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ECOGEO 2000 The International Conference on Practical Applications in Environmental Geotechnology conference concluded the Finnish five-year ecogeotechnology research programme, co-ordinated by Tekes, the National Technology Agency of Finland. The programme focused on the utilisation of industrial by-products in earth construction, on investigations and remediation of contaminated soils and groundwater protection technologies. The programme was financed by Tekes, private Finnish enterprises and R&D organisations. The total budget was about USD 10 million (FIM 60 million).

ECOGEO 2000 had the ambition to build a bridge between science and practical solutions to minimise the time lags in information and knowledge transfer. The scope of the conference was wide, as the reality in implementation projects.

ECOGEO 2000 provided a forum for transferring knowledge on practical applications. The presentations which are now published concern the technical and environmental aspects of industrial by-product utilisation, remediation of contaminated soils, and barrier structures for groundwater protection. The environmental risks connected with the use of industrial by-products are covered very thoroughly and the remediation methodology of contaminated soils is presented widely.

In addition to the reports from Ecogeotechnology research programme, a highly qualified collection of scientific papers from other countries were presented and are included in this Congress proceedings volume thus giving an excellent overview about the modern ecogeotechnological research.

Keywords: engineering, geology, by-products, earthworks, environmental geology, soils, pollution, remediation, ground water, protection, symposia

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PREFACE

Today, complex inter- and intra-relations between water, air and soil pollution, together with various time lags between the causes and effects, make practical decision-making in environmental matters very challenging. The temptation to postpone necessary decisions is in these circumstances perhaps understandable, but could be argued.

ECOGEO 2000 – The International Conference on Practical Applications in Environmental Geotechnology had the ambition to build a bridge between science and practical solutions to minimise the time lags in information and knowledge transfer. The scope of the conference was wide, as the reality in implementation projects.

ECOGEO 2000 provided a forum for transferring knowledge on practical applications concerning the technical and environmental aspects of industrial by-product utilisation, remediation of contaminated soils, and barrier structures for groundwater protection. The environmental risks connected with the use of industrial by-products were covered very thoroughly and the remediation methodology of contaminated soils was presented widely.

The conference was intended for corporate environmental managers, earth construction contractors, environmental experts and decision-makers from municipal and government sectors, entrepreneurs and private consultants as well as researchers.

The ECOGEO 2000 conference also concluded the Finnish five-year ecogeotechnology research programme, co-ordinated by Tekes, the National Technology Agency of Finland. The programme focused on the utilisation of industrial by-products in earth construction, on investigations and remediation of contaminated soils and groundwater protection technologies. The programme was financed by Tekes, private Finnish enterprises and R&D organisations. The total budget was about USD 10 million (FIM 60 million).

The results of the programme's individual R&D projects were presented at ECOGEO 2000. They formed the major part of presentations in the congress but, however, in addition a highly qualified collection of scientific papers from other countries were presented and included in the Congress proceedings volume thus giving an excellent overview about the modern ecogeotechnological research.

This volume consists of 28 selected papers from 60 presented in the ECOGEO 2000 – The International Conference on Practical Applications in Environmental Geotechnology -congress. Mostly these selected papers deal with new scientific data but in addition some overviews as well introductions of some very practical products are included in order to give a cross section about the information delivered in the conference. Many of the papers the authors improved by adding the newest results, and they were thoroughly peer reviewed by the scientific advisors of the conference. All papers presented in conference are available in their original format in the conference volume:

International Conference on Practical Applications in Environmental Geotechnology. ECOGEO 2000
Tammirinne, Markku (ed.)
2000. VTT Communities and Infrastructure , Espoo. 477 p. + app. 2 p.
VTT Symposium : 204
ISBN 951-38-5701-8 951-38-5702-6
(http://www.inf.vtt.fi/pdf/symposiums/2000/S204.pdf)

From the offered papers the scientific advisors selected 67 papers for presentation at the conference. The Conference proceedings volume includes 60 papers of those accepted. The three main topics of the conference were:

1) Use of industrial by-products in earth construction
2) Contaminated soils
3) Barrier structures for landfills and groundwater protection

The papers in this volume are organised according to these main topics, too.

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International conference on practical applications in environmental geotechnology ecogeo 2000,
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THE QUALITY CONTROL AND GEOTECHNICAL PROPERTIES OF RECLAIMED CONCRETE IN EARTH CONSTRUCTION

by
Juha Forsman[1)], Helena Korjus[1)], Lauri Kivekäs[2)] and Antti Määttänen[3)]

Forsman, Juha, Korjus, Helena, Kivekäs, Lauri & Määttänen, Antti 2001. The quality control and geotechnical properties ofreclaimed concrete in earth construction. *Geological Survey of Finland, Special Paper 32, 7–13*, one figure and 4 tables.

Reclaimed concrete material is generated through the demolition of concrete elements and structures during building demolition operations. In this article the quality control and geotechnical properties of reclaimed concrete have been studied.

The quality control of by-products is even more important than for “traditional” aggregates in order to provide an acceptable material for utilisation in earth construction. The assorting demolition is a base for acceptable raw material for reclaimed concrete and the quality control secures the properties of the product. The geotechnical and environmental properties of reclaimed concrete have been studied in the field on test roads and in a laboratory over several years. Both geotechnical and environmental properties of the crushed material indicate that the use of reclaimed concrete in road construction is acceptable.

On the basis of the field and laboratory studies and experience, user guidelines for the use of reclaimed concrete have been made for the Finnish National Road Administration (FINRA) and for the Association of Finnish Local and Regional Authorities. Also the quality assurance standard of reclaimed concrete is under preparation in Finland.

Keywords: construction materials, concrete, crushing, by-products, quality control, engineering properties, highways, construction, Finland

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INTRODUCTION

Reclaimed concrete has been used in pavement construction since 1994 in Finland. Reclaimed concrete crushed by Lohja Envirotec Ltd is known by the name Betoroc™-crush, and it is classified in grades by the raw material and technical properties. In Finland Betoroc™ has been used in road and street construction mostly in sub-base and base layers. Reclaimed concrete has shown favourable geotechnical properties in field studies on test roads and in laboratory tests and is thereby suitable for use in road construction. The quality control of by-product is important in order to have an acceptable material for utilisation. The by-product utilised in earth construction must have adequate technical and environmental properties and permanent quality. The Finnish quality assurance standard of reclaimed concrete will contain the quality control demands, methods and schedule of controlling for each phase from demolition operation to earth construction.

CLASSIFICATION OF THE BETOROC MATERIALS

Betoroc™ is classified in grades by its raw material and technical properties. A material can originate from building demolition operations or, for example, from hollow concrete production as waste, which has been abandoned due to manufacturing process requirements. The classification by raw material is presented in Table 1. Table 2 presents the technical and environmental classification of the material.

Table 1. Classification of Betoroc*'* by raw material.

Grade	Raw material
BeM I	Pure reclaimed concrete, which originates, for example, from concrete element manufacturing.
BeM II	Reclaimed concrete, which originates from demolition of concrete structures and buildings. It may contain some harmful materials.
BeM III	Reclaimed concrete, which originates from demolition of concrete structures. It might not possess any self-hardening properties.
BeM IV	Reclaimed concrete, which originates from demolition of concrete structures. It possesses no self-hardening properties and it may be frost susceptible.

Table 2. Basic properties of Betoroc*'* (a) and content of harmful materials and the use on the ground water areas (b).

a)	Grain size distribution	Self-hardening properties	Frost susceptibility	E-modulus
BeM I	0–50 mm	Hardens	No	700 MPa
BeM II	0–50 mm	Hardens	No	500 MPa
BeM III	0–50 mm	Uncertain	No	280 MPa
BeM IV	Varies	No hardening	Varies	*£* 200 MPa*

* to be considered in each case

b)	max. content of bricks [weight-%]	Max content of other * materials [weight-%]	Leaching tests in crushing phase
BeM I	0	0,5	Not demanded
BeM II	10	1	Demanded
BeM III	10	1	Demanded
BeM IV	30	1	Demanded

* wood, plastics, etc. In addition to the weight-% demand, there may not be harmful amounts of special light materials (such as polystyrene and other insulation materials).

GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES

The geotechnical properties of the crushed reclaimed concrete have been studied both in laboratory tests and in test roads and streets. Table 3 presents some test results of crushed reclaimed concrete materials. The values shown present the variation of values of testing (the real variation of the properties may be larger). The design values of E-modulus are presented in Table 2a. The determination of the E-modules on the basis of the field and laboratory tests is presented in detail in the article "Geotechnical Properties and Bearing Capacity of Reclaimed Concrete" (Forsman *et al*. 2000).

The bearing capacity of the reclaimed concrete structures has been measured using the plate load test or falling weight deflectometer (FWD). The first measurements have usually been done straight after compaction of the crushed reclaimed concrete layer and soon after paving. Later the bearing capacity has been measured in springtime and/or in summertime.

The E-modulus of the reclaimed concrete structure has been back calculated on the basis of the field measurement data using both the Odemark and APAS methods. APAS is a software developed by FINRA and Neste Ltd for analytical pavement design and it is based on the NOAH (Nynäs Overall Approach) calculation module developed by Nynäs in Belgium (Pienimäki 1994). Using this APAS program it is possible to fit the calculated bowl to the measured FWD-bowl and that way back calculate the E-modulus of road materials layer by layer.

Table 3. Geotechnical properties of reclaimed concrete based on some test results (Viatek 1999).

Property *	Unit	Betoroc*'* I (hollow core slab waste)	Betoroc*'* II (demolition waste)	Crushed concrete in general
Optimum water content	%	8…10	8…12	8…12
Maximum dry weight	kN/m³	18…20	17.5…20.5	
Minimum dry weight	kN/m³		12.7…14.5	
Specific gravity	t/m³			2.55…2.65
Compression strength, 7 d	MPa	1.2…1.3	0.3…1.1	
Compression strength, 28 d	MPa	2.0…2.1	0.6…1.3	
Capillarity	m	0.25	0.20	
Permeability	m/s	$1…7 \times 10^{-5}$		
pH		12.7…12.9		≥ 11
Segregation potential	mm²/Kh	0.11…0.28		
Heat capacity (unfrozen)**	Wh/m³K	485…590		
Friction angle	∞			40
CBR-ratio	%			90…140
Los Angeles -ratio		23	28	

* E-modules used in dimensioning are shown in Table 2a.
** approximated from the field observations by back-calculation.

The environmental properties of Betoroc™ have been tested at the Technical Research Centre of Finland (VTT)/Chemical Technology (VTT 1996, Wahlström *et al.* 1997). The results from these chemical analyses and from tests made later show that Betoroc™ is environmentally acceptable for road construction. On the basis of the chemical analyses the target values for leaching from mineral demolition waste have been given (shown in Table 3). The target values shown in Table 4 concern the replacing of class I (material that can be used without limits in base layers). VTT Chemical Technology (1996) has also proposed recommendations for the quality assurance system for the utilisation of reclaimed concrete. The quality control will be done by the manufacturer.

Table 4. Target values for leaching from reclaimed concrete proposed by VTT [1996]. Proposed test method is CEN-batch leaching test with protocol 3 (prEN 12457 1996).

Element	Sulphate	Chromium	Cadmium	Copper	Lead
Target value (mg/kg)	750	0.5	0.02	0.4	1.0

QUALITY CONTROL SYSTEM

In the case of by-products, the quality control is even more important than with a "traditional" aggregate in order to have an acceptable material for utilisation in earth construction. Both the geotechnical and environmental properties of the reclaimed concrete have to be studied by a detailed quality control plan and with the proper methods agreed in the user guidelines.

In Finland the quality assurance standard preparation of reclaimed concrete (VTT 2000) is in progress and is to be created in co-operation between VTT, Lohja Envirotec Ltd and Viatek Ltd as a part of a wider quality assurance standard. The draft of the quality assurance standard of reclaimed concrete contains the required quality controls and approved methods of control. The generation process and the quality control of reclaimed concrete is presented in Fig. 1.

The main phases in processing reclaimed concrete are as follows: the delivering of raw material, transportation, receiving raw material at operating site, stockpiling of raw material, crushing, grading, stockpiling of crushed material and supplying material to the utilisation site. In each phase the quality of the material is controlled. The studies the supplier does are grain size distribution, frost susceptibility (on the basis of the grain size distribution), maximum bulk density and optimum water content (if needed), compression strength, material purity and environmental qualifications.

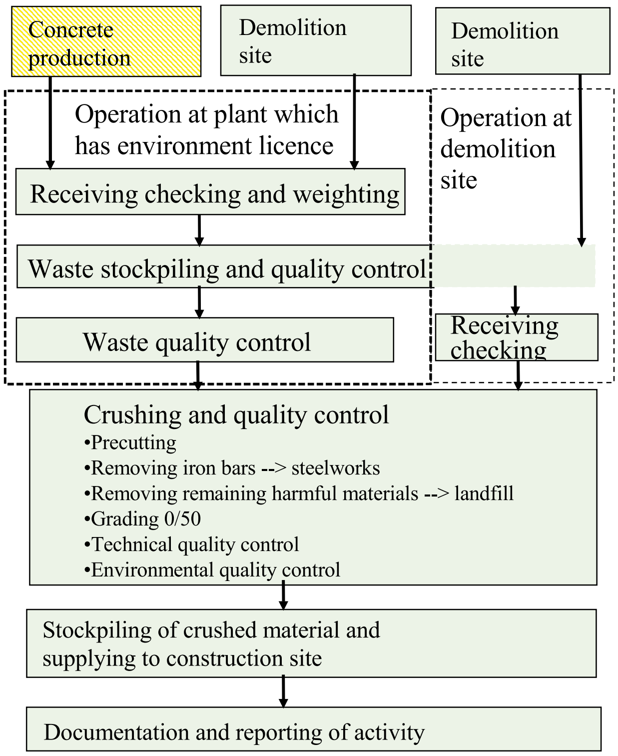

Figure 1. The generation process and the quality controlling of reclaimed concrete.

METHODS OF QUALITY CONTROL

Waste concrete

The first control of the waste concrete is visual checking of the material and its purity. The crushing stations of Lohja Envirotec Ltd have detailed guidelines for checking and classifying the received material. Materials containing harmful components such as PCB, creosote, asbestos, oil, heavy metals or sulphates are not accepted as raw material. The purity of the material is also checked visually throughout the manufacturing process from raw material until the utilisation site.

Grain size distribution and frost susceptibility

The grain size distribution is determined by grading (SFS-EN 933–1). One grading has to be done per 2000 tons of material, or at least twice a week. The grain size distribution curve must meet the requirements for the base layer grain size distribution presented in the FINRA's guidelines (FINRA 1985). Frost susceptibility of the material is determined by the grain size distribution. The frost susceptibility of the material is monitored with the same sampling interval as the grain size distribution. The reclaimed concrete in groups I, II and III (Tables 1 and 2) must be non-frosting, in group IV the frost requirements depend on the case.

Maximum bulk density and optimum water content

If needed the maximum bulk density and optimum water content are determined by the improved Proctor test or the IC test. In the IC test the work pressure is 4.0 bar and the rounds are 160.

Compression strength

For determining the compression strength and to be able to follow the hardening, one sample set/10 000 t or at least one sample set/crushed parcel is created with specimens compacted by the IC-tester equipment. One sample set includes 7 specimens. The specimens are prepared in the same way as the maximum dry weight is determined. The compression is done following the guidelines of BY 15 Concrete Norms 1993. Three specimens are compressed for 7 days and three specimens are compressed for 28 days. The seventh specimen is a spare sample which is compressed if needed. The specimens are kept at +20ºC covered with plastic foil.

Material purity

Material purity must be determined sufficiently often, at least at 20 000 t intervals. The determination of the amount of organic impurities (wood, plastic etc.) and the amount of bricks is done following the standard NEN 5942 (the Dutch norm 1990) with the corrections as follows:

– The grains over 8 mm are divided approximately into three groups: concrete, bricks and others.
– The weight proportions (weight %) of each material are calculated from the total mass left on the 8-mm sieve.

The classification of the reclaimed concrete regarding impurities is presented in Table 2b.

The determination method of material purity has been developed by testing several methods and comparing the advantages and disadvantages of the different methods. Such methods as combustion, water weighing, photographs and picking have been tested for determining the amounts of organic impurities and bricks. Combustion, floating, blowing and photography have been used for determining the amounts of special light materials (such as polystyrene and other insulation materials).

Combustion

Combustion is a method which might be used for determining the amount of light materials but also for example wood, etc. Combustion was done in an asphalt furnace at a temperature of +500 ºC. The problem was that at the temperature as high as used causes loss of water of crystallisation in the concrete material and stones and the results are therefore unreliable. If combustion is used in determining the amounts of impurities, it needs the correction curves done for the loss of the water of crystallisation.

Water weighing and floating

The volume of the crushed concrete specimen was determined by sinking it into water. The specimen was weighed before sinking. The problem of this method was that the water intrudes into the concrete and brick grades and therefore the measured weight is not correct. Another problem was the relative close density of concrete and bricks which causes difficulties, especially in determining the amount of small proportions of bricks.

Floating is used for determining the amounts of special light materials (such as polystyrene and other insulation materials). When using floating, the material must be dehydrated after floating for further determining (amounts of bricks etc.).

Blowing

Blowing, like floating, is used for determining the amounts of special light materials (such as polystyrene and other insulation materials). Blowing loosens not only the special light materials but also cement from crushed material and is not therefore a reliable method for determining impurities.

Photography

Photographs were taken of materials which were made by mixing predetermined amounts of impurities into pure crushed concrete. The idea was to compare visually the crushed concrete specimens to the photographs and determine the amount of impurities by the reference photographs. The problem was that the small amounts of impurities gather on the surface of the pure concrete and the reference specimen looks less pure than it actually was. The method is suitable for a rough estimation but not for an exact determination of impurities.

Picking

In this method the impurities of the specimen are picked and sorted. The method was modified from the standard NEN 5942 (Dutch norm 1990). This method needs an experienced examiner, but it is by far the most exact and reliable method and therefore is chosen as the used method. The method used will continuously be developed by Lohja Envirotec Ltd.

Environmental qualifications

The environmental qualifications are determined following the principles shown in Fig. 1. Before the crushing of the specimen the purity and the content of harmful materials is estimated visually.

Studied sample taken from the crusher run is crushed to a grain size under 4 mm and then the sample is divided into laboratory samples (2 kg). The width of the testing depends on the raw material and the replacing site. The total content of harmful metals is determined using methods prEN 13657 or prEN 13656. It is recommended that PAH and PCB are determined using the methods Nordtest recommends. The defining of metals in solutions is performed using the prEN 12506 and prEN 13370 standards. The leaching of harmful compounds is determined by L/S relation 10 following test prEN12457–3 or using column test NEN7343 or NT ENVIR 002.

"USER GUIDELINES"

In Finland user guidelines for the use of reclaimed concrete and the guidelines for quality control have been made for FINRA and for the Association of Finnish Local and Regional Authorities with the financial support of The Finnish Technology Development Centre. The dimensioning parameters of reclaimed concrete and the construction procedures with reclaimed concrete have been studied on the basis of Finnish and foreign experiences. Dimensioning parameters have been reported in detail in a separate report "Design parameters of crushed reclaimed concrete" (Viatek 1999).

The bearing and frost dimensioning parameters have been presented in the first part of the user guidelines. The design considerations and ready-made dimensioning tables have also been presented. The E-modulus of reclaimed concrete (grade I-III) used in dimensioning has been 280–700 MPa depending on the properties of the material. By using highly classic reclaimed concrete in some cases, it is possible to make thinner bitumen bound surface layers. In the second part of the user guidelines the construction procedures of reclaimed concrete pavements have been presented following the format of FINRA's guidelines.

The user guidelines for the use of reclaimed concrete and the guidelines for the quality control made for FINRA have been translated into English by Lohja Envirotec Ltd (Viatek 2000).

CONCLUSIONS

In the case of by-products, quality control is even more important than with "traditional" aggregates in order to have an acceptable material for utilisation in earth construction. Both the geotechnical and environmental properties of the reclaimed concrete have to be studied by a detailed quality control plan and with proper methods agreed in the user guidelines.

The sorting at the demolition site is a basis for acceptable raw material of the reclaimed concrete. The quality control is needed when receiving the material at crushing stations. Also the whole process from crushing to delivering of the crushed material is under continuous quality control for securing the properties of the product.

Reclaimed concrete has shown favourable geotechnical properties in field studies on test roads and in laboratory tests. The reclaimed concrete, Betoroc™, has self-hardening properties (grades BeM I-II) and it is not frost susceptible (grades

BeM I-III). The results from the chemical analysis show that Betoroc™ is environmentally acceptable for road and street construction outside the groundwater areas.

Crushed reclaimed concrete has been used several years in street and road structures mainly in base and/or sub base layers. The structures made with Betoroc™ can be constructed by using normal road construction methods. The most important difference is the need to maintain the necessary humidity for the hardening process of the concrete structure.

In Finland user guidelines for the use of reclaimed concrete have been made for FINRA and for the Association of Finnish Local and Regional Authorities. The guidelines contain information concerning material properties and classification of reclaimed concrete, dimensioning the structures with reclaimed concrete and guidelines for construction procedures. Preparation of the quality assurance standard of reclaimed concrete is in progress and is to be created in co-operation of VTT, Lohja Envirotec Ltd and Viatek Ltd as a part of a wider quality assurance standard in Finland.

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FINNISH GUIDANCE FOR THE USE OF SECONDARY PRODUCTS IN EARTH AND ROAD CONSTRUCTION

by
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Mroueh, Ulla-Maija, Mäkelä, Esa, Wahlström, Margareta, Kauppila, Jussi, Sorvari, Jaana, Puolanne, Juhani, Juvankoski, Markku, Tammirinne, Markku, Heikkinen, Päivi & Salminen, Reijo 2001. Finnish guidance for the use of secondary products in earth and road construction. *Geological Survey of Finland, Special Paper 32, 15–21,* one figure and 2 tables.

