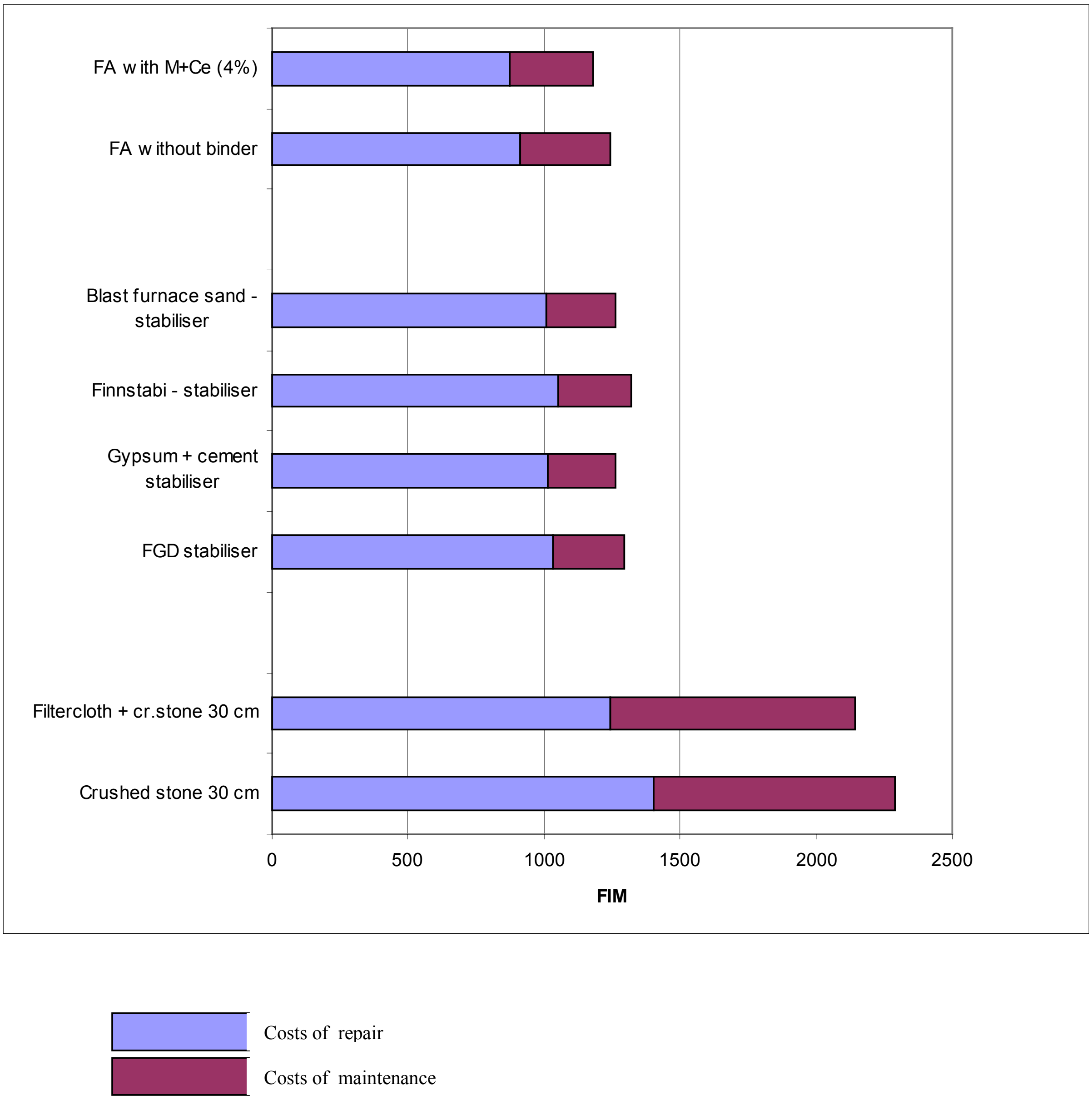


Figure 6-1: *Total costs of structure [29]*

6.3 Environmental Impact

Sampling and analyses of the groundwater at each of the test sites, and the soil at some of the test sites, have been included in the studies dealing with the environmental impacts of NRC-structures. These studies indicate that these NRC- structures entail no risk to the environment.