In the project "Secondary products in earth construction – assessment of applicability" guidance was developed for the assessment of the environmental and technical applicability of secondary products for use in earth and road construction. The project was a part of the Finnish Environmental Geotechnology Programme. The preparation of the guidance was a collaboration involving several research institutes.

The guidance presents the legislative requirements for the utilisation of secondary products in earthworks, recommendations for the investigation of environmental and technical applicability, recommendations for environmental and technical criteria of the utilisation in earthworks and recommendations for product quality control procedures.

A tiered system is presented for the assessment of environmental compliance. The assessment levels are 1) Concentrations of harmful components, 2) Leaching of harmful components from unpaved and paved constructions and 3) Risk assessment.

Keywords: engineering geology, earthworks, highways, construction, construction materials, by-products, utilization, risk assessment, Finland

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INTRODUCTION

About 70 million tonnes of natural mineral aggregate are used each year in Finland for earth and road construction. Depletion of the best materials, the need for resource conservation and increased transport distances have all stressed the need to introduce substitute materials for natural aggregates. At the same time, industry, construction and other similar activities produce large quantities of potentially usable secondary products. Current waste legislation also supports the use of waste as substitutes for natural materials. Usage of the secondary products of industry and other activities requires that they be proven to be environmentally friendly and technically suitable.

The usage of secondary materials has been hindered by uncertainty about their environmental impacts and technical performance. There is very little practical experience of the long-term performance of most of the materials. There has also been confusion about the procedures that should be used to assess the technical and environmental applicability of the products. The methods of investigation have been developed or changed, and the data on older projects is not comparable with the present investigation data. Up until the 1980s, the assessment of environmental acceptability was not considered as necessary as it is today.

To investigate the environmental, technical and legal preconditions of the use of secondary products, the project "Secondary products in earth construction – assessment of applicability" was started as a part of the Finnish Environmental Geotechnology Programme. The main objective of the project was to develop guidance for the assessment of the environmental and technical applicability of industrial by-products and other secondary products for use in earthworks and road construction (Mroueh *et al.* 2000). Several research institutes participated in the work. In addition, all the interested parties had an opportunity to contribute to the contents of the guidance through participation in the steering groups or project workshops and during circulation of the guidance for comment.

SCOPE OF THE GUIDANCE

The guidance applies to the utilisation of industrial by-products and secondary products in earthworks and road construction. Most of the potential materials are mineral products comparable to natural aggregates. Some organic-based materials may, however, also be used, for example in balancing structures. The pollutant content of these materials must be low or they must be bound to the material so that their migration into the environment is minimised.

Table 1 presents industrial by-products and other secondary materials that have been used in earth construction in Finland. These include fly and bottom ash of coal combustion, blast-furnace slag and some other steel and metal industry slag. The use of crushed concrete began a few years ago and has since grown considerably. Some organic or predominantly organic products, e.g. shredded tyres, are already being used in various types of construction. Asphalt pavement is being recycled into material for new pavement and other structures. Moreover, the prerequisites for the usage of several other types of material have been investigated in research and test construction projects.

The guidance covers conventional earth constructions, such as road and street constructions, various field structures and their foundations. It is recommended that, in the first place, secondary materials be used in large or medium sized cases, because control of the utilisation in small constructions is far more difficult.

The following applications are beyond the scope of the guidance:

- Landscaping, agricultural and forestry use, which are regulated by fertiliser legislation.
- The disposal of waste into the sea, which has a permit procedure of its own.
- The utilisation of secondary products in landfill constructions, for which the requirements clearly differ from those for road and field constructions.

THE BASIC STUDIES

The environmental, legal and technical preconditions for the use of secondary materials were extensively investigated during the preparation of the guidance. For example, the following aspects were studied during the project:

Environmental and health risks of the use of industrial by-products and the methodologies of risk assessment (Wahlstrom *et al*. 1999). The report deals with the effects of most common harmful components present in secondary products on human health and the environment, the migration of harmful components and the possibilities of exposure during various stages of construction. The risks caused by this exposure are also assessed. The risks considered are primarily related to human health because the data needed for ecological risk assessment is still under development. The proposed risk assessment concept was also tested in a case study on the use of coal fly ash in earth construction.

Life-cycle environmental impacts of the use of secondary materials and natural aggregates, and the methodologies of life-cycle environmental impact assessment of road construction (Eskola *et al*. 1999, Laine-Ylijoki *et al*. 1999). A life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was proposed. Additionally, a database containing the environmental burdens of the most significant construction materials and unit operations as well as the information required for the calculation of the data was constructed. In order to evaluate the applicability of the methodology, the use of coal ash, crushed concrete waste and granulated blast-furnace slag was compared with the use of natural materials in corresponding applications. An Excel-based computer application was compiled on the basis of the data.

Environmental criteria of the utilisation of industrial by-products in earth constructions (Sorvari 2000) Environmental criteria for the utilisation of secondary products in earthworks were drawn up during the project. For the basis of the study the environmental criteria and approaches used in various countries were studied. A tiered system is presented for the assessment of environmental compliance. The system is based on soil guideline values and on leaching values, which are calculated on the basis of Dutch leaching models.

Methods for laboratory-scale functional testing of the secondary products used in earthworks (Tammirinne *et al*. 1999, 2000). Guidance and descriptions of laboratory methods recommended for investigation of the technical performance of secondary products in road constructions were compiled. Reference values for the assessment of results were also presented.

The binding and transport of harmful components in soil (Heikkinen 2000). The factors that impact on the fate of harmful components in soil were studied based on the literature and a field investigation. The focus of the study was on the most common components leaching from secondary products, their migration and binding in Finnish soil. In the field study the migration of inorganic compounds from an older fly ash construction was investigated. On the basis of the study recommendations were given about the soil and bedrock conditions to be considered when planning the utilisation of by-products.

The Finnish environmental permit practice and suggestions for the development of more adaptable legal measures (Kauppila 2000). Those factors in the present legislation and administrative practice which hinder the use of secondary materials in earthworks were studied. The aim was to establish a knowledge base for deregulation of the present permit procedure and harmonisation of permit practices.

Quality control system for the production and use of the secondary materials in earthworks. The aim of the project is to draw up a quality control standard for the production of secondary materials used in earthworks and to draft material standards for three reference materials. These materials are crushed concrete, blast-furnace slag and bottom ash from pulverised coal combustion.

Landfill acceptability of industrial waste (Wahlstrom *et al.* 2000). Recommendations about the landfill acceptability of mineral by-products, such as parameters to be investigated and investigation methods suitable for these investigations, are presented. Some examples of criteria applicable for assessment of the landfill acceptability of typical industrial by-products are also given.

Table 1. Industrial by-products used in earth construction in Finland and their estimated annual consumption, 1998–1999.

Activity	Production, t/a	Amount used in earthworks		Usage in earth construction/(other usage)
		t/a	%	
Energy production				
Coal fly ash	350 000	190 000	40	Road and field construction, earth- fill/(Production of cement and concrete 30 %, asphalt filler 5 %)
Coal bottom ash	78 000	53 300	70	Road and field construction
Peat fly ash	180 000	78 800	60	Mainly earthfill
Peat bottom ash and slag	33 000	11 000	33	Mainly earthfill
Metallurgic industry				
Blast furnace slag	550 000			(Production of cement, use as fertiliser)
– unground sand and slag		200 000	36	Road constructions
– ground slag		120 000	22	Binder in soil stabilisation
Slag from LD steel production	170 000	18 500	10	Use as fertiliser
Slag from ferrochrome production	290 000	290 000	100	
Construction				
Crushed concrete	200 000	100 000	17	Road and field construction
Tyres	30 000	27 700	92	Road and landfill construction
Road construction				
Pavement materials	150 000	150 000		Recycling to pavements
Structural courses	160 000			
Forest industry				
Fibre and paste suspensions	128 000		55	Landfill construction
Ash	210 000			Landfill construction/(forest fertiliser), total usage 55 %
Chemical industry				
Ferro sulphate gypsum	70 000			Binder in soil stabilisation

PERMIT PROCEDURE

An environmental permit is required if an industrial by-product or secondary material is regarded as waste, which is usually the case. According to the Finnish Environmental Act, the permit is issued by the local environmental authority if the amount of waste being used is less than 5 000 t. For larger amounts the permitting authority is the regional environmental centre. It usually takes more than four months to obtain the permit. This is one of the biggest barriers to the use of secondary products, because the use of natural aggregates is much less complicated.

On the basis of the study of the legislative barriers, the Ministry of the Environment has started to prepare a decree of the Council of State. The decree covers the use of selected waste materials in earth construction. The aim is to give general regulations concerning the conditions on which the use of the materials is permitted and thus to release their use from the permit obligation.

INVESTIGATIONS FOR THE ASSESSMENT OF ENVIRONMENTAL COMPLIANCE

When industrial by-products or secondary products are used in earthworks, the migration of harmful compounds from the material is considered to be the most significant environmental hazard. Besides leaching, it is also important to consider other properties of the material and to check the environmental impacts of the entire utilisation chain. Before assessing environmental compliance, the testing agency has to ensure that all the potentially hazardous compounds and properties of the material have been measured or investigated.

Besides the conservation of natural materials, the utilisation of by-products may have other positive effects, such as reduction of energy use or emissions. Up to now, the legislation has not required consideration of these impacts during the permit procedure for waste utilisation in earthworks. According to the new environmental legislation, however, more weight is put on integrated environmental assessment.

The main phases of investigations for the assessment of environmental compliance of industrial by-products or secondary products are presented in Fig. 1.

The basic characterisation of industrial by-products is usually a demanding task. The testing must be planned on a case by case basis. At least the following compounds and parameters will be selected for further investigation:

- Compounds with a concentration that is expected to be at least on the level of Finnish soil target values
- Compounds on which there is insufficient information about their concentration or harmfulness
- Compounds with a concentration that may exceed the Finnish occupational exposure limits.

When the investigations are planned, one must ensure that all the significant parameters are studied, that the methods used are reliable and suitable for the investigation and that the expertise of the investigator of the study is sufficient.

Sampling is one of the most critical stages of experimental investigations, because the sample has to reliably represent the material or batch of material under investigation. The sampling plan must be based on the objectives of the study and on the properties of the material to be investigated. For example, for environmental characterisation it is recommended that at least 20 samples be taken systematically, one sample per day over a period of four weeks.

The report also presents the methods recommended for basic characterisation, which include determination of the concentration of inorganic and organic compounds in the material, determination of leaching behaviour using the column leaching test (NEN 7343 or Nordtest ENVIR 002), the diffusion leaching test (NEN 7345) and the pH-stat leaching test, and methods for analysis of test eluates.

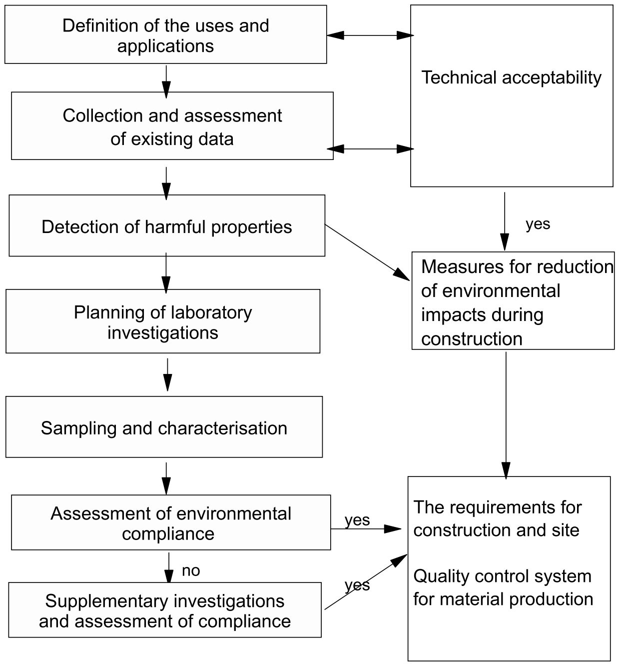

Figure1. Environmental assessment of secondary products: the main phases of investigation.

ASSESSMENT OF ENVIRONMENTAL COMPLIANCE

A tiered system is presented for the assessment of environmental compliance. The assessment levels are as follows:

1. *Concentrations of the harmful components.*

If the concentrations of all the inorganic compounds are below the Finnish soil target values and the concentrations of the hazardous organic compounds are below the detection level, the material is suitable for use in earthworks without restrictions. In the case of these values being exceeded, the use of material in ground water areas suitable for water supply is not recommended without a risk assessment.

2. *Leaching of harmful components from constructions.*

The leaching of inorganic compounds from the material is compared to the leaching values which were drafted as a part of the project by the Finnish Environment Institute. The recommended leaching tests are the column-leaching test, NEN 7343, and the diffusion-leaching test, NEN 7345.

Long-term performance is assessed by using a test simulating varying pH conditions or on the basis of expert assessment.

The leaching values (Table 2) are presented for unpaved constructions and for constructions paved with slightly water-permeable material, such as asphalt. The material must be placed above the upper ground water level. Sites on which the ground is from slightly to moderately permeable are considered as most suitable for the use of these products.

3. *Risk assessment.*

In the case of non-compliance with points 1 or 2 above, the material may be used on the basis of material- or site-specific risk assessment.

TECHNICAL COMPLIANCE

In most cases it is recommended that the technical compliance be investigated step by step. If the material is totally ”new” the basic parameters to be investigated usually include grading, compactibility and hardening. In most cases it is possible to make a preliminary screening of potential applications based on the above-mentioned data, the mode of production and chemical content of the material.

Further studies are then scheduled on the basis of the planned application. The report presents recommendations for the laboratory investigation of industrial by-products which are planned for use in road construction.

PRODUCTION CONTROL OF THE MATERIALS

In most cases it is not necessary to repeat the extensive basic characterisation of materials. In connection with the characterisation, a production control system for the assurance of conformity of the materials with environmental and technical specifications is established. Only in the case of significant changes of the quality of the material, such as changes in the production process or raw materials, it may be necessary to renew some or all the characterisation tests.

The production control system is material-specific. The technical characteristics that are significant for the application and the most critical environmental characteristics are selected for periodic control. Homogeneous materials with well-known basic characteristics require less monitoring than more complicated and less investigated materials.

Table 2. Suggested Finnish leaching values for the mineral materials used in earth construction (Sorvari 2000).

	Granular material	Granular material	Monolithic material
Substance	Unpaved	Paved	
	Emax, mg/kg	Emax, mg/kg	Emax, mg/m^2
As	0.14	0.85	58
Ba	10	28	2 800
Cd	0.011	0.015	2.1
Co	1.1	2.5	280
Cr	2.0	5.1	550
Cu	1.1	2.0	250
Hg	0.014	0.032	1.6
Mo	0.31	0.50	70
Ni	1.2	2.1	270
Pb	1.0	1.8	210
Sb	0.12	0.40	36
Se	0.060	0.098	14
Sn	0.85	3.1	280
V	2.2	10	700
Zn	1.5	2.7	330
F	11	25	2 800
CN, free	0.060	0.098	14
SO_4	1 500	N/A	N/A
Cl	250	N/A	N/A

SUMMARY

Based on an extensive study of various factors affecting the acceptability of secondary products for earth construction, guidance was developed for the assessment of the environmental and technical applicability of these materials. The guidance was prepared as a collaboration involving several research institutes.

The guidance presents the legislative requirements for the utilisation of secondary products in earth construction, recommendations for the investigation of environmental and technical applicability, recommendations for environmental and technical criteria of the utilisation in earthworks and road construction and recommendations for product quality control procedures.

There are many material- and site-specific factors that affect the environmental and technical applicability of the materials. At the same time, practical experience in the use of the materials is mostly quite limited. Therefore the recommended general requirements are conservative. The objective is to ensure the technical performance, to safeguard human health and to protect the environment. Exceptions can be made if it is possible to prove the applicability of a material at a determined site or at sites of a determined type, based on material or site-specific risk assessment or on technical investigations and construction requirements.

Adequate certainty about the applicability of secondary products will improve the prerequisites of utilisation, because it is possible to avoid negative experience resulting form the improper use of the materials.

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LIFE CYCLE INVENTORY ANALYSIS PROGRAM FOR ROAD CONSTRUCTION

by
Paula Eskola, Ulla-Maija Mroueh and Jutta Laine-Ylijoki

Eskola, Paula, Mroueh, Ulla-Maija & Laine-Ylijoki, Jutta 2001. Life cycle inventory analysis program for road construction. *Geological Survey of Finland, Special Paper 32, 23–30,* two figures.

The Finnish LCA-database and inventory analysis program for road construction was developed as a part of the Technology Development Centre's (Tekes) Environmental Geotechnology Programme. In the first stage of the study a life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was proposed. Additionally, a database containing the environmental burdens of the most significant construction materials and unit operations and the information required for the calculation of the data was constructed. In order to evaluate the applicability of the methodology, the use of coal ash, crushed concrete waste and granulated blast-furnace slag was compared with the use of natural materials in corresponding applications.

All the work stages, from material production to road management, as well as the materials most commonly used in the structural courses of road constructions, are covered in the analyses. The environmental loadings dealt with have been limited to those assessed as being the most important.

During the later phase of the work, a practical calculation model based on the developed methodology and existing data was formulated. The data obtained in the first stage was also augmented to the extent necessary for this purpose. For example, leaching tests of natural aggregates were performed. The Excel-based life cycle inventory analysis program created is suitable for the routine calculation of the environmental loadings of the most common road constructions and for their comparison.

Keywords: highways, construction, construction materials, by products, environmental effects, life cycle assessment,

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DEVELOPMENT OF THE LCA-METHODOLOGY

Background

About 70 million tons of natural mineral aggregates are used each year in Finland for road construction and earthworks. Depletion of the best materials, the need for resource conservation and lengthened transport distances have all increased the need to introduce substitute materials for natural aggregates. At the same time industry, construction and other similar activities produce large quantities of secondary products, which may be suitable for use.

One of the barriers to the wide-ranging utilisation of the secondary products of energy production and industry in road construction has been uncertainty about the environmental impacts. In order to prevent potentially hazardous effects it is important to identify all the positive and negative impacts of these materials. Life cycle impact is also being increasingly used as a selection criterion for products and materials both in industry and in other activities.

Describing the total environmental impact of activities and products reliably and in such a way that alternatives can be compared is no simple task. The ”cradle-to-grave” life cycle always involves numerous stages and activities that give rise to a number of different environmental loadings. In order to keep the amount of work within reasonable bounds, the assessments must always be limited and efforts must be made to identify the critical stages of the life cycle and those factors responsible for environmental loading. This requires not only adherence to the basic principles of life cycle analysis, but also knowledge of the product or activity in question.

Scope

The basic aim of the study was to provide a clear and functional procedure for the life cycle impact assessment of road constructions and for the comparison of alternative structural solutions. It was hoped that the assessment procedure would be so simple to use that it could easily be applied by road planners and designers. However, the assessment should cover the main life cycle phases of the constructions as well as the most important environmental impacts, and it should also meet the other basic requirements set for life cycle analysis. One premise was also that the assessment procedure should be applicable as a part of road planning, and that the results could be used as selection criteria for alternative constructions and materials.

The assessment procedure should also take into account the special features of road constructions, which are the large volumes of materials used, the long service lives of the finished products, the need to examine constructions as a whole rather than comparing alternative materials, and the significant effect of the constructions’ longevity and need for repair on their life cycle environmental loadings.

The work was carried out in two stages so that in the first stage a proposal was made for a procedure suitable for the life cycle impact assessment of road construction (Eskola & Mroueh 1998, Eskola *et al*. 1999). In order to evaluate the applicability of the procedure, the use of coal ash, crushed concrete waste and granulated blast-furnace slag in road construction was evaluated in case studies. The use of these industrial by-products and waste materials was compared with the use of natural materials in corresponding applications. The necessary data was also collected during the studies. The aim of the work’s second stage was to transfer the assembled data for utilisation as a practical model by creating an inventory analysis program to calculate and compare the life cycle impacts of the most common road constructions. The data obtained in the first stage of the study was augmented to the extent necessary for this purpose (Laine-Ylijoki *et al*. 2000, Mroueh *et al*. 2000).

Methodology

The basic phases of life cycle impact assessment are goal definition and scope determination, inventory analysis, i.e. calculation of the material and emission flows, impact assessment and, if necessary, improvement assessment. In this study the life cycle assessment methodology was adapted to meet the requirements of road construction. The material and emission flows were determined at all stages of the life cycle, and the most important environmental impacts as well as their associated factors were identified. The following general procedural guidelines on life cycle assessment were applied: SETAC's (Society of Environmental Toxicology and Chemistry) 'Code of Practice' (1993), Nordic Guidelines on Life-Cycle Assessment (Lindfors *et al*. 1995) and ISO standards (ISO 14040, ISO 14041).

System boundaries

Functions and work stages

The analysis included all the significant life-cycle stages covering the production and transportation of materials, their placement in the road structures and the use of the construction. The situation after the use of the construction was not included in the analysis because the structures most commonly remain in place after they have been withdrawn from service. The structures were examined as entities because in road construction the selection of a material often influences the quality and quantity of other materials used, the work methods employed, the need for upkeep, and so on. Pavement and sub-grade structures were analysed separately and can be combined when necessary. The environmental loading data was calculated for each individual structural component and work stage, so that it is possible to examine flexibly the alternative constructions under study at any given time. The principal road construction and usage phases, which were taken into account when comparing structures and materials are shown in Fig. 1.

If industrial by-products are used in the constructions, the environmental burdens of landfill disposal can also be assessed, as an alternative to their use in road construction. This requires that landfill disposal is a real alternative to utilisation.

Those stages of road construction and use that have no significance for the comparison of constructions were ruled out of the analysis. These include:

- Site clearance,
- Functions associated with road use (e.g. lane markings, the installation and use of traffic signs and lights),
- Regular or seasonal maintenance (e.g. snowploughing, road salting and sanding)
- Traffic emissions.

Environmental loadings

The environmental loadings assessed as being essential during the life cycle of road constructions were selected on the basis of the case studies for inclusion in the analysis. The included environmental loadings were the following:

1. *Use of resources*: natural materials, industrial by-products, energy and fuel consumption
2. *Atmospheric emissions*: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOC), particles and carbon monoxide (CO)
3. *Leaching into the ground*: heavy metals, chloride and sulphate
4. *Other loadings*: Noise, dust and land use

On the basis of a preliminary assessment of the quantity and significance, the following environmental loadings were excluded from the inventory: water use, discharges of COD and nitrogen to water, emissions of PAH, heavy metals and methane, ordinary and hazardous waste and accident risks.

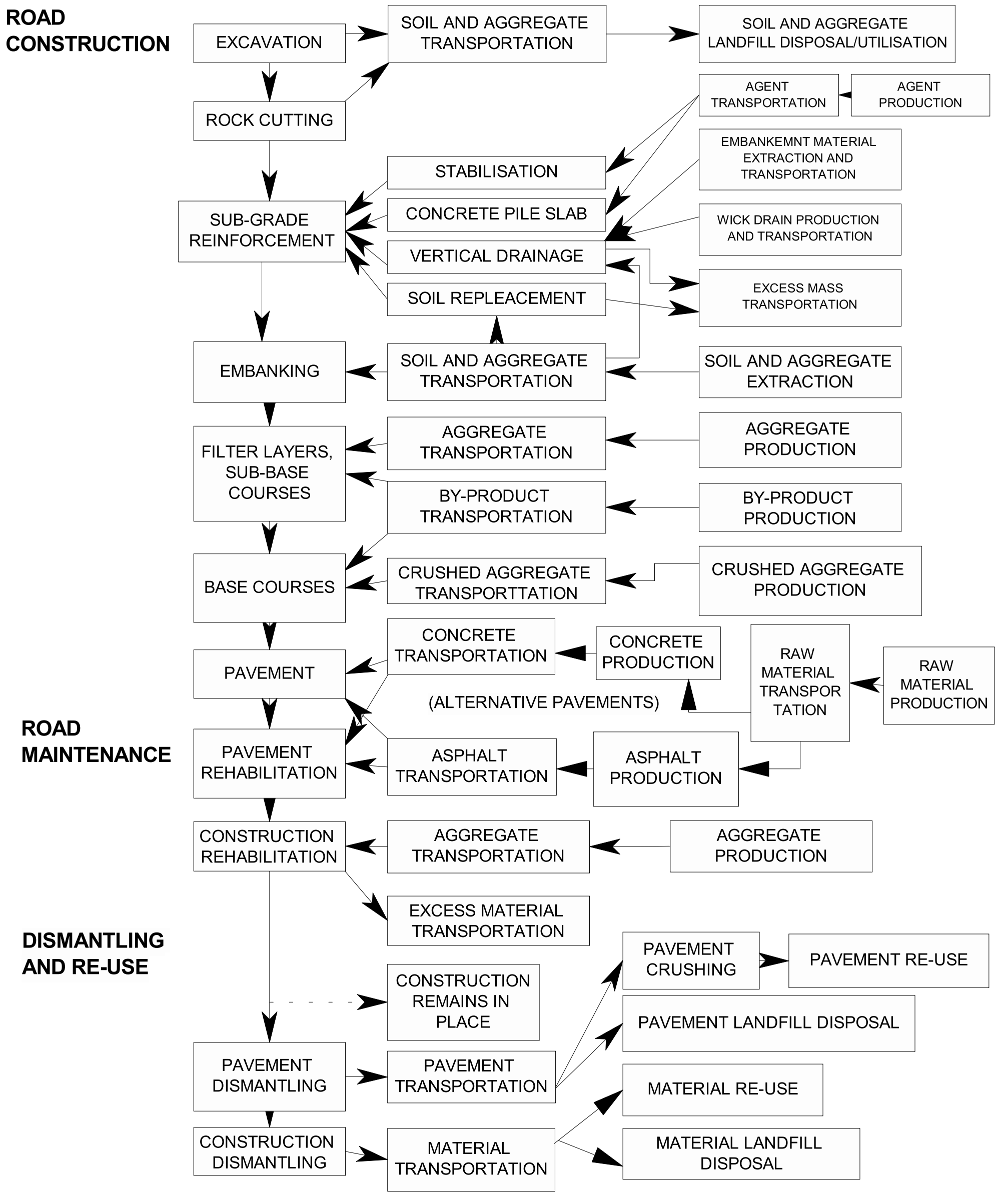

Figure 1. The principal road construction and usage phases.

Material production chains

The production chains of natural aggregates started from bedrock excavation or excavation from the ground. For cement and lime the starting point was extraction of raw materials and for rubber the production of crude oil. The production chains of industrial by-products were limited so that the environmental loadings of the by-product production process were not included in the analysis. By-products are defined in waste legislation as wastes for which no loadings are allocated in life cycle analyses. An alternative to the use of most by-products as recycled fill is disposal of the inert waste in landfills.

Other boundaries

Functional units: When comparing constructions, the functional units should always be structures of the same length that meet the same performance requirements and are designed for the same site. In practical cases, the entire construction can also be the functional unit.

Period of analysis: The period of analysis should include the entire life cycle of the material or product from raw material extraction to withdrawal from service and final disposal. In the life cycle assessment of a road construction the period of analysis must be sufficiently long to include the impacts of its service life.

Machines and equipment: The loadings caused by the manufacture of work machines and lorries and by the maintenance of machines were excluded from the analysis. The manufacture and transportation of blasting materials and fuels were also excluded.

Situation after use: It was assumed in the analysis that the construction would remain in service for 50 years. As road constructions usually remain in situ after use, no cases in which a construction was dismantled were examined in this report.

Landfill disposal: The program can give an approximate estimate of the environmental loadings avoided by using industrial by-products as recycled fills. The program calculates the minimum avoided loadings, i.e. the landfill volume needed for the inert waste and the emissions that would be released in transporting the material to the landfill site. The loadings caused by any sealing and covering of the landfill have not been included in the analysis because of their site-specific variability. Neither has leaching into the soil on the landfill site been assessed.

ENVIRONMENTAL IMPACT ASSESSMENT

Significance assessment

The aim of the life-cycle environmental impact assessment is to convert the inventory results into a form that can be more easily interpreted and compared. The impact assessment procedure is performed in three stages:

1. *Classification*, i.e. sorting the environmental loadings into impact categories on the basis of potential impacts;
2. *Characterisation*, i.e. weighting the emissions and other environmental loadings within the category according to possible impact potential; and
3. *Valuation*, i.e. weighting the environmental loadings or impacts in relation to each other.

The advantage of the valuation methods is the simplicity of result interpretation. The final outcome is either one environmental loading index or an impact matrix of mutually comparable effect scores. Further exploitation of the results does not require any expertise on the part of the user.

The creation of significance factors that are as reliable and widely applicable as possible is one of the greatest problems of valuation. Effect scores generated by different methods also make it more difficult for the users themselves to assess the significance of the results. They often also arouse suspicion, because valuation means an increase in the influence of experts in decision-making, which some fear will lead to the influence of citizens being reduced and one-sided views being over-emphasised.

Several assessment methods have been proposed for the results of life cycle analyses, none of which can be regarded as being generally accepted or even applicable in all situations (Lindfors *et al*. 1995). The best known are the Swedish Environmental Priority Strategy (EPS) system, the impact categorisation method, which has been developed in Holland and Sweden, and the ecopoints method developed by BUWAL of Switzerland.

In this study the effect scoring was made on the basis of expert assessment. The environmental loadings of the constructions were converted into relative values using the reference construction made of natural materials as the base level. After the relative environmental loading levels had been calculated, the impact categories were proportioned to one another by multiplying the effect scores by the comparative scores obtained on the basis of expert assessment. Because the construction and the transport distances always affect the outcome of such comparisons, the results as such cannot be generally applied to the comparison of materials. When comparing the alternative constructions it is notable that in all respects the differences between the constructions are not particularly great, and that the differentiating factors act in opposite directions.

Data sources and uncertainties

Because of the local nature of the effects of road constructions, primarily local or material-specific data was used. Use was also made of general Finnish know-how, which was supplemented by international sources of data where necessary.

The availability of data on by-products is limited by the fact that their utilisation is not yet well established. For this reason it is not always easy to determine the most usually employed working methods and the most general implementation methods of the work stages. As yet there is still relatively little experience- or measurement-based data on the work stages and their environmental loadings.

The release of dust emissions from materials during the different stages of production, transportation and construction is a significant environmental loading factor due to the comfort and heath risks that they pose. However, little measurement data on the release of dust emissions was found and its conversion into a comparable form was problematic. In practice, small particulate matter (SPM) can be more significant than dust particles. SPM emissions remain airborne for a very long time and are carried long distances by winds. Moreover, they pose a more serious health risk than dust particles. Because SPM emissions have attracted attention only recently, there is even less data available on them than on dust emissions.

The quantities of substances leaching out of secondary materials were simulated on the basis of laboratory-scale leaching tests. In practice, numerous factors affect leaching from construction materials. There can also be significant differences between the same material when produced under different conditions. Because there was no leaching data for natural aggregates, a few materials were tested during the project. The tests used were CEN pr EN 12457 (1996) and a pH-static test. The leaching of heavy metals from natural aggregates was found to be very small.

Because it is necessary to make many assumptions when assessing the environmental loadings, the uncertainties and ranges of the results are quite large. However, the fact that the same assumptions have been made when examining the various alternatives improves the reliability of the results.

THE INVENTORY ANALYSIS PROGRAM

In the second stage of the project, an Excel-based life-cycle inventory analysis program for road construction was created and the suitability of the program for calculation of environmental loadings of various constructions was tested.

Characteristics of the program

The inventory analysis program created on the basis of the developed methodology is suitable for the routine calculation of the environmental loadings of the most common road constructions, and for their comparison. Most of the data needed for calculations is included in the program. Only the dimensions of the construction, materials and thicknesses of the structural courses and transport distances of materials are required as input data.

The environmental loadings are presented in numerical form or using various standard graphical presentations included in the program. The program enables comparison of pavement structures as such, in relation to fixed reference construction or as effect scores.

The environmental loadings of constructions or structural courses (embankment materials, filter layer, sub-base, base course and pavements) can be presented by principal work stage or as total loading.

The pavement structure and the sub-grades are analysed separately and the results can be combined if necessary. The program includes the following alternative sub-grades: soil replacement, soil stabilisation, deep stabilisation, vertical drainage + drainage course + temporary loading berm and concrete pile slab.

If necessary the program can be extended to include new materials, structural components and alternative sub-grades.

Case studies

For testing of the life-cycle inventory program, the environmental loadings of five actual road planning cases were calculated (Laine-Ylijoki *et al.* 2000). The calculation of environmental loadings of case studies proved to be a relatively simple and fast task. The use of the comparison worksheet ena-

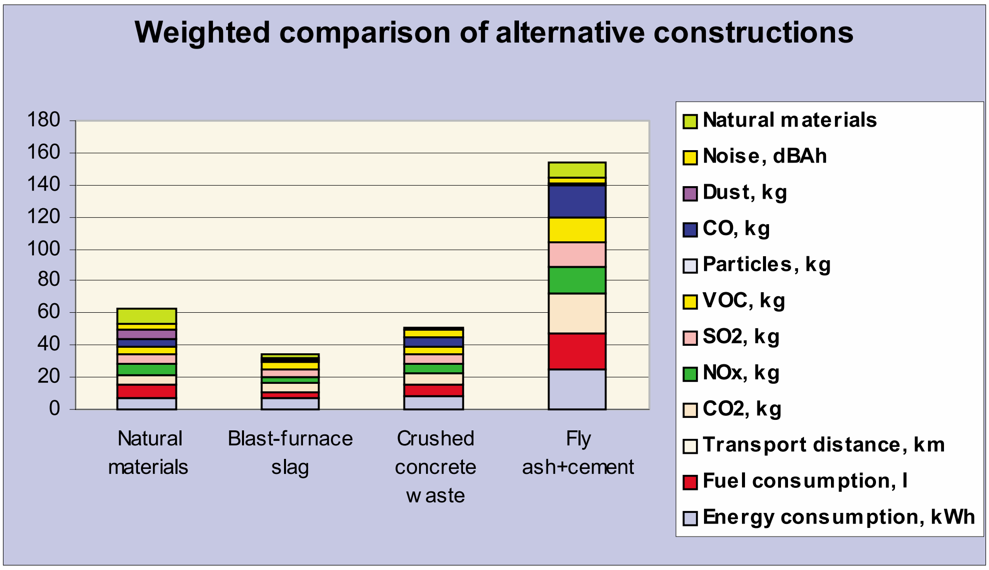

Figure 2. Example of the graphical presentations included in the program. Weighted comparison of alternative pavement constructions.

bled straightforward comparison of the alternatives and presentation of the results of calculations. An example of the graphical presentations included in the program is presented in Fig. 2.

CONCLUSIONS

A life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was developed. The procedure focused especially on the comparison of industrial by-products and natural aggregates, but the assessment of other constructions is possible as well. An Excel-based life cycle inventory analysis program for road constructions was developed on basis of the procedure. The program covers all the work stages from material production to road maintenance as well as the materials most commonly used in the structural courses of road constructions. The environmental loadings of the constructions and structural components made from the materials within the scope of the program can be calculated simply using only the dimensions of the construction, the thicknesses of the structural courses and transport distances as input data.

The program is suitable for routine calculations of environmental loadings of different road constructions. The environmental loadings are presented in numerical form or using various standard graphical presentations included in the program. The environmental loadings dealt with in the program have been limited to those assessed as being the most important. However, the loading factors in question described the total environmental loadings quite well as long as the life cycle inventory pertains to complete constructions. The environmental loadings regarded as being the most important for road construction in the expert assessment made when creating the inventory analysis procedure were the use of natural materials, energy and fuel consumption, the leaching of heavy metals into the soil, and atmospheric emissions of NO_x and CO_2.

The simplicity of the inventory analysis program makes it suitable for use by structural designers and other groups not so familiar with LCA methodology. The program has an extensive basis database and extensions with new materials, structural components and sub-grades are possible.

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Geological Survey of Finland, Special Paper 32, 31–37, 2001.

INDUSTRIAL SLAG USE IN GEOTECHNICAL ENGINEERING: SLAG IN THE GEOTECHNICAL ENGINEERING PROJECT

by
Marko Mäkikyrö

Mäkikyrö, Marko 2001. Industrial slag use in geotechnical engineering: slag in the geotechnical engineering project. *Geological Survey of Finland, Special Paper 32, 31–37,* seven figures.

The use of industrial slag has for decades been based on experience with no dimensioning instructions being available until the 1990's. Attention was not paid to the systematic development of slag before the late 1980's, at which point the use of air-cooled blast-furnace slag was so extensive that there was an evident need for drawing up instructions in order to avoid structural problems possibly arising from its incorrect use. The first set of instructions were completed in 1989, accompanied by the introduction of new applications particularly for the use of granulated blast-furnace slag both in structural road layers and in stabilising the base course. The new applications and the stricter technical requirements placed on the products were one reason for launching the five-year "Slag in geotechnical engineering" project. According to the aim set for the project, design, dimensioning and construction instructions should be drawn up for all the slag produced at the Rautaruukki Group's works in Finland with regard to their use for earthwork and road construction purposes. To achieve this aim, the project was divided into three sub-fields, that is the use of slag 1) in structural road layers, 2) as a binding agent in stabilising structural layers and 3) as a binding agent in mix and deep stabilisation.

Keywords: construction materials, by-products, slag, utilization, earthworks, highways,

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INTRODUCTION

A remarkable number of different kinds of slag are produced in the different phases of the steel-making process. In Finland, total slag production from the Rautaruukki Raahe steel works and Fundia Wire Koverhar steel works is 1 000 000 tonnes. Even in a very modern integrated steel works, like the Rautaruukki Raahe steel works, the amount of slag per tonne of steel produced is more than 300 kg. This amount of slag is a total amount, which consists of blast-furnace slag, desulphurizing slag, converter slag and slag from secondary metallurgy (Fig. 1).

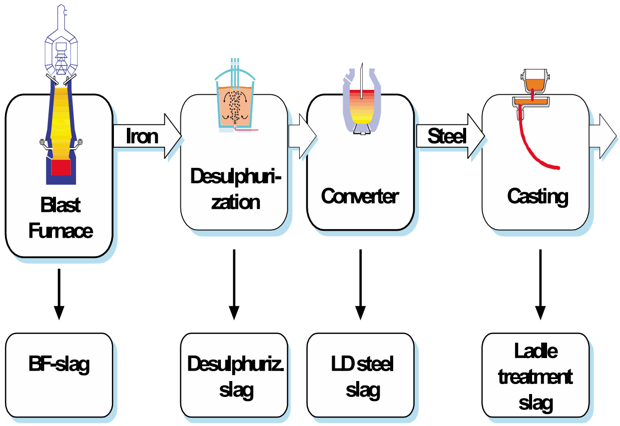

Figure 1. Slag types from integrated steel-making processes.

The first step in slag utilization is separating the metallic part, i.e. scrap from slag. The most valuable part of slag utilisation is the returning of this separated scrap back to iron- and steel-making processes. However, ever-increasing attention is paid to non-metallic slag and its utilisation. The main reasons for this kind of development are cost savings in storaging and avoidance of environmental penalty fees. A very essential part of the main product, i.e. steel, is the fact that the steel producer must show how it is taking the environment into consideration. It has been recognised that by systematic R&D work and effective marketing, by-products utilisation may also be a good business.

Over recent years, more and more emphasis in road building has been placed on cost saving. As a result of this, the recycling of used road materials and the use of cheaper industrial by-products has been developed. Environmental factors have also played their part in this development.

R&D PROJECT IMPLEMENTATION

Preliminary preparations and project organising

The principal responsibility in the whole project management and implementation was carried out by SKJ Ltd, which is a subsidiary of Rautaruukki Oyj, the biggest steel producer in northern European countries. Prior to the actual planning of the project a seminar was held in order to get new ideas and perspectives for the project. Experts from a wide variety of interest groups were invited and representatives from research institutes, universities and road constructors were present in the seminar.

After comprehensive analysis and several smaller work group meetings, the actual project organising and detailed planning were started. Contacts with the research institutes, universities and road constructors played an important role and thanks to effective netting, SKJ Ltd managed to create a project, which would be able to work technically efficiently.

Financial support was received from the Technology Development Centre of Finland (Tekes). Rautaruukki Oyj and the Finnish Road Administration also played an important role; the former by offering R&D services and the latter by constructing the experimental road sections. The University of Oulu took care of most of the laboratory work. The Geotechnical laboratory carried out a huge number of various kinds of laboratory tests. Some research work was also done in the Department of Geology and the Department of Chemistry. The Research Centre of Finland (VTT) had an important role as a coordinator of several associated projects, which were financed by Tekes and by-product companies like SKJ Ltd.

Actual project work

The actual project work was started at the beginning of 1995 and the project was carried out according to the diagram shown in Fig. 2. Total implementation time for the project was five years with one additional year being needed to finish all the instruction work. The most important instructions were made during the project.

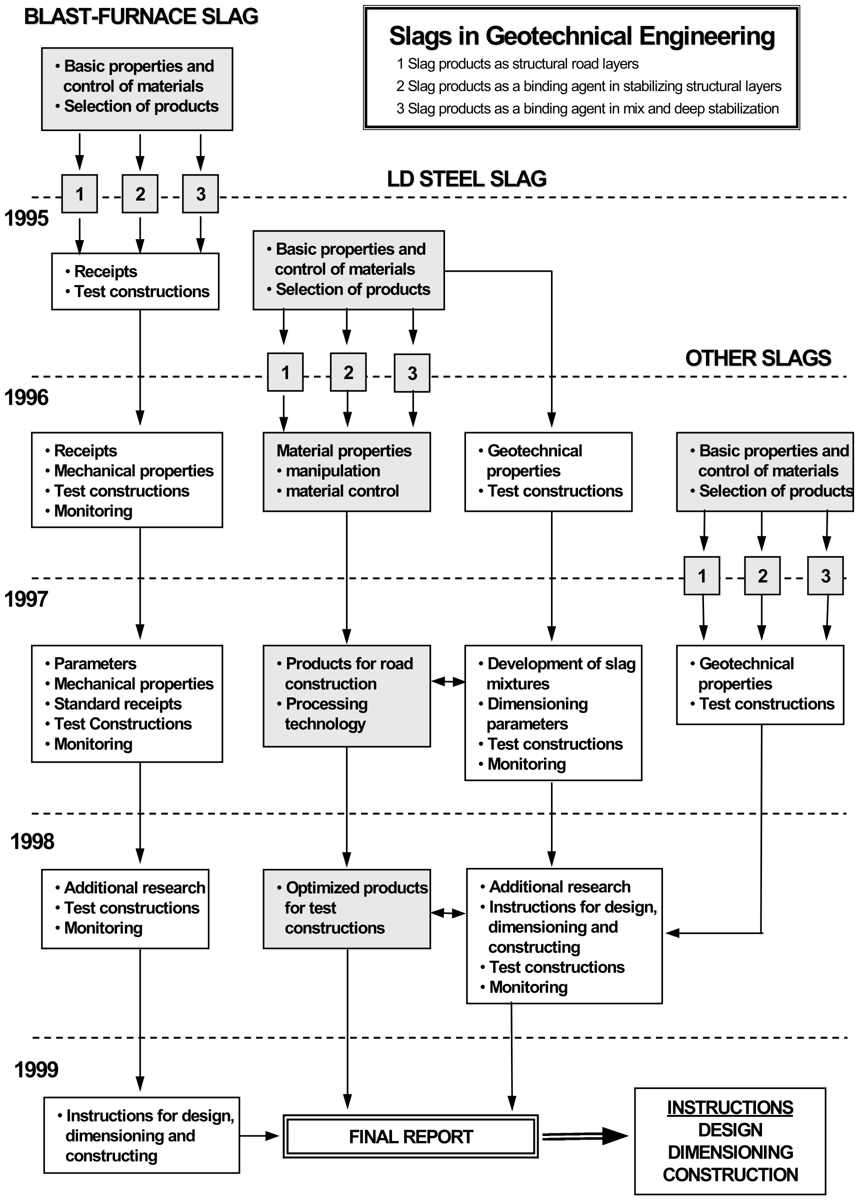

Figure 2. Research sectors in actual project work according to slag types under research.