In addition to the studies noted above, most of the industrial residues included in the studies have been subjected to leaching tests, mainly column tests (NEN 7343), and the results are shown in *Table 4-10*. The results indicate that the limit values suggested, for example for molybdenum (Mo) [31], may be too low and restrictive to the use of industrial residues, as the amount of molybdenum leaching from most residues, such as FA, usually will exceed the limit values. Therefore, more detailed studies for the effects of molybdenum have been carried out in the project "Tuhkat hyötykäyttöön" [6]. The leaching and distribution of molybdenum from coal ash structures to the soil and groundwater have been studied by using a mathematical dynamic transportation model [VI]. The results can be summarised as follows:

- Molybdenum occurs in coal fly ashes in different percentages: a readily soluble fraction, a less readily soluble fraction and an insoluble fraction.
- The relative amounts of the different fractions differ between FAs from different sources.
- The solubility of molybdenum is controlled by pH as shown in *Figure 6-2*. The pH of a FA structure is typically high (10.5 – 12.0). Thus, the soluble molybdenum will be leached from the FA layer relatively quickly, but it will be retained below the FA layer in the soil layers with lower pH (6.0 – 7.0) as shown in *Figure 6-3*.
- *Figure 6-3* shows pH and water content at different courses of a seven years old test construction with FA –structural course. Ten centimeters beneath the FA-course the pH-value is already close to the pH-value of the subsoil.
- The calculations of the dynamic transportation model are based on results from a large amount of laboratory tests involving leaching tests (the column test NEN 7343 and the batch leaching test CEN 12457) as well as tests to determine the adsorption of molybdenum on different soil types. The validity of the model has been tested by comparing the results with results from samples that were taken from the test pits of two and twenty year old FA structures. The samples were taken from different depths at both of the sites and analysed for the concentration of molybdenum. The model has proved to be valid. Therefore, it is now possible to reliably determine the long-term transportation of molybdenum into the subsoil and groundwater. Similar studies could be carried out for other constituents as well.
- The calculations of the dynamic transportation model on road structures indicate that molybdenum concentrations in groundwater will not exceed the drinking water limit values for at least 100 years after construction. These results were independent of the thickness of the FA layer (less than one meter) and the subsoil type. In fact, the concentration values will be far lower than the limit values for drinking water in Finland. This corresponds with the results from follow-up studies at the test sites (see Chapter 5).
- The calculations have also shown that soil courses immediately beneath FA-courses (0 – 20 cm) will adsorb molybdenum. The highest concentration is caused by the readily soluble fraction, and the leaching of this fraction will take place during the first year after construction. This fraction will be transported to

lower layers depending on the adsorption capacity of the soil. However, the concentrations will be so low that the limit values for polluted soil will not be reached. The calculated values correspond with results from the test sites.

– Based on the dynamic transportation models nomograms have been created to estimate the amount of molybdenum that will be transported into groundwater and soil for a period of 100 years after construction. The molybdenum concentration is given as a function of the NRC-layer's thickness, the type of subsoil beneath it, and the column test results for the material in question. If required, similar nomograms could be created for many other constituents as well (e.g. for Ba, Cr, Ni, Se, V).

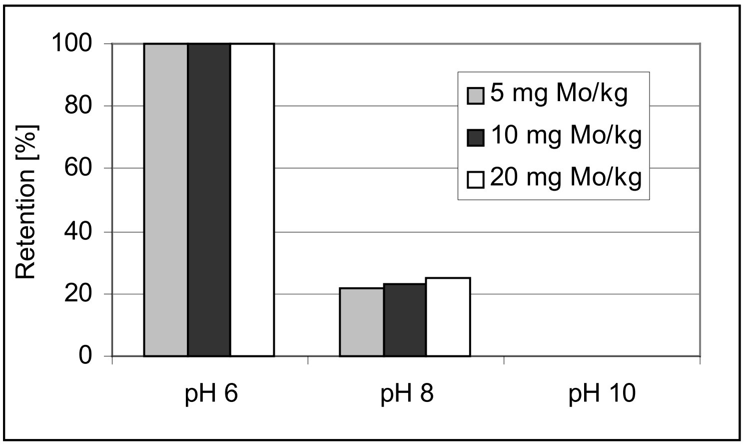


Figure 6-2: Solubility of Mo as a function of pH. The figure shows the retention of Mo in a clay at different pH-values [32]