The project was divided into three parts. These were: 1) slag products as structural road layers, 2) slag products as a binding agent in stabilising structural layers and 3) slag products as a binding agent in mix and deep stabilisation. A number of smaller studies on the use of slag as structural materials in road construction was also implemented, and a number of slag products with greatly varying grain-size distributions were examined and developed.

In all these areas of research, there was in progress an effort to increase knowledge of the basic properties of these materials. For the LD steel slag, desulphurizing slag, and ladle treatment slag, this means determining the technical properties, and for the blast-furnace slag and LD steel slag, the binding properties.

Area 1 research concentrated upon developing LD steel slag and blast-furnace slag products. In addition, the suitability of desulphurization and ladle treatment slag was studied. The main goal for area 1 research work was to increase understanding concerning material behaviour of each slag type.

In area 2 studies water cooled blast-furnace slag, refined in various degrees, for use as a binder in the stabilising of road courses, was developed. The products were granulated blast-furnace slag, preground granulated blast-furnace slag and ground granulated blast-furnace slag. In addition, included in this area of the research was LD slag, which was used in its original form or as an activator refined to various degrees. Cement was also used as an activator.

The main emphasis in area 3 was on the binding properties of ground granulated, cement-activated BF slag, primarily in the stabilisation of clay materials.

There are two possible ways of implementing the research and development work in order to improve the quality of the final product. One way is to change the properties of the product (Fig. 3). This would happen for example by grinding coarse slag gravel into a finer product. The other way is to develop a new way of using the product. For example granulated blast furnace slag has conventionally been used in Finland as massive layers in road construction. In the early 90's its utilisation was developed in such a way that nowadays exactly the same product is used for a more demanding purposes, that is as a binding agent in road stabilisation.

For the blast-furnace slag the research concentrated on binder techniques of stabilisation, and its uses in massive layers (unbound layers).

In relation to the study of stabilising binder materials, a comprehensive investigation was already done on factors affecting the strength of stabilised materials (Mäkikyrö 1995). The development of binder material mixes, and determination of technical properties with the aim of producing procedures and instructions, was done on the basis of this previous study. These studies were focused on stabilisation of recovered road materials and till. In parallel with these, studies were made in connection with the stabilising of crushed rock. Materials to be used as binder were cement-activated granulated blast-furnace slag, preground granulated blast-furnace slag and ground granulated blast-furnace slag.

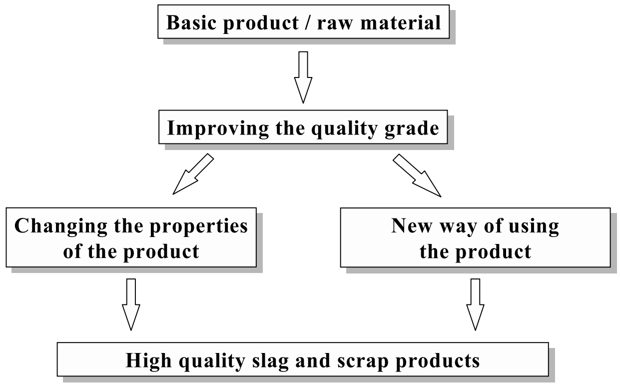

Figure 3. Two ways of implementing R&D work.

Mix- and deep stabilising studies were done on the stabilising of clays using cement activated ground granulated blast-furnace slag.

For LD steel slag the research concentrated on two main sections: 1) the use of LD steel slag as a replacement for natural materials and air-cooled blast-furnace slag in massive constructions and 2) the use of LD steel slag in slag binders for the stabilising of road courses. The use of LD steel slag in slag mixtures was studied only in some minor extent.

The emphasis in research was to put on producing LD slag products of a more valuable nature. The overall aim of the research was to determine the design parameters for construction courses using slag, and those using slag binders. The determination was made in relation to bearing capacity and frost resistance properties.

The use of LD steel slag as a replacement for natural materials and air cooled blast-furnace slag in massive constructions means in practice determining the properties of LD slag aggregates and comparing those properties to natural aggregates and blast-furnace slag. Possible changes in technical properties over the course of time were also taken into consideration.

The slag products, which were used in the binder material research, were granulated blast-furnace slag, preground granulated blast-furnace slag, ground granulated blast-furnace slag (400 m^2/kg, Blaine), LD steel slag (0–3 mm), preground LD slag, ground LD slag (150 m^2/kg, Blaine) and cement. The aim of the binder material research was the replacing of the cement, used as activator, by LD slag wherever possible. In addition, the binding properties of LD slag itself were studied. The first stage of the research was to develop more reactive slag binders. In the second stage the regulation of the ratio of binder materials in relation to the natural materials used for binding was investigated.

One of the most important studies regarding LD steel slag was that of determining the expansion properties, and in particular, the means of controlling expansion. The primary aim was to find a structural solution to stability.

Only some minor laboratory studies has been done concerning desulphurization slag and ladle treatment slag. The aim was to determine the basic properties of these slag types and get some idea of their technical behaviour.

The amount of laboratory tests performed and material used during the whole project were huge. Several thousands of single tests were made and about 15 tonnes of material were handled in the laboratory alone. Testing methods were the so-called 'basic geotechnical tests', i.e. the number of results is remarkable and the methods were quite simple.

A central part of all areas of the research was the constructing of trial road constructions in co-operation with the Finnish National Road Administration. The design of the trial constructions was based on the results of the laboratory tests. A very important part of the monitoring of the trial road courses was that of measuring both bearing capacity and any possible changes occurring due to frost.

In the summer of 1995 seven trial stretches (each 100 m) of on-site stabilised road using cement-activated granulated blast-furnace slag stabiliser were built. Stabilisation was carried out so that the materials of the old road pavement were utilized as aggregate of the new layer, which was stabilised (Fig. 4). The existing natural rock material and the old bituminous pavement materials were used for improving the road. New material was used only for laying the new wearing course. The typical thickness of stabilised layer was 150–200 mm and the wearing course was bituminous asphalt concrete, thickness 50–100 mm.

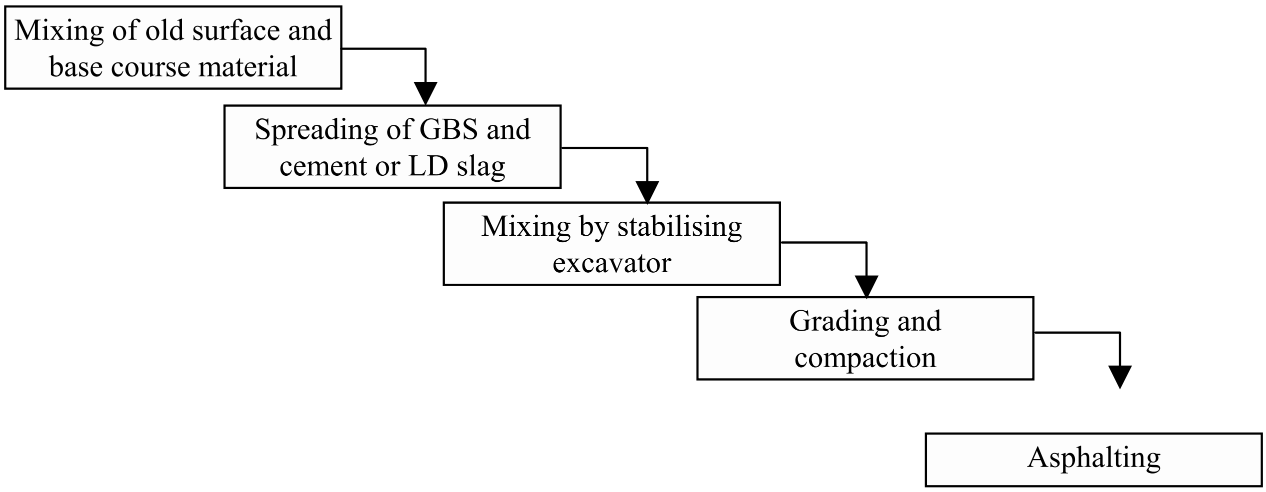

Figure 4. Different stages in so-called on site stabilisation technique.

At the end of 1995, a trial in connection with pillar type, deep stabilisation was carried out, using cement-activated ground granulated blast furnace slag. This test construction was made as a part of the Road Administration's research project TPPT. In 1996, the first instrumented trial constructions using LD slag were built, in connection with massive constructions. In the summer of 1997, a total of 10 trial sections were built. Five sections were made with the on-site stabilisation techniques and five were made as massive layers. A schematic picture of the test sections with massive slag structure is presented in Fig. 5.

Instrumented constructions included the following measurements: frost penetration, moisture content in different layers, thermal regime from 10 different depths (10 cm to–350 cm), thickness of snow in road slope and thermal conductivity. Measurements have been performed 6 times a year and load bearing measurement with a falling weight deflectometer three times a year. Monitoring of test sections will be continued several years from now on.

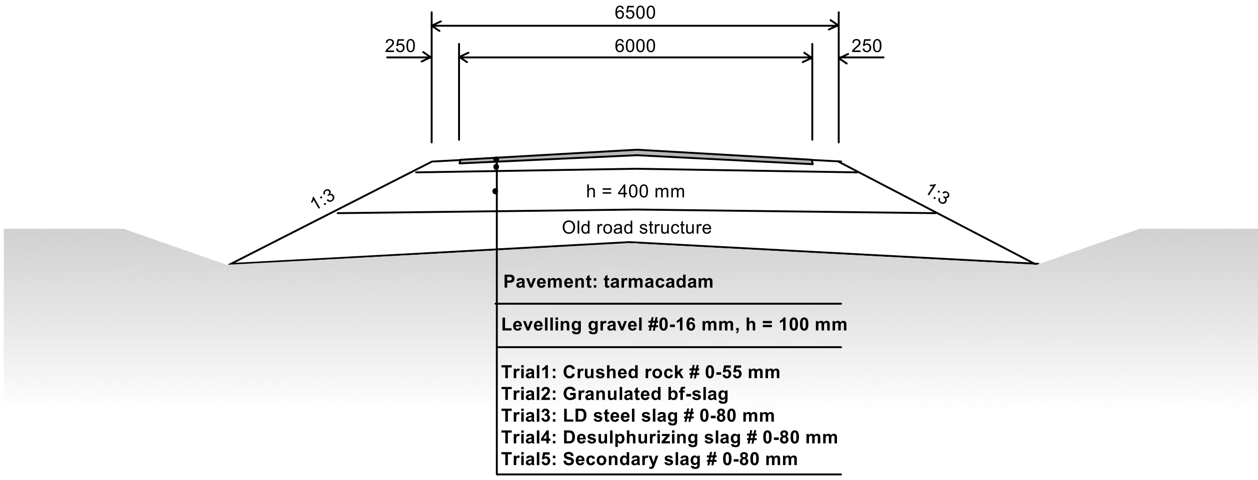

Figure 5. A schematic cross-section of test constructions with massive slag structures.

Results

During the whole project thousands of tests were performed in the laboratory. The majority of these tests were so called basic laboratory tests, the aim of which was to produce as much measured data as possible in order to get a reliable idea of the material behaviour of different slag types, especially those for LD steel slag. Research work was done for various product fractions from fine powder up to very coarse crushed aggregates.

The main result of the entire project was the development of instructions for the use of slag products in road construction. Some of the instructions were drawn up during the project implementation (Tielaitos 1998; Finnra 18/1999, Siira *et al*. 1999) and others (Slag products in earth structures, Slag products in construction on weak subsoils and Stabilisation with granulated blast-furnace slag) are still under preparation and will be finished by the end of 2001.

Fig. 6 shows one example of development work for slag-based binders. The effect of the amount of slag components in slag-based binder was tested by mixing selected slag components and using them as binder for stabilising of crushed rock material. LD3 is ground LD steel slag (150 m^2/kg, Blaine) and GBS is normal granulated blast-furnace slag produced in the Rautaruukki Raahe steel works. In this kind of binder LD slag is used as an activator instead of cement. Results indicate that the increasing amount of activator results increasing compression strength. However, the degree of strength should be higher in order to fulfil the demands set for stabilised road base.

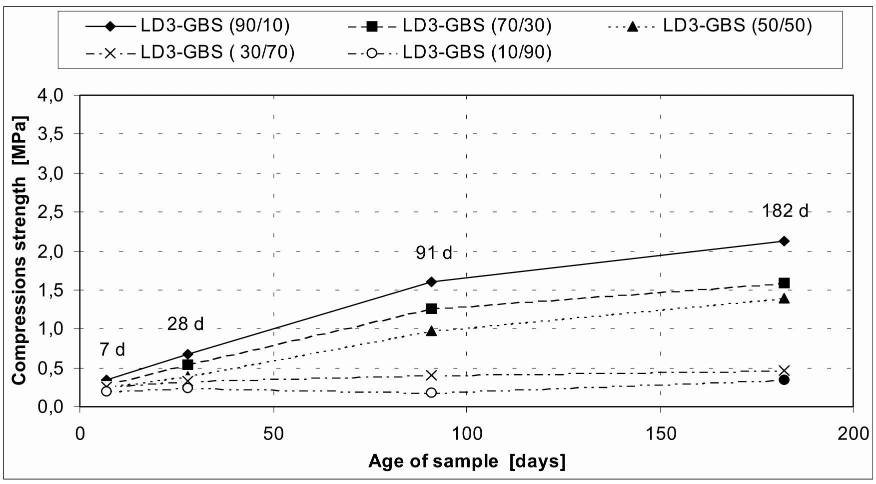

Figure 6. The effect of the amount of slag components in slag-based binder. Stabilised material was crushed rock.

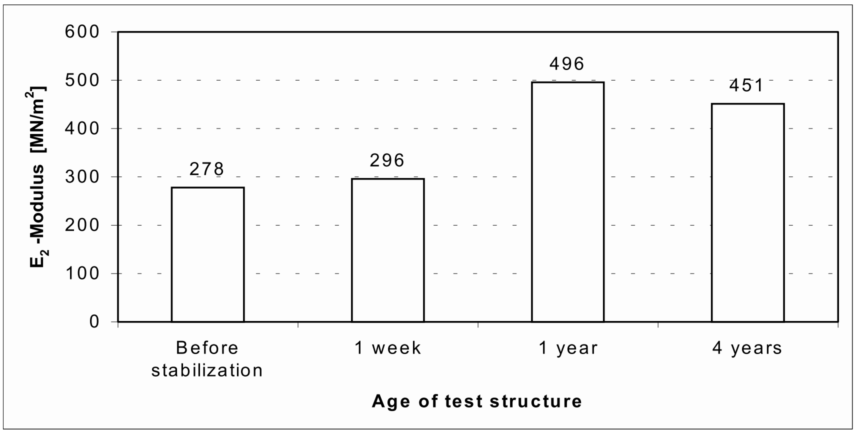

Figure 7. The improvement of bearing capacity of one test structure made in 1995. Values are mean values from ten different measuring points.

The measurement of bearing capacities of stabilised roads was an essential part of monitoring test road sections. Fig. 7 shows the development of the bearing capacity for one test section made by stabilising old road base with granulated blast-furnace slag, which was activated by cement. A remarkable increase for E_2 -modulus was achieved during the first year of monitoring, after which the value has remained at the same level.

SUMMARY AND CONCLUSIONS

The main goal for the project was to prepare instructions for the use of slag products in road construction. To achieve this result a lot of research work was done both in the laboratory and in actual conditions, i.e. on test constructions. The project was implemented according to a time schedule, which was set at the beginning and only some changes were made to the plans during the project. The main result, that is the making of new instructions, was also achieved and in this way one big step was taken forward in upgraded slag utilisation in Finland.

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FIELD HYDRAULIC CONDUCTIVITY OF A PAPER MILL SLUDGE HYDRAULIC BARRIER USING TWO STAGE BOREHOLE TESTS

by
Juan D. Quiroz[1], Thomas F. Zimmie[2] and Benjamin D. Rosenthal[2]

Quiroz, Juan, D., Zimmie, Thomas F., & Rosentha, Benjamin D. 2001. Field hydraulic conductivity of a paper mill sludge hydraulic barrier using two stage borehole tests. *Geological Survey of Finland, Special Paper 32, 39–45,* one figure and 2 tables.

This paper deals with the field hydraulic conductivity evaluation of a paper sludge landfill cover located in Corinth, New York that was completed in 1995. This landfill cover, a demonstration project, consists of compacted clay and paper sludge hydraulic barrier sections. Laboratory flexible-wall hydraulic conductivity tests were performed on in-situ samples obtained adjacent to in-situ two-stage borehole (TSB) test locations. The TSB test is a field infiltration test that has gained popularity over the last several years for the evaluation of hydraulic barriers. The objectives of this study were to evaluate the paper sludge long-term field hydraulic conductivity, and compare relative differences between laboratory and field hydraulic conductivity values. Results indicate that paper sludge is a suitable hydraulic barrier material alternative since laboratory and field hydraulic conductivity values were near or less than 1×10^{-9} m/s (the typical regulatory requirement), similar to compacted clays. Overall, the paper sludge field hydraulic conductivity values were about half an order of magnitude to one order of magnitude greater than those measured in the laboratory. In contrast, the compacted clay field hydraulic conductivity values were slightly lower than the measured laboratory values. The main difference between laboratory and field hydraulic conductivity values for each hydraulic barrier material type is attributed to effective stress sensitivity. Paper sludge is very sensitive to effective stress relative to compacted clay. Additional factors, advantages and disadvantages were discussed for laboratory and in situ TSB tests.

Keywords: landfills, disposal barriers, paper industry, by-products, sludge, hydraulic conductivity, boreholes, testing, Corinth, New York, United States

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INTRODUCTION

Paper mill sludge landfill covers

In recent years, paper mill sludge has emerged as an alternative landfill cover hydraulic barrier material instead of compacted clay. Paper mill sludge is the residual material from the paper making process produced by a wastewater treatment plant. Recycling paper sludge often creates a win-w*in situ*ation for the landfill owner (often a municipality) who saves the cost of obtaining clay that may not be readily available, and the paper mill which saves the cost of sludge disposal.

Paper sludges are high water content materials that typically have high organic contents, high compressibilities and low shear strengths. Several researchers have investigated the geotechnical and geoenvironmental properties of paper sludge (e.g., Zimmie *et al*. 1995, Moo-Young and Zimmie 1996, Kraus *et al*. 1997, Benson & Wang 1999 and Quiroz 2000). These studies have shown that paper sludge hydraulic barriers can achieve hydraulic conductivity values of 1×10^{-9} m/s or less, comparable to compacted clays. Moreover, the unique geotechnical field behavior of paper sludge is a result of its geotechnical properties, which are in a different range when compared to typical soils (e.g., sands, silts and clays). For example, after construction, paper sludge barriers undergo high settlement stains due to primary and secondary consolidation ranging from 18% to 35%, even under the low overburden pressures of a typical landfill cover. These settlement strains induce large reductions in void ratio causing decreases in hydraulic conductivity. This behavior is especially important in cases where marginal hydraulic conductivity values are measured, since the paper sludge hydraulic barriers improve with time. Thus the long-term evaluation of in-situ hydraulic conductivity is an important issue and should be considered in post-closure paper sludge landfill cover monitoring strategies.

Objectives

The purpose of this project was to evaluate the long-term field performance of a paper sludge landfill cover constructed in 1995, and compare the differences between laboratory and field hydraulic conductivity values. Currently, little information exists on the in-situ measurement of hydraulic conductivity for paper sludge landfill covers. The measurement of hydraulic conductivity using flexible-wall triaxial cell permeameters is probably the best method of laboratory testing (Zimmie 1981, Daniel *et al*. 1984). However, in general, one problem with laboratory tests is the amount of disturbance applied in the sampling process. This disturbance is significant in the retrieval of paper sludge samples due to high fiber contents and low shear strength ranges. In addition, the stress condition applied in a triaxial cell is different from actual, in-situ stresses (i.e., $\sigma_1 = \sigma_3$ versus K_0 stress condition). Therefore, the measured laboratory hydraulic conductivity values may be different from the in-situ values. An alternative is the in-situ measurement of hydraulic conductivity using the Two-Stage Borehole (TSB) test, also known as the Boutwell test (Daniel 1989, Trautwein & Boutwell 1994). The comparison between *ex situ* and *in situ* hydraulic conductivity testing will provide additional hydraulic conductivity behavior information essential to the application of paper sludge hydraulic barrier technology.

TOWN OF CORINTH LANDFILL

The paper sludge landfill is located in Corinth, New York and has a footprint of about 5.2 ha. Since paper sludge was considered experimental and nonconventional within the State of New York, this landfill closure was approved as a demonstration project. Thus the landfill cover had a compacted clay and paper sludge barrier layer section to provide a direct comparison between each barrier layer type. Approximately 4.1 ha is covered with a 1.2 m thick paper sludge layer, while the remain-ing 1.1 ha is covered with compacted clay about 45 cm thick. An overburden sand layer about 75 cm to 100 cm was placed on the paper sludge hydraulic barrier as a barrier protection and top soil layer. The landfill closure was completed in 1995.

The paper sludge for the hydraulic barrier was obtained from the International Paper (IP) Co. located in Corinth. Fresh paper sludge produced by the wastewater treatment plant and old paper sludge harvested from the paper mill's sludge landfill was used for the barrier layer. Moo-Young and Zimmie (1997) and Floess *et al*. (1998) have presented the construction aspects and geotechnical properties for the Town of Corinth Landfill and IP paper sludge.

IP paper sludge geotechnical properties

The initial geotechnical properties of the IP paper sludge were measured during the construction phase of the Town of Corinth Landfill cover (Moo-Young & Zimmie 1996). In general, water contents, organic contents, and specific gravities varied from 150% to 220%, 42% to 56%, and 1.80 to 1.97, respectively. These geotechnical properties are in a completely different range when compared to typical compacted clays. High water contents and high organic contents account for the large compression index (C_c) values, 1.27 to 1.96, measured for IP sludge. As a result, large settlement strains due to consolidation are expected after construction of the barrier layer.

METHODOLOGY AND APPROACH

A comparative testing program was developed to measure laboratory and field hydraulic conductivity values for the Town of Corinth Landfill cover. Four testing locations were selected on the landfill hydraulic barrier, three in the sludge section and one in the clay section. The tests were conducted during the summer and fall of 1999.

Sample retrieval

Hydraulic barrier specimens were obtained using 73 mm diameter thin-walled Shelby tubes. Compacted clay samples are typically retrieved using a slow, steady insertion effort such that a continuous, intact sample is obtained. However, this method is not very effective for paper sludge sampling due to the low shear strengths and high organic contents of the sludge (Moo-Young & Zimmie 1996, Benson & Wang 2000, and Quiroz 2000). A slow insertion and resistance to shearing by the organic fibers often compresses the sludge, greatly disturbing the soil matrix. Therefore, paper sludge samples should be retrieved using a clean, dynamic effort to obtain a more "undisturbed" sample and higher recovery rates. The most common method is to simply place a Shelby tube on the paper sludge then apply a dynamic effort, say with a sledge hammer, to quickly insert and cut through the fibrous sludge. A block of wood placed on top of the tube during hammering is often used to protect the Shelby tube. Shelby tubes samples were obtained adjacent to the two-stage borehole test locations. These samples were extruded and trimmed for laboratory hydraulic conductivity testing.

Laboratory hydraulic conductivity tests

Laboratory flexible-wall triaxial hydraulic conductivity tests were performed on *in situ* specimens in accordance with ASTM D-5084. The procedures were modified when testing the paper sludge specimens to account for its unique behavior. Large volume changes can be expected due to the compressible nature of the sludge, and gas generation has been encountered in some cases during hydraulic conductivity tests (Benson & Wang 2000). The effective stress applied during testing was 34.5 kPa, a typical landfill cover stress, which was accomplished using a cell pressure of 310.5 kPa and a back pressure of 276 kPa. A gradient of about 21 was applied across the specimen during the permeation phase of the test.

One important aspect of laboratory paper sludge hydraulic conductivity testing is effective stress specification. Since paper sludge is highly compressible, it is sensitive to testing pressures. Thus, as the applied effective stress increases, the hydraulic conductivity decreases. For example, by simply doubling the applied effective stress from 34.5 kPa to 69 kPa, a one order of magnitude decrease in hydraulic conductivity is not unusual for paper sludges. In practice, laboratory hydraulic conductivity tests are conducted at two effective stresses, 34.5 kPa and 69 kPa, for predictive purposes (Moo-Young & Zimmie 1995, Quiroz 2000). The 34.5 kPa test results represent current hydraulic conductivity values or those immediately after construction, while the 69 kPa results are used to provide long-term hydraulic conductivity values (i.e., a decreasing hydraulic conductivity trend) after subsequent consolidation.

Field hydraulic conductivity tests (two-stage borehole tests)

The *in situ* hydraulic conductivity was measured using the two-stage borehole (TSB) test following the procedures outlined in ASTM D-6391. This field test is often used to evaluate compacted clay hydraulic barriers within the United States due to its lower cost and shorter testing times in comparison to other field methods such as the sealed double ring infiltrometer test (SDRI) (Trautwein & Boutwell 1994). Holes about 1.3 m × 1.3 m were excavated down to the paper sludge barrier layer for TSB testing.

The TSB test method uses a sealed, cased borehole and monitors the water level in a standpipe. Using the falling head method, the rate of flow into the soil is measured. The first of the two stages is conducted with the casing flush with the bottom of the borehole. In this phase, the vertical hydraulic conductivity, k_v, is dominant (Fig. 1 a.). Flow into the soil is monitored until it is constant, then the first stage hydraulic conductivity, k_1, is determined. The subsequent second stage involves extending the borehole below the bottom of the casing and monitoring the falling water level (Fig. 1 b.). During this phase, the horizontal hydraulic conductivity, k_v, is dominant. Again, once the inflow is constant, the second stage hydraulic conductivity, k_2, can be determined. Finally, knowing k_1, k_2, and various test parameters, the values of k_v and k_h can be uncoupled.

From a practical standpoint, if the test is performed to determine if k_v is less than some specified value, sometimes only the first stage may be conducted. If the "apparent hydraulic conductivity" (arithmetic time-weighted average hydraulic conductivity) for the first stage is constant and below the specified value, then the test may be terminated (ASTM D-6391).

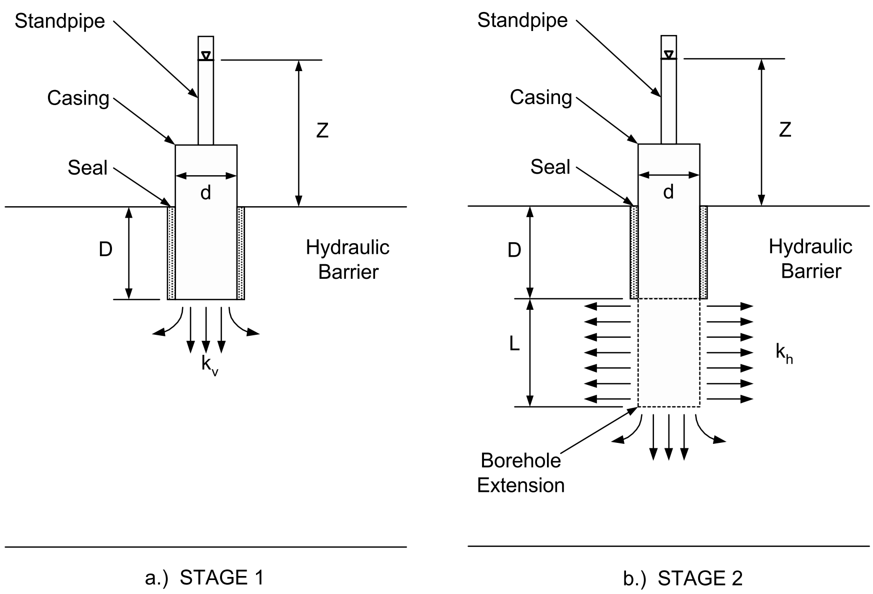

Figure 1. Two-stage borehole test for hydraulic barriers: a.) first stage of infiltration, b.) second stage of infiltration (after Trautwein and Boutwell 1994).

When conducting TSB tests on paper sludge, Benson and Wang (2000) recommended keeping Z less than D. This prevents hydraulic fracturing due to near zero effective stress at the bottom of the borehole, which can cause a rapid head loss in the standpipe, yielding incorrect hydraulic conductivity values. This was generally not a problem for the tests conducted in this study since the barriers had an overburden sand layer about 75 cm to 100 cm, resulting in relatively high effective stresses. The estimated effective stress at the bottom of the casing was about 18.9 kPa and test times lasted about 1 month to acquire constant k_1 and k_2 values.

RESULTS AND DISCUSSION

The results of the laboratory hydraulic conductivity tests conducted on *in situ* samples of the Town of Corinth Landfill cover are presented in Table 1. In general, under an effective stress of 34.5 kPa the hydraulic conductivity values were less than the typical regulatory limit of 1×10^{-9} m/s. The paper sludge proved to be an effective hydraulic barrier material similar to the compacted clay.

Table 1. Laboratory flexible-wall hydraulic conductivity test results for the Town of Corinth Landfill cover.

Sample	Effective Stress (kPa)	k_{lab} (m/s)
clay-1	34.5	2.0×10^{-10}
sludge-1	34.5	5.2×10^{-10}
sludge-2	34.5	7.9×10^{-10}
sludge-3	34.5	5.2×10^{-10}

Table 2 shows the results of the *in situ*, two-stage borehole tests conducted on the clay and paper sludge sections of the Town of Corinth Landfill. The k_v value is the main parameter of interest for landfill covers and liners. For an average effective stress of 18.9 kPa, the paper sludge k_v values (including the "apparent hydraulic conductivity" value for sample sludge-3) were about half an order of magnitude or less greater than 1×10^{-9} m/s; while the compacted clay exhibited a k_v much lower than 1×10^{-9} m/s. Since the paper sludge is a highly compressible material that can experience a large degree of secondary consolidation (Quiroz 2000) it is expected that continued barrier layer settlement will further decrease the vertical hydraulic conductivity to meet regulatory requirements.

Table 2. Two-stage borehole, field hydraulic conductivity test results for the Town of Corinth Landfill cover.

Sample	Effective Stress (kPa)	k_h (m/s)	k_v (m/s)
clay-1	18.9	1.0×10^{-8}	9.1×10^{-11}
sludge-1	18.9	2.3×10^{-9}	2.3×10^{-9}
sludge-2	18.9	1.3×10^{-8}	2.2×10^{-9}
sludge-3[a]	18.9	–	–

[a] Only stage one was completed ("apparent hydraulic conductivity" = 5.2×10^{-9} m/s).

For the paper sludge, the laboratory and field results indicated that field k_v values (including the "apparent hydraulic conductivity" value for sample sludge-3) were about half an order of magnitude to one order of magnitude greater than those measured in the laboratory. This is primarily due to differences in effective stress, 34.5 kPa in the laboratory versus about 18.9 kPa in the field. Since paper sludge is highly compressible, it is sensitive to confining pressures, i.e., as the effective stress increases the hydraulic conductivity decreases due to reductions in void ratio and/or constriction of microscopic flow channels. Therefore, for the paper sludge hydraulic barrier, greater hydraulic conductivity values were measured by the *in situ* two-stage borehole tests. In contrast, for the compacted clay samples, the difference in hydraulic conductivity between laboratory and field values was less than half an order of magnitude, which is not surprising since typical compacted clay barriers are not very compressible. LaPlante & Zimmie (1992) and Othman & Benson (1992) showed less than a half an order of magnitude decrease in hydraulic conductivity for compacted clays subjected to effective stress levels increasing from about 15 kPa to 200 kPa. Testing considerations which also affect hydraulic conductivity results are sample size or test volume affected, soil saturation levels, and quality of soil tested (how many defects present, micropores versus macropores, etc.). An additional hydraulic conductivity testing aspect specific to paper sludge is sample disturbance since it is a low strength and highly compressible material. The *in situ* TSB test for paper sludges may be a more suitable method for evaluating field performance since it minimizes sample disturbance. However, as discussed previously, laboratory tests may provide additional data since you can vary effective stress levels to acquire an indication of sensitivity to confining pressures and potential long-term predictions after subsequent consolidation.

SUMMARY AND CONCLUSIONS

Hydraulic conductivity analyses was performed on the Town of Corinth Landfill cover located in the State of New York. This unique 5.2 ha landfill cover demonstration project had a 4.1 ha paper sludge hydraulic barrier layer section and a 1.1 ha compacted clay barrier layer section. A total of four locations (one on clay and three on paper sludge) were tested via laboratory flexible-wall triaxial hydraulic conductivity tests and *in situ* two-stage borehole tests. The objective of this study was to evaluate the long-term performance of the landfill cover, especially the paper sludge barrier layer section, and compare the differences in laboratory and field hydraulic conductivity values.

The laboratory hydraulic conductivity tests performed using an effective stress of 34.5 kPa showed that the paper sludge and compacted clay samples had hydraulic conductivity values less than the typical regulatory limit, 1×10^{-9} m/s. This is not surprising for compacted clay barriers, however, it does show that paper sludge is a suitable hydraulic barrier material alternative. The *in situ* two stage borehole tests conducted at an average effective stress of about 18.9 kPa showed that the compacted clay k_v value was much less than 1×10^{-9} m/s, however, the paper sludge k_v values were half an order magnitude or less greater than 1×10^{-9} m/s. Also, the differences between laboratory and field hydraulic conductivity values were about half an order of magnitude to one order of magnitude. The differences between the compacted clay and paper sludge k_v values, as well as the laboratory and field hydraulic conductivity values, was a result of the high compressibility of paper sludge. Since paper sludge is very sensitive to effective stress (i.e., as the effective stress increases the hydraulic conductivity decreases) relative to clay, higher hydraulic conductivity values are expected from the tests conducted at lower effective stresses. Nonetheless, it should be noted that for all practical purposes the paper sludge hydraulic barrier is an effective hydraulic barrier. Moreover, due to high water contents and high organic contents, the paper sludge barrier layer is expected to undergo a considerable amount of consolidation which will continue to reduce void ratios and decrease hydraulic conductivity.

It was also noted that sample disturbance can play an important role in sludge hydraulic conductivity values due to its low shear strengths and high organic fiber contents which can impede the retrieval of quality “undisturbed” samples. Typically, a dynamic sampling method is best for sludge to minimize sample disturbance. As an alternative, *insitu* hydraulic conductivity tests such as the two-stage borehole test can give a more accurate estimation of field performance. However, the flexibility of laboratory tests which can be used for predictive purposes by testing under two confining stress levels (see Section 4) is an advantage. Overall, hydraulic conductivity monitoring strategies should be closely examined for paper sludge hydraulic barriers since there are several differences, advantages and disadvantages between laboratory and *in situ* hydraulic conductivity tests.

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FINNISH NATIONAL REPORT ON THE ALT-MAT PROJECT

by
Leena Korkiala-Tanttu and Hans Rathmayer

Korkiala-Tanttu, Leena. & Rathmayer, Hans 2001. Finnish national report on the ALT-MAT project. *Geological Survey of Finland, Special Paper 32, 47–55,* seven figures and 3 tables.

The environmental aspects strongly necessitate more extensive utilisation of the alternative materials. This utilisation needs more information on the mechanical and leaching properties, functional requirements and long-term stability of the materials. The European ALT-MAT project defines methods by which the suitability of alternative materials for use in road construction can be evaluated under appropriate climatic conditions. The Finnish national work in the ALT-MAT project concentrated on the development of the climate chamber test. The purpose of these tests was to simulate the field conditions of road structures (miniembankment) without a pavement. The test consisted of 20 wetting-drying and freezing-thawing cycles. Miniembankments were wetted with salt solution. The leaching of contaminants due to these accelerated climatic cycles and added salt solution was studied. The tested materials were two types of slag: ferrochrome slag and blast furnace slag. The test results showed that the leached amounts of many metals were very low, usually below the limit of detection. These results were verified by other leaching test results. All test data showed that the leaching of contaminants for both types of slag is very moderate. The climate chamber test proved to be a good, but expensive method to test the environmental suitability of alternative materials.

Keywords: construction materials, highways, by-products, slag, pollutants, leaching, experimental studies, Finland

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INTRODUCTION

Every year the Finnish steel industry produces over one million tonnes of by-products, mostly different kinds of slag. This slag has mechanical properties that satisfy ideally the material requirements of road construction layers. In some respects, such as low weight and stress- and deformation resistance, slag is even better than natural aggregates. During the last few decades, a part of the annual production of blast furnace and ferrochrome slag types has been utilised as road construction materials. This utilisation has occurred mainly in the vicinity of steel factories. The growing awareness of environmental aspects and the lack of high quality road materials in some regions have increased the interest in utilising slag more efficiently.

The greatest obstacles to more efficient utilisation of slag lie in the uncertainties of environmental impacts. The environmental impacts of by-products are normally studied with leaching tests. To study varying climatic conditions and their effect on the leaching, we developed a new test method called the climate chamber test. The aim of climate chamber tests is to simulate field conditions of a road construction without a pavement. This method provides opportunities to bridge the gap between small-scale laboratory experiments and full-scale trial embankments. The test is designed to study the release of contaminants (leaching) due to accelerated climatic cycles and salt solutions used for winter maintenance in Finland.

The development of the climate chamber test method is a part of the ALT-MAT project. The main objective of the ALT-MAT project is to define methods to evaluate the suitability of alternative materials in road construction. The methods evaluate the suitability under appropriate climatic conditions. We also compared the results of the climate chamber test with other leaching test results to exhibit leaching under various circumstances.

As test materials we selected ferrochrome slag and blast furnace slag, because their general use as road construction material is always subject to special permission from the Finnish Environmental Institute.

MATERIALS AND METHODS

Test materials

The two materials studied are blast furnace slag (BFS) and ferrochrome slag (FCS). Their chemical composition is displayed in Table 1.

Blast furnace slag is a by-product obtained from the manufacturing of pig iron in a blast furnace. Blast furnace slag is formed by the combination of the rock constituents of the iron ore with a limestone flux. Because the constituents of slag are important for the function of the blast furnace, they must be kept as constant as possible. The quality of slag produced in a particular steelwork is highly consistent and its variability matches that obtained in the exploitation of conventional aggregates (Lee 1974). The production sites of BFS in Finland are the steel factories in Raahe and Koverhar.

The temperature in the blast furnace is over 1 300°C. Lighter slag floats on pig iron. Slag is conducted away from pig iron to the cooling process. There are two possible cooling methods: air- or water-cooling. In the air-cooling method the melt slag is poured out onto a cooling embankment where it cools slowly. Because the cooling is slow, minerals have time to crystallise. In the water-cooling method a high-pressure water jet cools the slag. This rapid solidification produces a granulated glassy material. The internal structure of this glassy slag is more fractured, which means that it is more reactive than air-cooled slag. Nowadays, most of the BFS produced in Finland is water-cooled.

The major components of BFS are silica, sodium and magnesium oxides (together 83 %). The main minerals of BFS are melilite, oldhamite, mervinite and some glass.

In addition to the chemical composition, the glassy structure of BFS affects its binding properties. BFS binds hydraulically, but considerably slower than cement. The addition of cement or mincing of grain size accelerates the binding reaction. The binding reaction happens on the surface of grains. After crushing binding starts up again on a new surface. This crushing in structure is then self-reconstructive in the long-term.

The cooling method affects the mechanical and chemical properties of the slag. The water-cooled

BFS (granulated) is a porous, slowly binding material that looks like sand. The bulk density of BFS is low, 11–13 kN/m^3, which means that it can be used as a lightweight material. The air-cooled BFS is a little heavier and its grains are bigger than water-cooled slag. The hydraulic, deformation and strength properties of both BFS are excellent, and they fulfil ideally the material requirements of unbound road construction material. The thermal properties of BFS are also very good; therefore it is natural that BFS is also used as a thermal insulating material.

Ferrochrome slag is a by-product obtained from the manufacture of refined steel in Tornio. The manufacturing process resembles that of the BFS. Correspondingly, FCS can be cooled with air or with water. The mechanical and chemical properties of FCS are quite similar to BFS. Yet, there are two important differences: the abrasion values of FCS are much better than BFS's and FCS does not have the capability to bind itself.

The major components of FCS are silica, aluminium and magnesium oxides (together 77 %). FCS includes 6.5 % chrome, which exceeds the total recommended concentration of chrome (Table 1).

Table 1. The chemical compositions of ferrochrome slag and blast-furnace slag.

Ferrochrome slag (water cooled) (aqua regalis) (%)	Typical analysis of ferrochrome slag (%)	Blast furnace slag (air cooled) (%)	Blast furnace slag (water cooled) Koverhar (%)	Granite, Teisko (%
CaO 3–8	CaO 2.1	CaO 37	Mg 9.41 XRF	CaO 2.4
SiO_2 27–29	SiO_2 28.6	SiO_2 35	Al 6.14 XRF	SiO_2 69.7
Al_2O_3 23–28	MgO 24.3	MgO 11	Si 15.0 XRF	MgO 0.9
MgO 22–27	Al_2O_3 27.0	Al_2O_3 9	P 0.006 XRF	Al_2O_3 15.4
S 0.1	Ti 0.29	TiO_2 2.5	S 1.79 XRF	K_2O 3.3
Cr 6.5	Mn 0.15	MnO 1.0	K 0.43 XRF	Na_2O 3.8
Fe 4.0	K 0.08	K_2O 1.0	Ca 24.0 XRF	Fe 2.6
	Na 0.02	Na_2O 1.0	Ti 1.12 XRF	Ti 0.2
	S 0.16	S 1.5	V 0.057 XRF	Ba 0.074
	Fe 4.5	FeO 0.5	Mn 0.12 XRF	Mn 0.062
	P <0.0005	P 0.003	Fe 0.63 XRF	P 0.042
	Ba 0.01	Ba 0.038	Cr 0.004 XRF	S 0.029
	C 0.12	Ce 0.012	Ni 0.001 XRF	Sr 0.018
	Cr 7.7	Cr 0.003	Sr 0.047 XRF	Zr 0.016
	Cu 0.01	La 0.006	Zr 0.015 XRF	Cr 0.013
	Co 0.03	Sr 0.042	Nb 0.001 XRF	Zn 0.008
	V 0.020	V 0.030	Mo 0.000 XRF	V 0.004
	Zn 0.010	Zr 0.017	Sn 0.001 XRF	Cu 0.003
	Sn <0.0010	Sn 0.002	Ba 0.056 XRF	Ni 0.002
	Li <0.01	Nb 0.001	La 0.006 XRF	
	Ni 0.03	Ni 0.001	Ce 0.009 XRF	
	Mo <0.01	B 0.004 2	Ca_{ASTM} 39.7	
	Sb <0.001	Cu 0.000 8	Ca_{pH5} 6.9	
	As <0.001	As 0.000 67	Fe_{met} 0.3	
	Bi <0.001	Zn 0.000 2	F 0.1	
	Pb < 0.001	Pb < 0.000 05	Zn 0.000 4	
	Cd < 0.001	Cd < 0.000 005	As 0.000 5	
	Hg < 0.000 002	Hg < 0.000 002	Cd <0.000 005	
			Pb <0.000 01	
			Hg <0.000 005	
			B 0.0487	
			Cu 0.000 08	

Test methodology

The climate chamber test boxes were constructed to bear stresses from compacting, moving and freezing during the test. The width and length of a box were 700 mm each and its height was 300 mm. The body of a box was made of plywood and its inside was covered with a plastic membrane of HPDE. A filter cloth was placed between the specimen and the plastic membrane. In the bottom of the box there was a lead-through for draining and leachate collection. The boxes were placed on movable carriages. Fig. 1 illustrates the construction of the miniembankment.