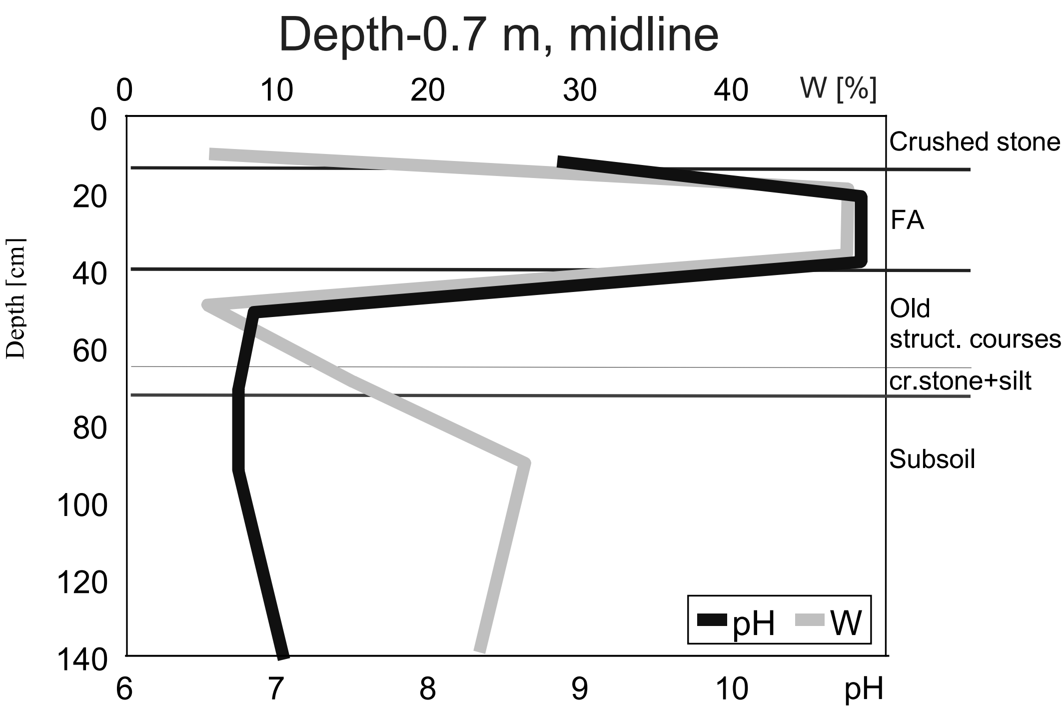


Figure 6-3: pH –values in the FA layer and below the FA layer (w = water content of the materials in different layers) [15]

7 CONCLUSIONS AND FURTHER RESEARCH

7.1 In General

The studies indicate that it is most profitable to recycle the FA 1) as binder for processing other construction materials and 2) as base material and without further processing, for a solid structural course. In soil construction there are several applications that meet the principles for sustainable development for FA. The general conclusions of the studies on FA as a NRC-material are as follows:

– PFA, WFA and MFA are equal in quality and are often better than CFA for NRC-applications.
– FA can be used as a stabilising component for the stabilisation of stone materials or soft soil (peat, clay, gyttja).
– FA plays an important role in the manufacture of NRC-materials when combined with other industrial residues such as fibre sludge, phosphogypsum and stainless steel slag.
– NRC-structures based on the use of FA are particularly cost-effective over their total lifetimes.
– By using NRC-structures, it is possible to obtain significant savings of natural stone materials and to reduce the need for disposal sites and landfills.
– The long-term durability of NRC-structures has been observed to be clearly better than the long-term durability of conventional stone material structures.

7.2 NRC-materials

Studies on materials have confirmed that the quality of most FA in Finland is adequate for use in NRC-construction. One of the most important reasons is the BAT[2] of incineration in Finnish power plants in general. Consequently, the loss of ignition (LoI) is relatively low at present. General aspects dealing with the use of FA as a soil construction material follow:

– FA is a quite valuable raw material for many soil construction applications
– Approximately 70 % of the total available amount of FA could be recycled for use in soil construction. The remainder can be recycled for use in other applications. Only a very small portion need to be disposed of in landfills or as secondary filling material because of inferior quality, the small amount available or the unfavourable geographical location of production.
– There is a significant variation in the quality of FA from different power plants, despite the use of similar fuels or fuels from same supply source. FA quality variations among peat combusting plants is larger than variations among coal combusting plants. Accordingly, separate FA batches from individual power plants may differ considerably from each other. Therefore, it is important to have continuous control of the geotechnical quality parameters of FA.
– During open-air pile storage of FA, a large part of the inherent and important geotechnical properties of FA will be lost because of excess moisture. A pile-FA cannot be recycled for use in as many applications as a dry FA, and the proper-

[2] BAT = Best Available Technology. The author wishes to emphasise that the applied technology utilised in power plants in Finland is the best possible.

ties of a pile-FA application will be of lower quality than with a dry FA. Therefore, adequate dry storage arrangements for FA will be an essential precondition for the development of a controlled recycling system. This is also necessary because most FA is produced during the coldest season, when there are very little on-going soil construction projects.

- Fibre-ash has proven to be an excellent road construction material. Fibre-ash structures are durable and withstand deformation. A fibre-ash layer in a road structure will effectively reduce frost damage such as frost heaves, settlements and cracking of the road surface / pavement. Fibre-ash properties can be varied widely by properly proportioning components and by properly choosing binders or binder mixes.
- Gypsum-ash and slag-ash are very suitable materials for base courses, as their rigidity can be quite easily controlled with the proper choice of a binder. High rigidity and appropriate long-term strength development as well as excellent durability against freezing and thawing, makes it possible to use slag-ashes even in very demanding construction projects. Both phosphogypsum and stainless steel slag are being produced in large amounts each year, but to date only small amounts are recycled.
- Reactive FA appears to be a competitive alternative for other more conventional binders, for the stabilisation of old road structures, or soft soils like peat, gyttja and clay.

7.3 Laboratory Tests

The research methodology described in Chapter 3 has been used in the studies dealing with different NRC-materials and -test structures. The research methodology is very functional and efficient. It will determine the most optimal material recipes. The geotechnical simulation tests in the laboratory will give reliable and relevant results concerning the behaviours of NRC-materials. The materials that have met the criteria for the laboratory tests are observed to exhibit corresponding behaviour in full-scale test structures, and achieve target properties quite well.

The criteria that have been established for durability, to resist the effects of saturation, frost, freeze-thaw cycles and frost heave appear to be at least adequate. Experience has shown that the laboratory tests on NRC-materials related to durability relative to saturation, frost susceptibility and frost heave resistance are essential. The criteria established for those effects are quite appropriate. The freeze-thaw test simulates conditions that are much more severe than actual conditions in situ. Accordingly, the test might lead one to conclude that a given material is inadequate relative to durability. However, good results in a freeze-thaw test would indicate that the material will have an adequate if not excellent long-term durability in arctic climate conditions such as in Finland.

Laboratory investigations during a NRC project are very important. Wide variations in quality and in project related requirements are important reasons for testing all materials. This applies to residues and material mixes that are being used for the first time, but it also applies to relatively well known NRC-materials. Because of variations in NRC-material properties, and variations in NRC-structures, the methodology shown in *Figure 7-1* (at the end of this chapter) enables one to optimise the most economically feasible solution for each project. This type of methodology makes it possible to obtain significant cost savings.

7.4 Environmental Acceptability

The environmental laboratory tests have indicated that there is little or no potential risk to the environment arising from the use of FA and its mixes that utilise other industrial residues. The industrial residues that have been researched and referred to in this study include fibre sludge, phosphogypsum, and stainless steel slag. In order to minimise or eliminate environmental risk, the natural precondition for this is that correct and proper methods must be applied to the manufacture and usage of the materials. However, one of the primary restrictions for the use of NRC-technology can be traced to the inadequacy of prevailing legislation. Industrial residues are considered as waste materials and are regulated according to the existing waste decrees. Consequently, the use of these residues is subject to a relatively laborious permit process, both for construction site and for material treatment. In addition, there are no official, geotechnical and environmental criteria and guide lines dealing with NRC-construction that could help the permiting authorities arrive at their decisions. Therefore, the authorities become very conservative due to public safety considerations, and the permitting process can become very unreasonable.