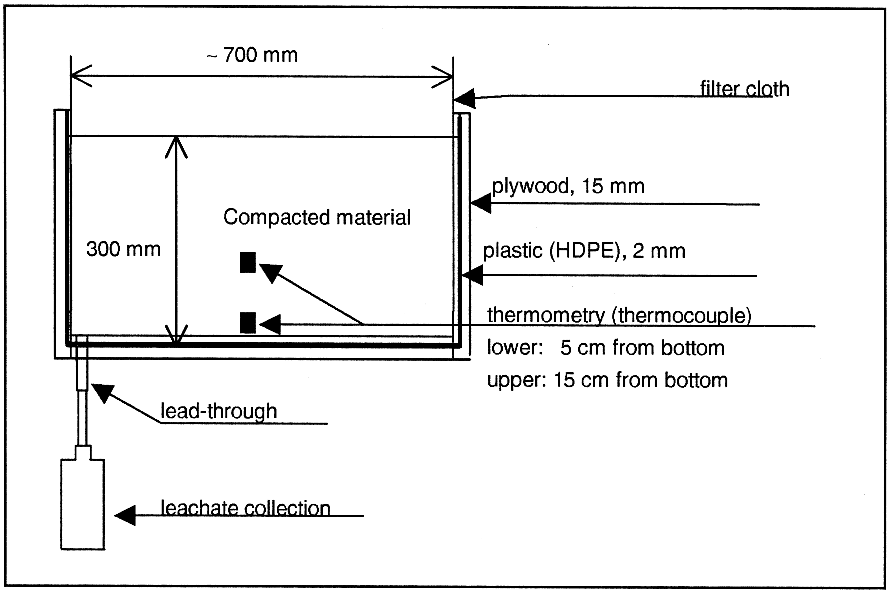

Figure 1. The construction of the miniembankment.

SKJ Company Ltd provided us with both types of slag. The tested materials were: air-cooled ferrochrome slag and water-cooled blast-furnace slag.

The test material was compacted into the box to a density of 95 % of the maximum density value of the Proctor compaction test. We had two concurrent specimens of both materials. In total we had four specimens. The technical data of these specimens are shown in Table 2.

Table 2. The technical data of specimens.

Data	Ferrochrome slag		Blast furnace slag		Remarks
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	
Volume (cm^3)	152.70	150.37	152.80	159.31	
Dry density (g/cm^3)	1.83	1.83	1.37	1.37	95% of Proctor density
Weight (kg)	294.72	290.21	209.34	214.15	

The climate chamber test (CCT) consisted of three main phases: wetting-drying cycles, freezing-thawing cycles and leachate collection. The liquid, which is in contact with solid, is referred to here as leachant and the liquid leaving the solid is referred to as leachate. The flow chart diagram of the whole CCT leaching test is illustrated in Fig. 2.

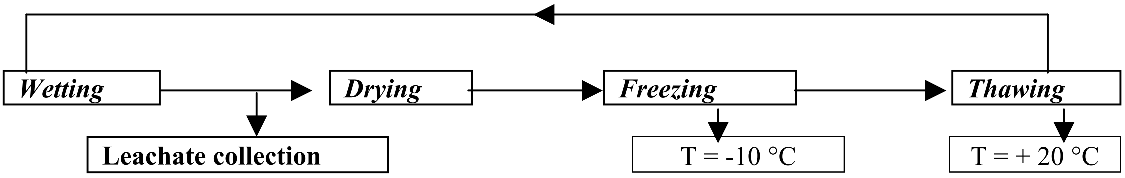

Figure 2. The flow chart diagram of the CCT test.

First, the specimens were wetted with a salt solution (leachant) composed of 10 % salt used by Finnish National Road Administration and 90% normal tap water. The typical chemical composition of salt is shown in Table 3. The total quantity of salt solution was about 25 kg in each wetting cycle. The wetting happened at a normal room temperature of +20°C. During the wetting, leachate was collected from the specimens into glass bottles. Leachate samples were analysed in the laboratory of VTT Chemical Technology. Leachate was collected:

- before first freezing
- after 2 freezing-thawing cycles
- after 10 freezing-thawing cycles
- after 20 freezing-thawing cycles

After the wetting and leachate collection, the specimens were dried for 1 day. Then, the lead-through was closed and carriages were moved to a cold room, whose temperature was –10°C. The temperature of the specimens during the freezing was monitored from two thermometers. When the whole specimen was frozen to –10°C, the specimens were taken to the thawing room (+20°C). In total, the specimens were treated with 20 freezing – thawing cycles.

In the beginning freezing – thawing cycles took at least 8 days each, thus to run all 20 cycles would have taken about five months. Since that was too long a period, the temperature of freezing room (-10°C) was be lowered to -30°C and the temperature of the thawing room raised to +40°C. With these test arrangements, one test cycle time could be lowered to 5 days. In spite of these accelerations, the climate chamber test is a very time-consuming test. In ideal conditions one whole test takes at least 3 months.

Table 3. The chemical composition of salt.

Component	Percentage (%)
NaCl	98.82
Ca	0.27
Mg	0.02
K	0.09
SO_4	0.80

RESULTS

Mechanical behaviour

We visually followed the behaviour of specimen during the test. The surface of the specimens cracked and heaved during freezing. These cracks and frost heave were due to the volume increase of the freezing water. After thawing some compaction occurred, but the structure did not get back to the original compaction ratio. The grain size distributions of specimens were tested before the first freezing and after the whole test (Fig. 3) to see whether any weathering had occurred during the test.

Chemical behaviour

We had two concurrent specimens of both slag types. The leachates were collected four times, so the total amount of analysed leachates was 16. We discussed with the chemists and chose together the most interesting elements from the environmental point of view to be analysed. The analysed elements were: Ca, Na, K, Al, As, Cd, Cr, Cu, Mo, Ni, Pb, Zn, Fe, Mg, Mn, sulphate and vanadium from blast furnace slag. The values of pH, conductivity and redox-potential were also measured. The concentrations of Ca, Na, K, Al, Cr, Cd, Mo, Zn, Fe, Mg, Mn and V were analysed using the atomic spectrometric technique (ICP-AES). The concentrations of Cu, Ni, Pb and As were determined using the GRAAS-technique and the concentration of sulphate was determined using the chromatograph – technique (FINAS T44/A1/95). The concentrations of many analysed elements were under the limit of detection. The accuracy of results varied from ± 10 % to ± 30% depending on the analysis technique.

DISCUSSION

Mechanical properties

The grain size distributions of the slag before and after the test cycles differ only a little. The largest grains are crushed a bit during the test (Fig. 3). The visual observations during the test cycles exhibit some loosening and frost heave.

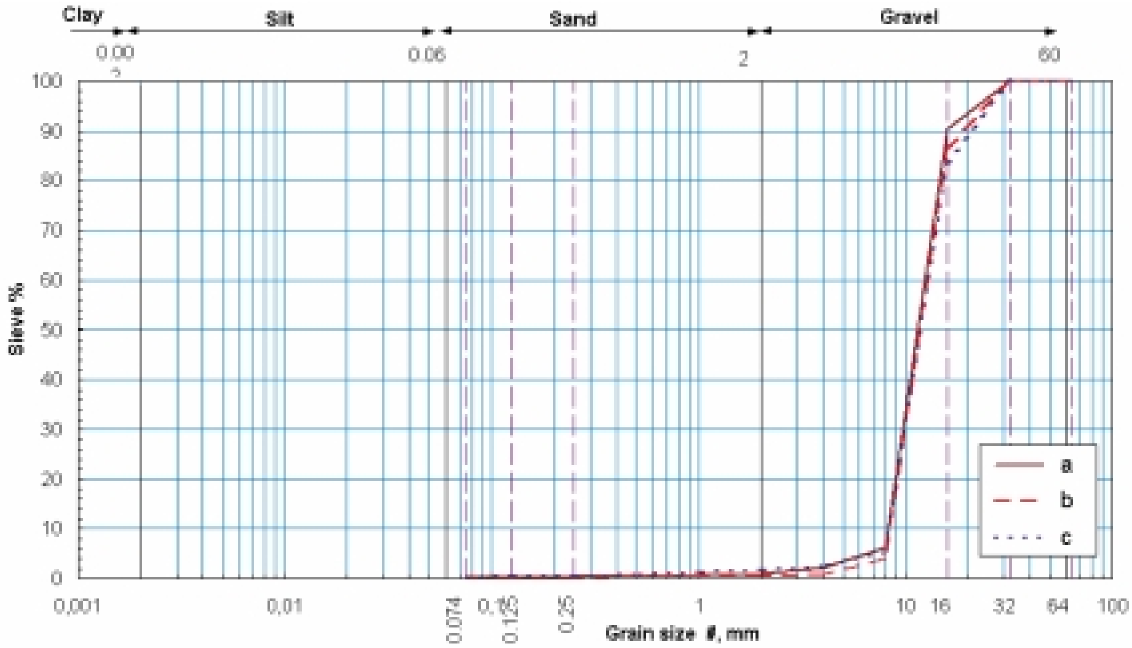

Figure 3. The grain size distribution of air-cooled ferrochrome slag (a = before test sample 1, b = before test sample 2 and c = after climate chamber test).

Leaching of blast furnace slag

The leaching of blast-furnace slag is very moderate in climate chamber tests. The test results indicate that freezing–thawing cycles and the use of salt solution do not accelerate the leaching process of any analysed element. Vanadium and sulphate, which are possibly the most harmful elements of blast furnace slag, stay in indissoluble form. Even though their total constituents are quite big, they leach very moderately in the climate chamber tests. We verified CCT test results with many other leaching tests successfully (Figs. 4 and 5). All test results confirm the impression that the leaching of blast furnace slag fulfils environmental requirements.

We changed all leaching test results to L/S-ratios, where L refers to liquid (the amount of used leachate flowing through a solid) and S to solid (the amount of alternative material). The use of L/S-ratio makes it easier to estimate leaching in relation to time, because the amount of liquid flowing through the solid increases with time. In many tests more than one L/S-ratio was analysed, so we summed up all these concentrations to get the cumulative concentration (mg/kg).

Most of the verification tests were different kinds of parametric tests, but we also included some simulation tests like the climate chamber, lysimeter, column and permeameter tests. In a parametrical test only one parameter, for example some leachant, is tested in ultimate conditions. Simulation tests, on the other hand, try to simulate the whole leaching process. That is why parametrical tests tend to overestimate real leaching. Leaching usually decreases with time, because the easily dissolvable elements leach out first. Thus, many illustrated test results, including climate chamber tests, exhibit a lower slope, when L/S-ratio is greater than 1 (Figs. 4 and 5).

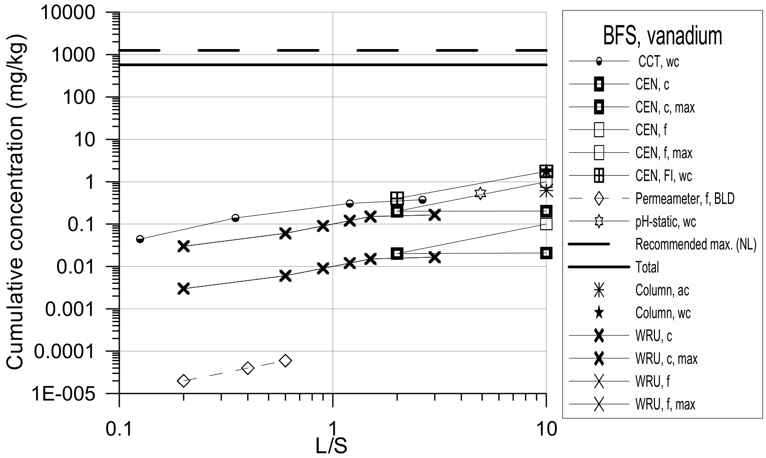

Figure 4. BFS. The leaching of vanadium.

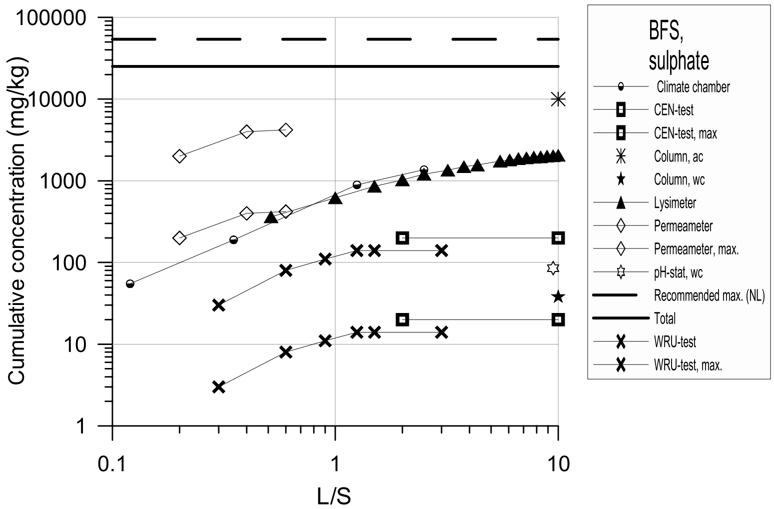

Figure 5. BFS. The leaching of sulphate.

The cooling method affects some leaching properties, especially the leaching of sulphate (Fig. 5). The leaching of sulphate from air-cooled (ac) slag in a column test is more than hundred times larger than leaching from the water-cooled (wc) slag (ac: about 10 000 mg/kg; wc: about 30 mg/kg). When slag is cooled with a high-pressure water jet, it is probable that sulphate components leach out with the cooling water. The leaching of sulphate in climate chamber tests increases up to 1000 mg/kg, even though the slag is water-cooled. This is because the salt solution contained sulphate and a great part of leached sulphate originates in salt solution.

Leaching of ferrochrome slag

The most interesting elements of ferrochrome slag from the environmental aspect are chrome and aluminium. The total constituent of chrome is 6.5 %, which is many times larger than the total concentration recommended by Dutch authorities. Because Finland does not yet have its own environmental recommendations, the Finns usually comply with Dutch recommendations. The chrome of FCS is mainly Cr^{3+} or Cr^{2+}, which are both difficult to dissolve. Hence, it is not surprising that no great leaching was detected from the climate chamber test (Fig. 6). Even though the recommended total constituent of chrome is exceeded, the leaching is very moderate and fulfils Dutch recommendations for a covered material. The other elements also leach moderately and fulfil Dutch recommendations. The most essential method of mitigating the environmental impacts of alternative materials is to decrease the amount of infiltrated water. Covering and bounding are common, effective and economical mitigation methods.

Wahlström & Laine-Ylijoki (1996, 1997) have studied widely the leaching of FCS in laboratory tests. Fig. 7 shows their test results of different kinds of leachants as a function of pH. The climate chamber test data agree with their test data. Ferrochrome slag's natural pH is over 10, but acidic rain water decreases its pH gradually. Yet, according to these test results, the leaching increases significantly only after the pH is less than 6. Wahlström & Laine-Ylijoki (*op. cit.*) have estimated that the time needed to neutralise a 0.3 m thick layer of ferrochrome slag from pH 10 to pH 7 takes 270 years. The pH in the climate chamber test is about 7.5.

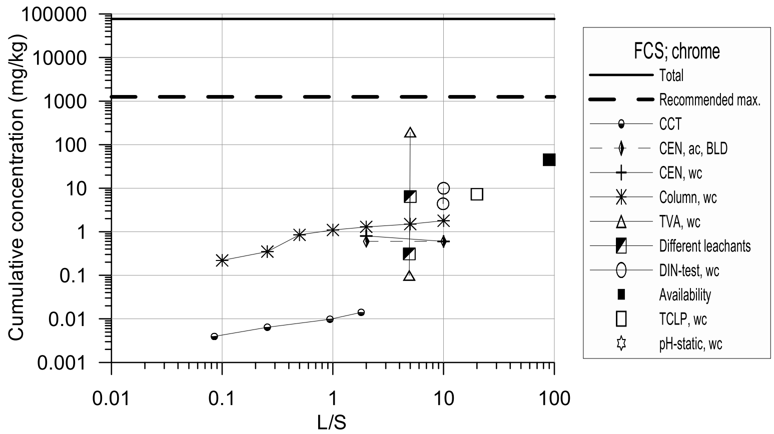

Figure 6. FCS. The leaching of chrome.

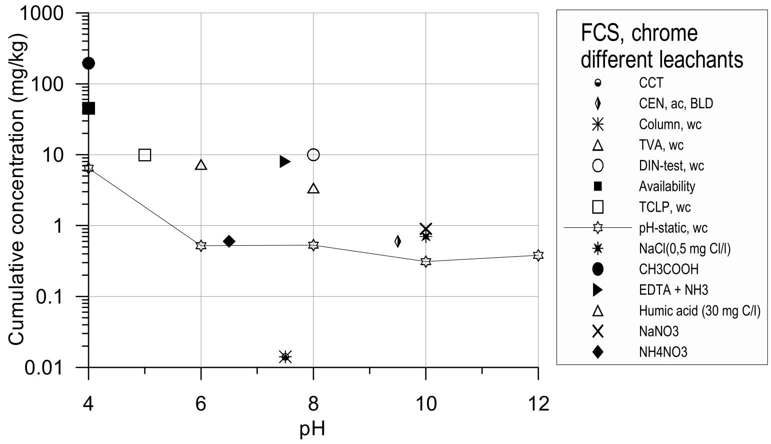

Figure 7. FCS. The leaching of chrome as a function of pH.

Future developments, limitations and errors

The climate chamber test is an expensive and time-consuming test. To make the test more efficient, more than two specimens should be handled at the same time.

The climate chamber test method has some limitations with leachate analysis. The first limitation is with the leachant. The use of salt solution as a leachant increases the leaching of sodium, potassium, calcium, magnesium and sulphate. The real leaching and its changes are difficult to distinguish from the initial constituency of these elements in salt solution. Because the parametrical and climate chamber tests have shown that salt solution does increase leaching, the use of fresh water instead of salt solution as the leachant would give a clearer picture of the leaching process. The second limitation is the analysis technique. The real scatter of test results is quite small. Yet the accuracy of analysis changed from ± 10 % to ± 30 %, which is quite big. The limit of detection with some elements is low, which hides the real leaching behaviour of that element. With more expensive analysis methods, the inaccuracy could be decreased and the limit of detection could be increased.

The simulated road construction is very simple: it has only one construction layer. This simplification causes some errors in test results. In a real road construction the flowing paths of water through the many construction layers are more complicated because of the covering asphalt layer. A new uncracked asphalt layer is practically impermeable. The ingress of water to a road construction occurs via the slopes, capillary rise from groundwater and through the cracks of an older asphalt layer. Thus, in the real road construction water infiltrates mainly horizontally, but in CCT water infiltrates vertically. The total quantity of water flowing through a road construction is also difficult to assess. In short, the flowing conditions in the climate chamber test are simplistic and they do not give the whole picture of the flowing in the sense of leaching.

CONCLUSIONS

The climate chamber test is a new, very promising test method to simulate the leaching of alternative materials. Even though it is expensive, it is the only test method which simulates the varying climatic conditions. The test includes twenty accelerated drying-wetting and freezing-thawing cycles. The tested materials were ferrochrome slag and blast-furnace slag. These climatic cycles did not increase the leaching of any element studied when we verified them with other leaching test results. Furthermore, the use of salt solution does not affect the leaching of the elements studied. On the contrary, the leaching in the climate chamber test, as in many other simulation tests, is clearly less than in small-scale parametrical tests.

The solubility of harmful elements of FCS is so small that the use of FCS is acceptable in every part of a road construction in which slag is covered or bound. In spite of the high total amount of chrome, the leaching of chrome is moderate. The leaching of harmful elements of BFS is also very moderate and fulfils today's environmental requirements where slag is covered or bound.

The flowing conditions in the climate chamber test differ from real road construction, where water ingress happens via slopes, though the cracks of asphalt layer and capillary rise from groundwater. The greatest part of water infiltrates the road construction horizontally. In the climate chamber test the water infiltrates through the specimen vertically from top to bottom.

Besides the error in flowing conditions, there are some limitations to the CCT method. First, the leached amounts of many metals are very low – in many cases below the limit of detection. The limit of detection and accuracy of results depend on the analysis technique, which could be increased with more expensive analysis techniques. Second, the use of salt solution as a leachant increases the leaching of sodium, potassium, calcium, magnesium and sulphate. It is difficult to distinguish the real increase in leaching from the initial constituency of these elements in a salt solution. Therefore, we recommend the use of pure water as a leachant in the future. Another future development could be the measurement of frost heave or some other mechanical property.

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RISK ASSESSMENT OF INDUSTRIAL BY-PRODUCTS USED IN EARTH CONSTRUCTIONS

by
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Wahlström, Margareta, Eskola, Paula, Laine-Ylijoki, Jutta, Leino-Forsman, Hilkka, Mäkelä, Esa, Olin, Markus & Juvankoski, Markku 2001. Risk assessment of industrial by-products used in earth constructions. *Geological Survey of Finland, Special Paper 32, 57–63*, one figure.and 2 tables.

Industrial by-products can be used in earth constructions provided their environmental properties are acceptable; for example, not exceeding defined acceptance values. Risk assessment is needed in cases where the disposal conditions significantly differ from the conditions considered when the acceptance values were set for by-products suitable in earth constructions; for example, in the case of sensitive disposal environments or in cases where the construction consists of several different by-products. It might also be possible through risk assessment to accept higher emission values in cases where more information is available about the properties of the harmful compounds.

A procedure for the risk assessment of industrial by-products to be utilised in earth construction is proposed. The procedure is designed to be as simple as possible to use, yet cover the most important aspects and environmental risks in the assessment. Additionally, the special characteristics of construction and the use of earth constructions were also considered. The risks were primarily related to human health because the background data needed for an ecotoxicological risk assessment is still under development.