7.5 NRC-structures and -construction

NRC-structures have exhibited excellent performance when tested in full scale and constructed according to the principles presented in Chapter 3. Conclusions;

– The thin and flexible NRC-structures utilised for the low-volume roads have been performing well, as outlined in Chapter 3, and their long-term durability might be even better than was described in Chapter 6.
– The NRC-structures were relatively simple to construct at different sites, and it has been possible to use available existing equipment for construction. However, the material manufacturers often request special equipment. However, in order to achieve better quality and higher productivity, this type of special equipment will have to be developed.
– NRC-materials based on the use of FA could also be used to develop structures for other applications, including highways, pedestrian routes, parking and storage areas, as well as sports grounds.
– Specific dimensioning standards applicable to NRC-structures should be developed.
– An effective quality assurance system that controls the total NRC-construction process is required in order to avoid inadequate materials and construction.
– The work methods used in full-scale construction operations have been adequate, but there is a need for improvement.

7.6 Further Research

Additional research and development efforts are preconditions for the wide implementation of NRC-technology based on the use of FA. Some suggestions for further research and development are presented by the author:

- Systematic research dealing with variations in the geotechnical quality of the FA
- Development of economically feasible and large enough dry storage systems for FA
- Development and testing of fibre-ash materials based on different types of fibre sludge (at present the only full-scale tests that exist have utilised deinking sludge)
- Development of FA binders into distinctive products for different end uses, especially for PFA, MFA and WFA.
- Development of different types of NRC-materials based on the use of slag-ashes that have very good geotechnical properties
- Continuing studies investigating the long-term properties of existing NRC-test structures, to obtain reliable estimates of their lifetime and durability, and to obtain additional long-term performance data (very important)
- Research and development dealing with the applicability of NRC-structures for different road types and field applications
- Development of applicable dimensioning standards for use with NRC-structures and research on their comparability with conventional dimensioning standards
- Dynamic transport modelling of potentially environmentally risky substances in addition to molybdenum (see Chapter 6)
- A thorough study dealing with the environmental and economic benefits derived from the use of NRC- technology
- Development of quality assurance / control systems, especially applicable to rapid and accurate proportioning of binders, and for more effective testing of structural density in the field.
- Development of a more appropriate laboratory procedure for the determination of the freeze-thaw behaviour
- Studies dealing with dynamic load durability of NRC-structures
- Research studying the effects of temperature and fatigue load on the strength development of FA materials at the early stages of construction and following construction
- Development of a mathematical model to predict the long-term duration of NRC-structures
- Research on the correlation between segregation potential, frost resistance and freeze-thaw durability of the materials.
- Thorough studies on the eco-efficiency of NRC-construction in comparison with the eco-efficiency of conventional soil construction based on the use of natural stone materials, both in Finland and in the total EU. In EU the total consumption of stone materials is about 2-milliard tonnes/year. How much of this could be compensated with NRC-materials and, consequently, what kind of ecological savings could be obtained?
- Development of equipment, especially for the mixing process (quality of the mixing, control system, moveability, price, capacity etc.).