The proposed risk assessment concept has also been tested in a case study on the use of coal fly ash in earth construction.

Keywords: construction materials, risk assessment, by-products, ash, earthworks, construction

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INTRODUCTION

Industrial by-products may possess detrimental environmental properties, the impacts of which need to be considered before the products are used in earth constructions. Some examples of the most relevant properties to be considered for by-products are the following:

- Direct toxicity of by-product for humans, plants, and animals
- Leaching properties with special attention paid to all relevant conditions at the disposal site (as a consequence of the transport of toxic metals into the environment)
- Formation of toxic gas emissions, e.g. due to degradation, reactivity
- Dust problems
- Risk for ignition (fire)

Risk characterisation means that all the unfavourable properties or conditions are listed and described, and if possible quantified, for example as doses or emissions. The risk assessment also covers assessment of the impacts of undesired phenomena. The results of the risk assessment can be used to choose an appropriate way of utilisation where the undesired phenomena are minimised or can be totally eliminated by suitable measures.

Guidelines for the risk assessment of contaminated sites have been developed. These guidelines are often very broad and general, covering all kinds of exposure pathways to humans and the environment. In particular, the future use of the site is considered in the risk assessment.

The guidelines for the risk assessment of contaminated sites have been the basis for this work. It is not necessary to take into account many of the exposure pathways when industrial by-products are used in earth construction. The following exposure pathways, however, are considered relevant with regard to the use of by-products for such purposes:

Human exposure:
- inhalation of dust
- inhalation of volatile compounds
- dermal contact
- intake of by-products and water that has been in contact with the by-product

Environmental risks:
- influence on plants and animal species near the deposit
- influence on ground and surface water quality

The direct risks to humans are mostly related to the transportation and handling of the by-product. Examples of typical risks are the inhalation of dust, dermal contact, and with respect to children also ingestion of by-products. Risks to the environment may be caused by contamination of the ground and surface water as well as the soil near the site. The risks are significantly dependent on the sensitivity of the surroundings, the geological conditions at the site and the use of the site. For examples in an urban area, where drinking water or irrigation water is not taken from wells, the effects on humans from the intake of water or food can be regarded as insignificant. Examples of exposure routes in the utilisation of by-products in earth constructions are given in Table 1.

The study is part of a larger research entity aimed at developing a guide for the assessment of the environmental and technical suitability of by-products in the permission and product qualification process.

DESCRIPTION OF MODEL

Scope and field of application

The procedure is designed to be as simple as possible to use, yet cover the most important aspects and environmental risks in the assessment. The procedure is simplified and gives an overview of the general risk factors involved in using the by-product. The model includes several assumptions and it may not be applicable in all cases. Therefore, special attention needs to be paid to the differences between the conditions of real cases and of the model presented.

The model procedure is mainly based on the properties of the by-product. In particular, the risk factors involved in the handling and the typical use of the by-product are emphasised. The material

Table 1. Examples of work stages in the utilisation of by-products in earth construction and possible exposure pathways related to these.

Work stage	Exposure pathway (condition)	Target group for exposure and likelihood for occurrence
Transportation of by-product	Dust can be spread to the environment if the by-products are transported in open vehicles and if the moistening of the powdered by-product has not been sufficient.	Dust emission may cause exposure to the lungs. Furthermore, dermal irritation and ingestion via the mouth are possible. Detrimental compounds in the dust particles may leach out to the soil. The risks are dependent on the amount of dust and the place. The risks are casual and local.
Temporary storage (heap)	In the case of a powder-like by-product, which is stored in a heap without a covering, dust emissions to the environment are likely to occur. Detrimental compounds may leach out from the heap if the by-product is not covered with a water impermeable by-product.	Dust emission may cause exposure to the lungs. Furthermore, dermal contacts and ingestion via the mouth (small children) are possible. Detrimental compounds in the dust particles may leach out to the soil. The risks are dependent on the amount of dust and the place. The risks are casual and local.
Earth construction	During the construction work dust emission may occur, especially in the case of powder-like by-products. Also leaching from the construction needs to be evaluated if the construction is not covered with asphalt or other by-products for a long time.	Workers may be exposed to dust inhalation and dermal contact. If the construction is situated in a residential area, the inhabitants of the area may also be affected by dust and ingestion. The risks are usually occasional.
Use of road	In the case of a non-covered by-product, rainwater percolates into the construction layer. In the case of an asphalt construction, the water might find its way through cracks. In both cases detrimental compounds may also leach out to the environment.	Humans and animals may use the surface or ground water as drinking water near the construction. The background levels in soil and water increase. The increase in the soil near the deposit may have effects on the plant and animal species.
Maintenance and remedial actions at the road/construction	For the maintenance and the remedial actions of the construction, the asphalt layer is often removed and the earth layers are dug up. These activities may lead to dust emission, and the leaching of detrimental compounds to the environment is enhanced.	Humans and animals use the water as drinking water. The background level in soil and water is increased. Workers are also exposed to possible dust emission.
Time after the road/ construction has been used	The road constructions are usually not removed even if the road is taken out of use. In some cases the road is broadened or reconstructed in such a way that the old road is left beneath the new. Only seldom, is the road construction demolished and the by-products removed. This means that the leaching of detrimental components continues.	Humans and animals use the water as drinking water. The background level in soil and water is increased.
Accidents	Accidents need to be considered, especially for transportation. The by-product may be spread into the surroundings causing dust emissions and leaching of detrimental compounds.	People passing near the accident site are exposed to dust. Also skin contacts or ingestion is possible. The risk is usually very local.

properties are also important for the site-specific risk assessment where the site conditions (e.g. geology and hydrogeology) are considered. The sensitivity of the environment and the future use of the site are especially evaluated in an extensive risk assessment.

It is not possible to give general recommendations on how specific environmental conditions should be included in a site-specific risk assessment, and therefore a case-by-case approach is recommended. Only lists of general aspects to be considered can be given.

The procedure is developed for inorganic by-products mainly containing inorganic contaminants; that is metals and salts that influence the behaviour of the metals. The environmental assessment of organic pollutants needs to be studied separately taking into account their special properties (degradation, colloid formation).

Procedure

The risk assessment of the by-product includes the following parts:

1. Description of material properties (origin, processes, raw materials, variations in quality).

2. Identification of detrimental properties during the whole life cycle of the by-product including the most important handling steps.
3. Evaluation of the mobility of contaminants at the site, including the storage of the by-product when necessary.
4. Evaluation of the transportation of contaminants into the environment (surface and groundwater, soil).
5. Calculation of exposure (doses) for critical target groups.
6. Evaluation of the results of the risk assessment based on the material properties including presentation of the acceptable risk level used.
7. Uncertainty analysis.
8. Site-specific risk assessment (when necessary).
9. Conclusions and recommendations.

Identification of properties detrimental to humans and environment

The first step is to collect all the relevant background information of the material (usually through the material's origin and chemical analysis) in order to be able to identify the detrimental properties. The content of harmful components is usually compared to the trigger and limit values given for the soils in the assessment of soil contamination. If the concentration of the harmful component is below the trigger value for clean soil, no further assessment is usually needed. On the other hand, if the concentration of some harmful component significantly exceeds the limit values for contaminated soils or exceeds the maximum leaching values, a risk assessment is needed.

Transportation of detrimental compounds to the environment

Usually the leaching of detrimental compounds needs to be considered in the risk assessment. This means that the mobility of the compounds from the by-product layer and also the factors controlling the leaching need to be assessed usually through a full characterisation of the leaching behaviour. Suitable test methods for the assessment are now under preparation in the standardisation organisation of CEN (CEN TC 292). The leaching is either governed by percolation of rainwater (in the case of a non-isolated construction), or through diffusion (in the case of an isolated construction). The leaching rate as a function of time can be modelled by mathematical equations. The proposed time-scale to consider in the model is 50 years, which is the lifetime of a road. During this period, the leached amount during some time intervals of 1, 3, 10 and 50 year is calculated. The magnitude of the water flow in a non-isolated construction is an important parameter and it can be estimated to vary between 70 and 300 mm/year.

The transportation of contaminants in the water to the surroundings of the site from the earth construction containing the by-product can be modelled in many ways. The simplest way is to calculate with dilution factors. Dilution factors of between 1 and 4000 have been suggested in the model.

Estimation of exposure

The most relevant exposure pathway for many powder-like by-products is via inhalation of dust. Unfortunately, suitable models were not found. For this reason, field measurements of dust emissions during different working stages are helpful.

The exposure pathways (e.g. dermal contact, leaching) are evaluated for human, plant, and animal species during the handling of the by-product, and the construction and maintenance of the earth construction (see Table 1). The doses to humans from other exposure pathways are calculated using simple mathematical models developed for the risk assessment of the contaminated site. Several models are available with different kinds of assumptions for the exposure. Usually, intake through e.g. drinking water, and in the case of playing children, direct inhalation of the by-products is estimated. The calculated intake values can be compared to tolerable daily intakes (TDI). In the assessment, the background exposure also needs to be considered, and in some cases other sources may be significant.

The direct contact (intake by animals or uptake by plants) of the by-product can be ignored because the earth constructions are usually covered and compacted. The environmental risk is due to harmful compounds in the leachates from the construction.

Evaluation of risks

The significance of the emissions from the considered scenario is estimated through comparisons to guideline values that indicate minimal risks for human beings and indicator organisms The assessment of ecotoxicological risks can only be made roughly, because only limited suitable reference values for no-observed effect concentrations (NOECs) are available. Moreover, the values are usually derived for certain laboratory conditions and certain chemical compounds. The applicability of these values may be poor, and therefore they should be used with caution. The ecological effects on plant and animal species are evaluated by comparing the calculated values with the toxicological values reported in literature.

The environmental risks can also be evaluated by comparing the calculated values in the leachate to the background concentrations or ecotoxicological target values, when available. This gives information on the need for dilution to reach the background concentrations in the environment.

In the risk assessment, the exposure of several different pathways (e.g. human exposure to dust and one or several heavy metals) should also be considered. However, today no guidelines are available for assessing the synergetic effect of several exposure pathways.

Uncertainty analysis

An important part of the risk assessment is to evaluate the impact of critical parameters on the results. Variations in input data and checking the influence of critical assumptions give important information on the sensitivity of the results.

Examples of typical parameters to be checked are:

- thickness of material
- chemical composition and leaching behaviour
- assumptions in the calculation of water flow (rate, percolation, surface wash)
- dilution factor for leachate from the earth construction.

Sit- specific risk assessment

Site conditions are taken into account in a more extensive risk assessment. The geology and hydrogeologial conditions of the site are especially considered. The risk assessment may include leachate handling, permeability of surrounding material and climatic and biological conditions. The background levels of detrimental compounds can also be considered in certain cases (e.g. in urban areas). The future use and the sensitivity of the site are important in the risk assessment.

Conclusions and documentation

The results of the material-specific risk assessment give information about which risks are most relevant. This information can be used to classify by-products into different classes (no risks – some risks in the earth utilisation). The risk assessment gives valuable information on the appropriate ways of utilisation in which all risks can be minimised. In the site-specific risk assessment, which is more extensive, especially the sensitivity of the site (hydrogeology, geology) and its future use are considered.

It is important that all the steps and assumptions in the risk assessment are well documented and transparent. The conclusions and the chosen acceptance criteria need to be carefully explained. Usually the risk assessment involves a broad expert group.

A CASE STUDY

The developed model has been tested for coal fly ash in earth construction. Two construction-types consisting of a one-metre material layer were studied: a construction isolated by asphalt and a construction covered by soil.

For the most relevant properties to be considered, dust was chosen as well as the following contaminants: chloride, sulphate, chrome, molybdenum and vanadium. The potential exposure routes and target groups for exposure were evaluated for typical handling procedures during the whole lifecycle of the by-product. Also the consequences of possible accidents were checked.

In the risk assessment it was concluded that dust emission might cause problems especially for workers if the fly ash is not moistened and handled according to the instructions given by the power plant. The most relevant risk factor was the mobility of contaminants into rainwater and transportation of the contaminant with water to the environment.

The assumptions of some parameters in the scenarios are presented in Table 2. An example of the estimated concentrations in the leachate before dilution, which presents the most critical scenario, is illustrated in Fig. 1. The predicted values have been compared to the Finnish background values, guideline values or reference values reported in the literature. In particular, no-observed effect concentrations (NOECs) for water organisms were used when possible. Only a few ecotoxicological values have been presented in the literature. Most values are set for the protection of human health.

The conclusions of the case study were the following:

- For the isolated construction: The concentrations of contaminants in the leachate from the construction were generally near the background concentrations of the Finnish environment or near the guideline values for human health. Because the leachate amounts were small, it could be concluded that the environmental impacts on surface and groundwater can be regarded as insignificant. This means, of course, that the isolation layer is without cracks during the lifetime of the construction.
- For the covered but non-isolated construction: The concentrations of contaminants may cause some kind of risk to the environment. The contaminant concentrations in the leachate were momentarily high and clearly exceeded the guideline values, e.g. the drinking-water values given for the protection of human health. A site-specific risk assessment is needed for the evaluation of impacts. Exclusion of the non-isolated construction in sensitive areas is recommended.

Table 2. Examples of input data in the scenarios considered in the case study.

	Non-isolated construction	Isolated construction
Properties of by-product		
Density	2000 kg/m³	2000 kg/m³
Porosity of the by-product	0,45	0,45
Content of some elements		
– Cr	120 mg/kg	120 mg/kg
– Mo	6,4 mg/kg	6,4 mg/kg
– V	200 mg/kg	200 mg/kg
Road dimensions:		
Width	10 m	10 m
By-product thickness layer	1 m	1 m
Leaching mechanism	Percolation of rainwater (300 mm/a)	Diffusion (D_e 2 10^{-9}m/s)
Leaching characteristics:	Results from column test at L/S 10	Pore water concentrations:
– Cr	11.6 mg/kg	150 mg/l
– Mo	3.3 mg/kg	15 mg/l
– V	4.9 mg/kg	49 mg/l

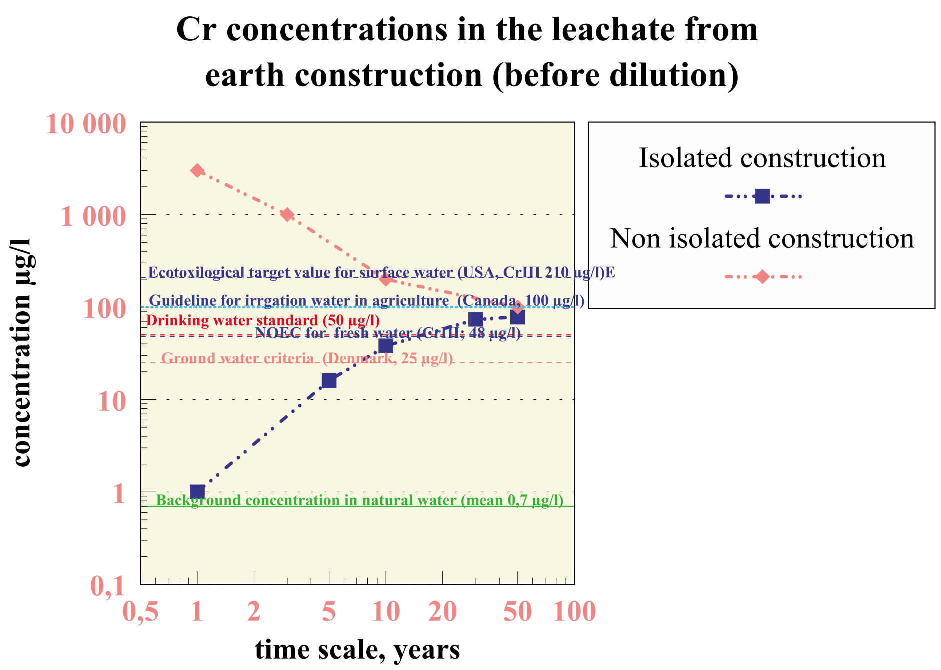

Figure 1. Estimated Cr concentrations in the leachate from two earth constructions during the lifetime of the road. The values can be compared to the following reference values: drinking water standard 50 *m*g/l, ecotoxicological target value for surface water 210 *m*g/l (USA), Canadian guideline for irrigation water in agriculture 100 *m*g/l, Danish ground water criteria 50 *m*g/l and Finnish background concentration in natural water 0,7 *m*g/l (mean).

CONCLUSIONS

The aim of the risk characterisation and assessment is to find an environmentally safe way to use by-products in earth constructions. The risk assessment is needed for by-products possessing properties that fall outside the general guidelines for by-products in earth constructions.

Documentation of the input data and assumptions is important for the evaluation of the results, especially if supplementary information should later become available, e.g. from field studies. The report of the work should be as transparent as possible.

The conclusions should at least contain the following information:

- Which risk factors, exposure routes, target groups have been considered
- Time frame of the evaluation
- Which risk level is assumed to be acceptable (motivations)
- Which environmental conditions (e.g. dilution of leachate) are included in the study
- Limitations of the study
- Assessment of the reliability of the input data and reference values (suitability for comparison)
- Expertise record of the experts.

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Edited by Reijo Salminen.
Geological Survey of Finland, Special Paper 32, 65–74, 2001.

TESTING OF LONG-TERM GEOTECHNICAL PARAMETERS OF BY-PRODUCTS IN THE LABORATORY

by
M. A. Juvankoski, R. J. Laaksonen and M. J. Tammirinne

Juvankoski, M. A., Laaksonen, R. J. & Tammirinne, M. J. 2001. Testing of long-term geotechnical parameters of by-products in the laboratory. *Geological Survey of Finland, Special Paper 32, 65–74*, seven figures and 2 tables.

The properties of four by-products were determined in this research project. These by-products were cement stabilised fly ash, blast-furnace slag sand, a mixture of fly ash and de-sulphuration product and cement stabilised wood or peat ash. The properties considered critical in relation to long-term stability were determined in the laboratory. The results obtained were compared to the requirements set for by-products used in road construction. One of these tested materials has also been used in a test section built before these tests were started.

All the materials tested here are in principle capable of producing adequate compressive strength and stiffness to be used in road construction. In practice some problems may arise particularly concerning the choice of parameters for design due to poor environmental durability. In other words, stabilised or self-strengthening materials do not necessarily last intact after repeated freeze-thaw cycles. Although the stiffness of stabilised material decreases significantly due to structural failure, it may still possess reasonably large stiffness to be of use in the sub-base of a road structure.

Keywords: construction materials, by-products, ash, slag, engineering properties, durability, laboratory studies, road tests, Finland

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INTRODUCTION

The properties of four by-products were determined in this research project. These by-products were cement stabilised fly ash, blast-furnace slag sand, a mixture of fly ash and desulphuration product and cement stabilised wood or peat ash. The properties considered critical in relation to long-term stability were determined in the laboratory. The results obtained were compared against the requirements set on by-products used in road construction. One of these tested materials has also been used in a test section built before these tests were started. This research project has been one project in the Tekes Ecogeotechnology Research &Development program.

TEST MATERIALS

The tested materials were cement stabilised fly ash from Fortum's Meri-Pori power plant, SKJ's blast-furnace slag sand, a mixture of fly ash and desulphuration product from Helsinki Energy and cement stabilised wood or peat ash from UPM-Kymmene's Kaipola factory. Blast-furnace slag sand was different from the other materials studied in that it was granular unbound material. The properties and behaviour of slag sand are well known and it has been used as a reference material for the test methods in this study. The test results obtained with slag sand are not presented in this article. Cement stabilised fly ash from Fortum's Meri-Pori Power plant has been used in a test road section in the Pori area built under the test construction program of the Ecogeotechnology R&D program.

A typical gradation curve of fly ash of Fortum's Meri-Pori Power plant is presented in Fig. 1. This fly ash was used in the sub-base layer of the Pori test road. Also shown in Fig. 1 is the typical gradation curve of the bottom ash, which was used as one component in the base layer of the test road. Typical gradation curves for fly ash from Helsinki Energy are shown in Fig. 2. Typical gradation curves for peat ash created by burning mixed peat, wood and waste wood at the UPM Kaipola factory are shown in Fig. 3. The mix ratios, quantities of additives and optimum water content together with maximum dry densities determined for mixtures are presented in Table 1.

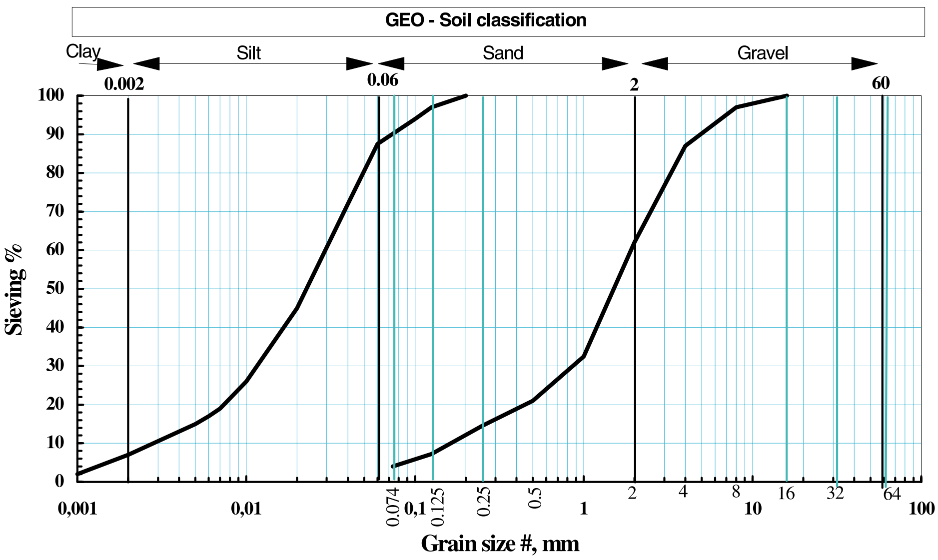

Figure 1. Typical gradations of fly ash (finer) and bottom ash (coarser) of Fortum's Meri-Pori power plant.