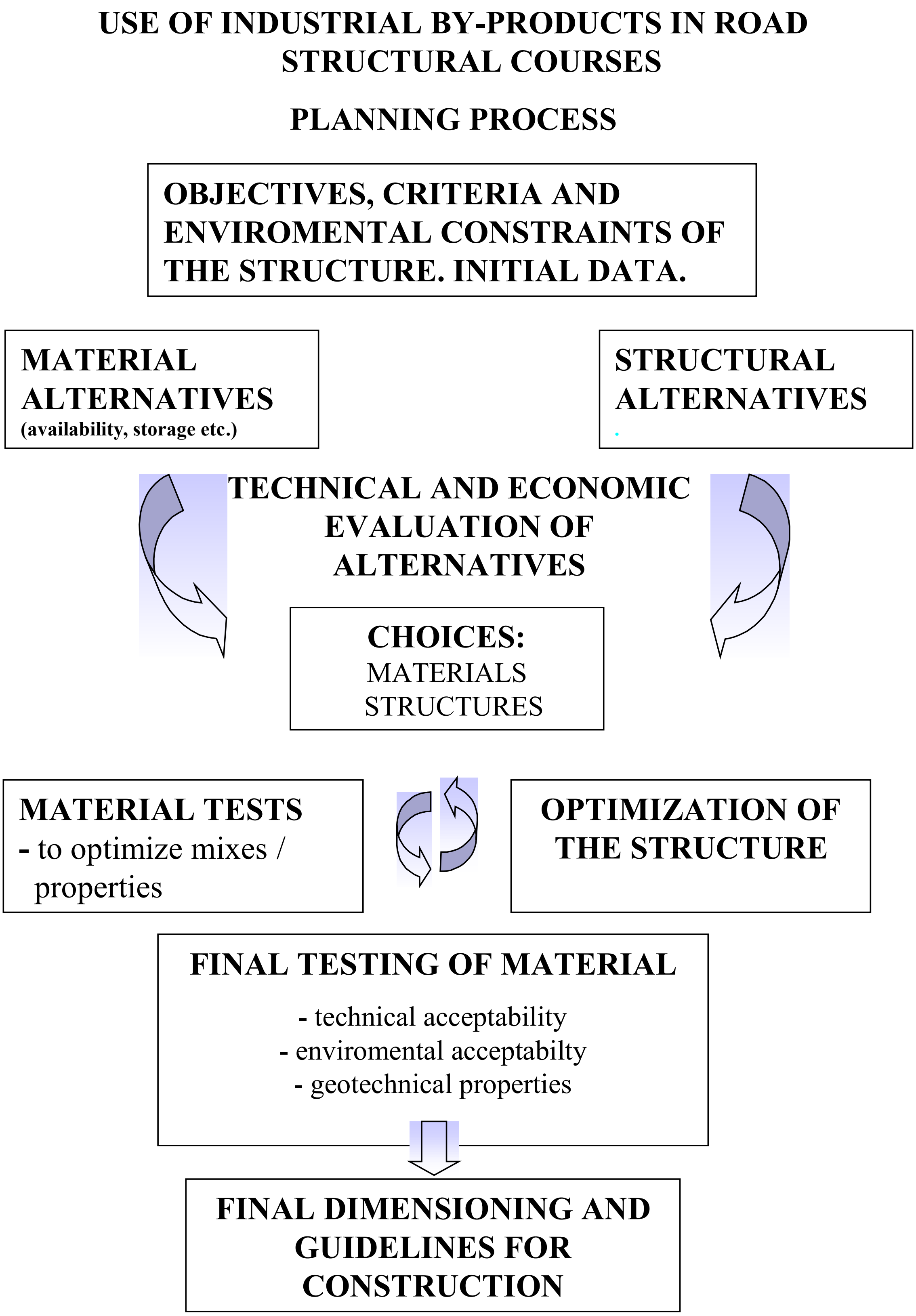


Figure 7-1: A methodology to optimise NRC-structures

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APPENDICES

Participation of the author of the Doctoral Thesis, Pentti Lahtinen, in the papers and corresponding studies

I New Methods for the Renovation of Gravel Roads

II Paper Sludge in Road Construction

III Deep Stabilisation of Organic Soft Soils

IV New Methods for the Renovation of Gravel Roads

V Use of Industrial Wastes in the Construction of Low-Volume Roads

VI Molybdenum transport in coal fly ash soil constructions Roads

Participation of the author of the Doctoral Thesis, Pentti Lahtinen, in the papers and corresponding studies

The doctoral thesis is based on several and separate studies and projects that have been carried out in the 1990's in Finland. Pentti Lahtinen's contribution to these studies and projects has been significant especially in the planning and management of the studies, in the analysis and evaluation of the results and in the reporting. In all of these studies and projects Pentti Lahtinen has been acting as a project manager and/or as an expert. Research groups to which Pentti Lahtinen's contribution has been outstanding have carried out the development of new materials and technology. All the papers (I – VI) that have been annexed to the doctoral thesis have been written by Pentti Lahtinen except a part of the Paper III. Pentti Lahtinen has presented himself all the papers except one in the conferences concerned. The background of the papers is shortly following:

I. New Methods for the Renovation of Gravel Roads

Lahtinen, P., Jyrävä, H., Suni, H. (1999). Paper for IRF Regional Conference, European Transport and Roads, Lahti 24.-26. May 1999. 7 Pages.

The paper is based on several studies on the improvement of the low-volume roads by utilising NRC-materials. One of the writers, M.Sc., Mr Heikki Suni acted as the representative of the client for the study and did not directly participate the research work. M.Sc., Mr Harri Jyrävä has had the central role in the studies. Pentti Lahtinen has acted as the co-ordinator and as an expert in the studies.

II. Paper Sludge in Road Construction

Lahtinen, P., Fagerhed, J.A., Ronkainen, M. (1998). Paper for the Proceedings of the 4th International Symposium on Environmental Geotechnology and Global Sustainable Development, 9.-13. August 1998, Boston (Danvers). University of Massachusetts, Lowell, pp. 410-419. 9 pages.

The paper is based, so far as is known, on the internationally first studies and development of fibre-ash materials and on the full-scale tests for a road (Rajalantie in Luopioinen) in 1996. The recipes for the material mixes have been given in codes as required by the industrial partner of the project. The representative of the industrial partner in the studies and in the paper was M.Sc., Mr J. A, Fagerhed who did not directly participate the research work. The main researcher of the studies was M.Sc., Ms Marjo Ronkainen. The work was carried out in close co-operation with Pentti Lahtinen who had a central role in the development of the materials and the technology as a whole.

III. Deep Stabilisation of Organic Soft Soils

Lahtinen, P., Jyrävä, H., Kuusipuro, K. (2000). Paper for the Proceedings of the Grouting Soil Improvement Geosystems including Reinforcement of the 4th GIGS, the International conference on Ground Improvement Geosystems, by the Finnish Geotechnical Society in Helsinki, 7-9. June 2000, pp. 89-98. 10 pages.

The author of the doctoral thesis has had a central role in the development of the technology for the mass stabilisation of peat at the beginning of the 1990's. The development project was carried out in co-operation of SCC Viatek Ltd SGT and the University of Oulu. The project gave rise to a wider European interest in the development of deep stabilisation technology for organic soil in EU. Thus, partners from 6 EU countries started co-operation in a EuroSoilStab project in which Pentti Lahtinen has had the main responsibility for the development of new binders based on industrial by-products. The paper is based on these studies on binder materials in which the use of fly ashes was an essential factor. Chapter 4 of the paper is written by M.Sc., Mr Kari Kuusipuro, and other chapters have been written by Pentti Lahtinen. In addition to the former writers central roles in the actual research work have had M.Sc., Mr Harri Jyrävä and M.Sc., Ms Aino Maijala .

IV. New Methods for the Renovation of Gravel Roads

Lahtinen, P., Jyrävä, H., Suni, H. (2000). Paper for the Proceedings of the NGM-2000, XIII Nordiska Geoteknikermötet, Helsinki 5.-7. Juni 2000. Building Information Ltd., Helsinki, pp. 531-538. 8 pages.

Like paper I this paper is based on several studies on the improvement of the low-volume roads by utilising NRC-materials. One of the writers, M.Sc., Mr Heikki Suni acted as the representative of the client for the study and did not directly participate the research work. M.Sc., Mr Harri Jyrävä has had the central role in the studies. Pentti Lahtinen has acted as the co-ordinator and as an expert in the studies.

V. Use of Industrial Wastes in the Construction of Low-Volume Roads

Lahtinen, P., Jyrävä, H., Suni, H. (2000). Paper for the conference of Geo-Denver 2000, 5.-8. August 2000. Proceedings pending. 11 pages.

Like paper I this paper is based on several studies on the improvement of the low-volume roads by utilising NRC-materials. One of the writers, M.Sc., Mr Heikki Suni acted as the representative of the client for the study and did not directly participate the research work. M.Sc., Mr Harri Jyrävä has had the central role in the studies. Pentti Lahtinen has acted as the co-ordinator and as an expert in the studies.

VI. Molybdenum transport in coal fly ash soil constructions Roads

Lahtinen, P., Palko, J., Karvonen, T. (2000). Paper for Ecogeo-2000, International Conference on Practical Applications in Environmental Geotechnology, Helsinki 4.-6. September 2000. Proceedings pending. 7 pages.

This paper is based on a specific research on the transportation of molybdenum from the soil structures to the surrounding environment. The responsibilities of the research have been following: Ph.D. Jukka Palko had the central role in the chemical analyses and in the studies for the soil's ability to absorb molybdenum. Professor, Dr. Tuomo Karvonen was responsible for the mathematical transportation modelling and Pentti Lahtinen for the geotechnical questions like typical structures and soil conditions. The paper focuses on the main conclusions of the research. The mathematical details of the model, the parameters etc. have been described more detailed in the research report.

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