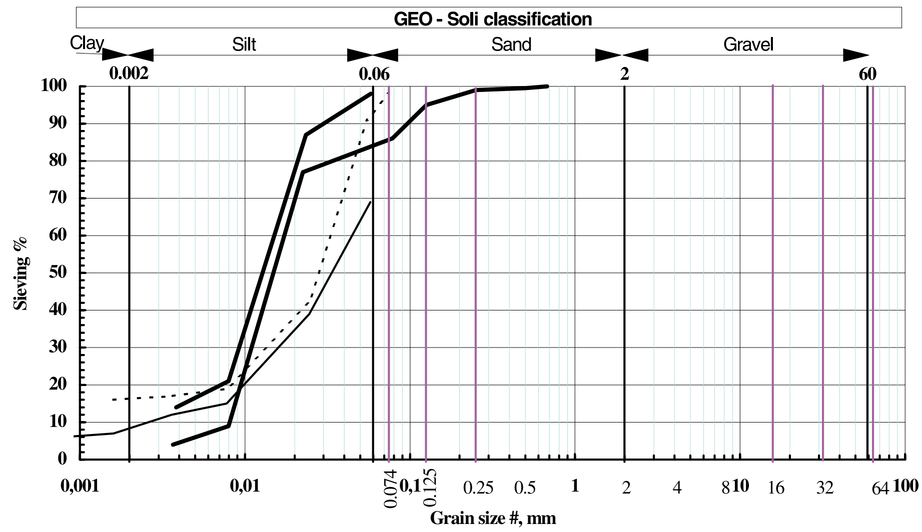

Figure 2. Typical gradation curves for fly ash from Helsinki Energy. The gradation of dry fly ash (thick lines, samples taken 26.3.97–7.5.98), desulphuration product heaped 30 days out of doors (broken line) and fly ash heaped 180 days out of doors (thin line).

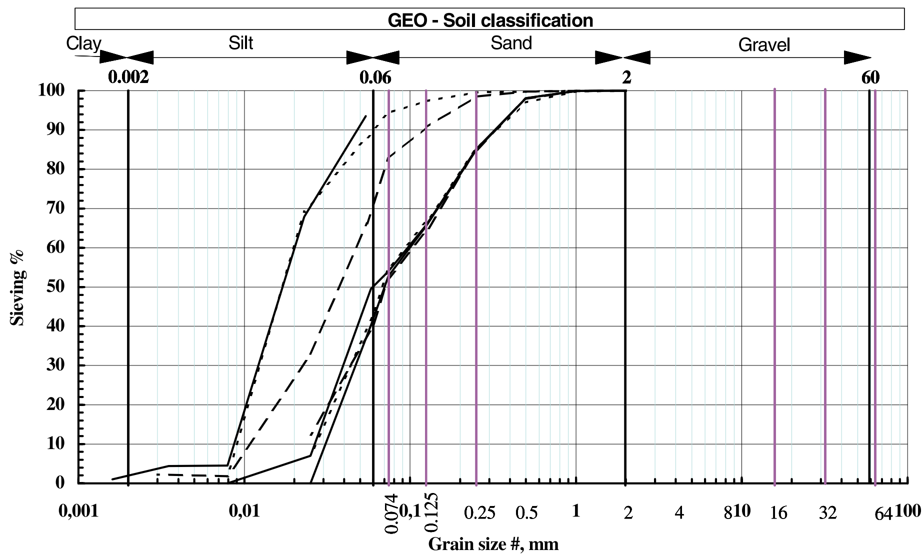

Figure 3. Gradations of Kaipola wood ash. The finer samples are dry ash and the coarser (four lines nearly on top of each other) heaped ash.

Table 1. Materials, mix ratios and basic properties.

Property	Stabilised fly ash	Fly ash/ desulphuration product	Stabilised peat ash
MIX RATIO OR CEMENT CONTENT, %	6 %	50 % / 50 %	4 %
w_{opt}, %	25.0	25.0	36.2
$\gamma_{d\ max}$, kN/m^3	12.9	13.3	11.6
Design relative density, D, %	90	95	92

TESTING PROGRAM AND TEST RESULTS

The testing program included determination of the dynamic stiffness modulus, compressive and tensile strength, thermal conductivity and permeability together with freeze thaw durability and frost heave parameters. In addition, a specific forced bending test with beam specimens (h * b * l : 100mm*100mm*500mm) was carried out.

The test specimens used in the tests were compacted under the optimum water content specific to each material to the desired densities. These densities are presented in Table 1. The stabilised fly ash specimens were manufactured to correspond to the density obtained in test road. The specimens of other materials were manufactured to correspond to the designed use of the material. The specimens were usually tested at the age of 28, 90 and 180 days.

The test results are presented in Table 2. Table 2 contains also the requirements submitted for materials used in the upper part of the road section. The requirements submitted for by-products with their complete justifications are presented in reference 2.

Table 2. Test results for each material and requirements in the upper layer of road section.

Property, parameter	Stabilised fly ash	Fly ash/desulphuration product	Stabilised peat ash	Requirement
Stiffness modulus, MPa (water content at compaction/saturated)				> 300
28 d	1400/2100	1100/700	4800/ 3300	
90 d	-/-	1200/2700	2300/ 3700	
180 d	2300/2300	2300/1000	-/-	
Compressive strength, MPa (wc at compaction/ saturated)				> 1.5
7 d	1.5/-	1.7/1.1	3.1/ .0	
28 d	2.2/2.5	2.6/2.0	5.4/4.8	
90 d	3.2/-	3.5/3.1	8.5/9.6	
180 d	3.5/2.4	4.8/2.9	-/-	
Tensile strength, kPa	290	247	715	-
Freeze-thaw durability, cycles (end cycles)	3	2	12 (30)	≥ 12
Frost heave parameters SP (2 kPa), mm^2/Kh	0.9...1.1	0.05	0.0	< 0.5
Water permeability, m/s	$2.0*10^{-7}$	$1.1*10^{-8}$	$1.2*10^{-9}$	$> 3*10^{-7}$
Bending capacity, R_{min}, m	94	108	84	$R_{longt} < 300$ $R_{shortt} < 150$
Thermal conductivity, W/Km, recommendation (frozen/thawed)	0.69/0.76	0.55/0.95	0.57/0.89	< 1/1

REVIEW OF THE RESULTS

All materials fulfilled the compressive strength and dynamic stiffness requirements at the age of 28 days, both under optimum water content and saturated state submitted for the upper part of the road structure.

Also the beam specimens of all materials sustained the required long-term and short-term bending test. On the other hand, none of the materials (excluding the slag sand) fulfilled the required permeability value or criteria.

Stabilised fly ash

The value of the frost heave parameter, the segregation potential (SP), did not fulfil the requirement submitted for the upper part of the road section. The requirement submitted for the lower part (SP < 1.5 mm^2/Kh, depth > 1.0 m) was on the other hand fulfilled.

The specimens did not survive the freeze-thaw test due to specimen failure after the third cycle. Also the permeability value determined failed to meet the required value.

Mixture of fly ash and desulphuration product

The value of the segregation potential determined met and exceeded the required value for the upper part of the road section, but the specimens failed to pass the freeze-thaw test due to specimen failure after the second cycle. The permeability value determined failed to meet the required value.

Cement stabilised peat ash

The value of segregation potential determined met and exceeded the required value for upper part of the road section. The specimens also passed the freeze-thaw test, which was carried out until 30 cycles were completed

THE ESTIMATION OF LONG-TERM DURABILITY OF MATERIALS

Stabilised fly ash

According to the test results, the cement stabilised dry silo fly ash is capable of developing reasonable compressive strength and high stiffness values. This leads to good structural bearing capacity and better thermal insulation properties than can be found with natural materials. Saturation was found to decrease the compressive strength and static stiffness modulus value.

The stabilised fly ash appeared to be mildly susceptible to frost in the frost heave test made according to the test program and it also failed to pass the freeze-thaw test simulating the climatic effects. Based on these results, the long-term stability of the cement-stabilised fly ash in question appears to be poor. Because of this the properties do not remain constant but they may change considerably when the structure fails. This result means that it is not possible in the pavement design to use the high stiffness level measured (of the order of 2400 MPa). One must estimate the structural modulus value level, which can be reached for the failed material. The modulus value of the layer of failed bound material may still be of the same order as in similar layers built with natural materials.

The properties of bound materials are always strongly dependent on the internal alteration of quality of the product. The test specimens were compacted to the density obtained in the test road. Before the test road was constructed a set of preliminary laboratory tests were carried out. In these tests material did not possess frost heave problems (larger degree of density) and it passed the freeze thaw tests, although it lost some of the compressive strength. The properties of fly ash studied during the test program and during the preliminary tests differed to some extent also in relation to compactability properties.

Mixture of fly ash and desulphuration product

The mixture of fly ash and desulphuration product was behaving almost like the cement stabilised fly ash. The mixture was found to be non-frost susceptible but it failed to pass the freeze thaw test simulating the environmental impact/stress.

Cement stabilised peat ash

Cement stabilised dry peat ash can produce very high compressive strength and a good stiffness value. At the age of three months the level of compressive strength is 8 to 9 MPa and the value of dynamic stiffness modulus varies between 2000 and 4000 MPa. The effect of saturation on these properties is small and inconsistent. The material is non-frost susceptible and it passed the freeze thaw test simulating the environmental impact/ stress. Based on the test results one can estimate that the long-term durability and also the bearing capacity stability are reasonably good. The thermal insulation properties of the material are better than those of natural materials.

It remains a slight problem to foresee whether the behaviour of material is due to quality variations (proportion of wood and peat) and at least in this case the extreme reactivity of used peat ash. Because of the latter property the ash behaved as a binder. At most, the ratio of stiffness values of comparable specimens was up to 7. This strong strengthening property was not observed during the earlier studies. If one wants to make use of the beneficial properties of this material one must check and verify the properties of the material and construction process with dry material on a case specific basis. Even a small amount of moisture beforehand reflects strongly on the strengthening of the material and a long-term wetting alters also the other material properties to a large extent. The permanent strengthening property disappears and the peat ash may become frost susceptible.

EXPERIENCE GAINED FROM THE FLY ASH TEST ROAD

The stabilised fly ash test road (Mt 272 Ämttöö-Poikeljärvi) has been closely monitored since the construction phase. The subject was one of the test road structures constructed under the test construction programme of Tekes's Ecogeotechnology R&D program and it is currently being monitored under the TPPT test road project. The results obtained since spring 2000, which are presented later in this document, are based mainly on this ongoing monitoring work (Tammirinne *et al*. 2000). This monitoring has included sampling, surveying, measuring of evenness (IRI) and bearing capacity determinations.

Cement stabilised (6 %) fly ash from Fortum's Meri-Pori power plant was used in the sub-base layer of this test road. Based on preliminary tests the stiffness modulus value of this stabilised fly ash in design was 400 MPa. The relative density was planned to be D = 92 %. The amount of binder was chosen to produce a compressive strength of 3 MPa at the age of 28 days to limit the effect of freezing on the material. According to the preliminary tests, the fly ash was non-frost susceptible. The bearing capacity requirement for the final fly ash structure was 416 Mpa, and the bearing capacity requirement for the reference (traditional structure) structure was 263 MPa.

The densities required in design were not fully achieved. The mean relative density of the sub-base layer was ca. 90 %. One reason for the lower density was probably the variation in fly ash properties during the construction phase, compared to the fly ash used in preliminary tests. The maximum dry density of fly ash varied between 12.8 and 15.8 kN/m^3 and optimum water content between 17.2 and 28.2 % during the construction. The variation in compactability properties of fly ash may, especially in lower relative densities, reflect other geotechnical properties of the material. The optimum water content of the material used in the preliminary tests was 15 % and the compacted specimens (D = 92 %) were non-frost susceptible. In the laboratory tests made after the construction (i.e. in this project) the optimum water content of fly ash was 25 % and relative density D = 90 %. In this case the material was slightly frost susceptible (SP = 1 mm^2/Kh).

In spite of a lower relative density than planned, the bearing capacity measured on top of the fly ash layer in-situ gave modulus values between 700 and 800 MPa. Samples taken in the autumn before the freezing season gave a compressive strength of 3.1 MPa.

Surveying

During the winter of 1997–98 frost heave values of 40 to 50 mm were monitored on the fly ash sections. These measured values corresponded well to the calculated frost heave value of ca. 40 mm determined based on winter's freezing index (9500 h°C) and laboratory and in-situ parameter values. The calculated frost depth (61 cm) corresponded reasonably well to the measured values (39 to 49 cm) from the road shoulder.

During the winter of 1998–99 (freezing index F = 14789 h°C) the maximum frost penetration of 1.09 m was reached in April 1999, at which time the frost had penetrated through both the stabilised fly ash layer (500 mm) and underlying filter sand layer (300 mm) into the subgrade. The frost penetration depths varied between 1.36 and 2.00 m in the reference structure.

The maximum frost heave of the fly ash structure varied between 28 and 88 mm. The largest frost heave (88 mm) was measured at pile number 750 on the right shoulder in March 1999. At that time the frost had just penetrated through the fly ash layer, which means that the frost heave measured is due to frost heave of the stabilised fly ash itself. The frost heave has been unevenly distributed in the section and the road shoulders have larger frost

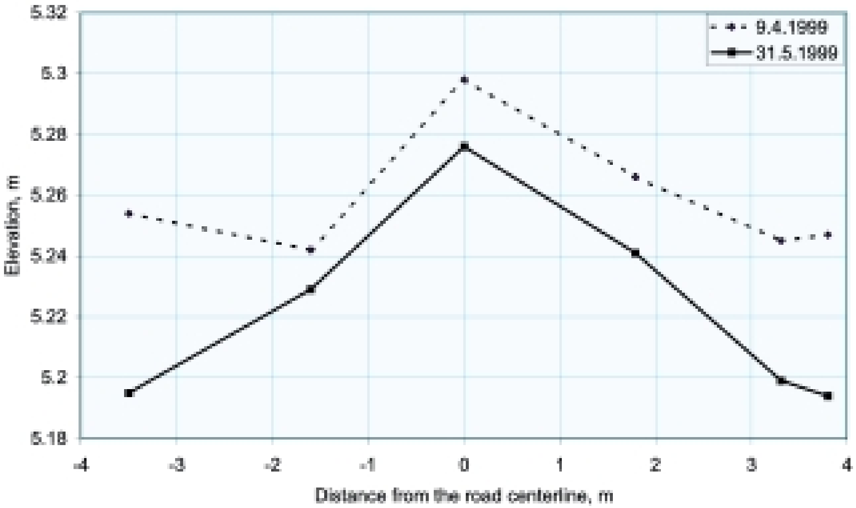

Figure 4. Cross-section surveying at pile number 750 during the maximum frost heave period in spring 1999 (9.4.1999) and early summer 1999 (31.5.1999).

heave than the central part of the road. The frost heave values of the reference structure varied between –10 and 11 mm.

The survey results at pile number 750 are shown in Fig. 4. From the cross-section one can deduce that the largest frost heave values appear to occur at the shoulders. The smallest frost heave values appear within 1.5 to 2 metres of the centre line, partly on both sides, where they form depressions collecting water. Pooling due to uneven frost heave of the stabilised fly ash is shown in Fig. 5.

In-situ samples

A second set of samples was bored in autumn 1998 at the same pile number as in autumn 1997. The age of the material was ca. 14 months when the samples were taken. Visual inspection revealed plenty of cracks and disintegration of stabilised material. The most intact specimens were chosen for laboratory tests.

Compressive strength, density and water content in in-situ condition were determined from these samples. Between the samplings (ca. 9 months), the

Figure 5. Pooling due to uneven frost heave of fly ash structure in spring 1999.

compressive strength of the intact parts of sub-base layer decreased from 3.1 MPa down to 2.1 MPa. The in-situ water content also increased by 4 to 8 % -units.

The third set of samples were bored, and this time from the frozen layer, in March 1999. The samples were taken at pile numbers 460 and 900 from the right lane. The lengths of these samples varied between 25 and 110 mm.

Water contents were determined for all the samples and the compressive strength from two specimens (the only ones long enough). In addition to that, thaw settlement and frost heave tests were carried out with the longest specimen. The compressive strength had decreased down to 25 to 50 % of the value determined in autumn 1997. The average values of compressive strength as a function of time are shown in Fig. 6, together with the average compressive strengths determined in the laboratory.

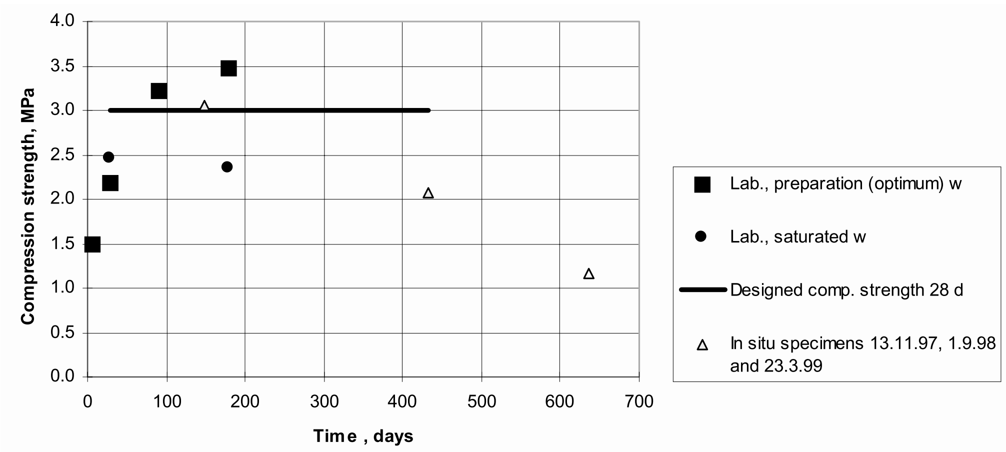

Figure 6. The compressive strength (average values) of specimen taken from test road at different times and the compressive strength (average values) determined at different ages in the laboratory.

A thaw settlement test was carried out with a specimen taken from pile number 460, which had been taken frozen from the depth of 0.32–0.43 m. This depth corresponds to the upper part of the sub-base layer. The settlement of the specimen was ca. 2 %. After the thaw settlement test a normal frost heave test was carried out, which gave the segregation potential of SP = 0.5 mm^2/Kh for the fly ash specimen.

A segregation potential value SP = 1.0 mm^2/Kh was determined earlier for a laboratory compacted stabilised fly ash specimen. Using temperature, frost depth and frost heave values measured during winter 1998–1999 as input, the back-calculated segregation potential value for the stabilised fly ash structure varied between 0.5 and 2.0 mm^2/Kh, depending on the absolute in-situ frost heave. According to the frost susceptibility criterion based on segregation potential SP, the material is slightly frost susceptible if SP varies between 0.5 and 1.5 mm^2/Kh and medium frost susceptible if SP varies between 1.5 and 3.0 mm^2/Kh.

The bearing capacity

In autumn 1998, about one year after the construction, the average bearing capacity level at the road surface of the fly ash structure measured with FWD was 476 MPa. The average bearing capacity of the reference structure was 430 MPa. The average bearing capacities for both structures were in excess of the design value.

In spring (May) 1999 the average bearing capacity of the fly ash test structure was 415 MPa, which corresponded to the design value. The average bearing capacity of the reference structure was 430 MPa. The bearing capacity values for reference sections are well above the design values (263 MPa). The results of these FWD measurements are shown in Fig. 7.

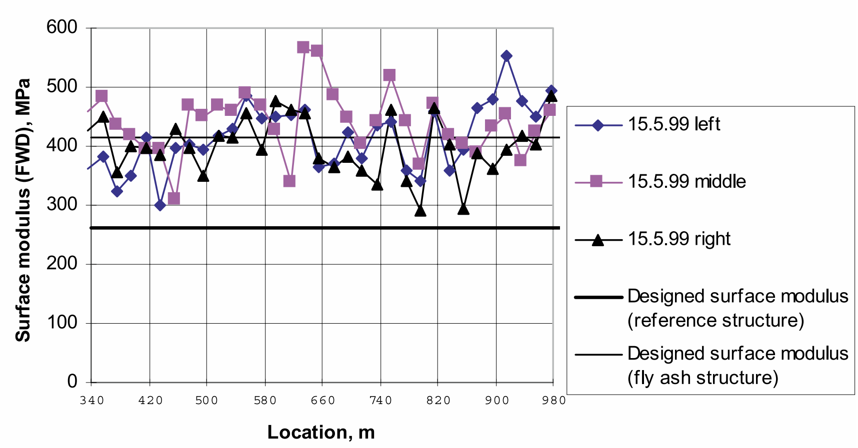

Figure 7. Temperature corrected FWD results, May 1999.

Wearing course damage

The first longitudinal crack was observed after the first winter (1998–1999) between pile numbers 442.4 – 445 on the centre line of the road. The width of the crack was ca. 5 mm. In spring 2000 there were found to be five cracks in separate places along a 70 m length. In addition, there was one 5–10-mm wide crack on the left lane at 2-m distance from the centre line. The frost behaviour during winter 1999–2000 is quite similar to that during the previous winter.

Summary of the test road

As a summary of the behaviour of the fly ash structure one can conclude that the structure as a whole has behaved reasonably well, despite the unevenness and pooling during late springtime. In spite of uneven frost heave, cracking of stabilised fly ash and decreased compressive strength, the fly ash structure still had the design bearing capacity during spring 1999 and the bearing capacity was better than that of the reference structure. Frost heaving, material cracking and decrease in strength probably even down to less than half of the design value had no detrimental effects on the bearing capacity of the stabilised fly ash layer. This badly cracked stabilised fly ash layer behaves similarly to unbound crushed aggregate.

If the modulus value of the other layers are in agreement with design values, then the modulus of stabilised fly ash is also in line with the design value (400 MPa). This value is only 19 to 15 % of the dynamic modulus value determined with saturated intact specimens at the age of 28 and 180 days. In previous studies with cement stabilised glacial till it has been found that the average dynamic modulus values of broken specimens are ca. 16 to 17 % of that of corresponding intact specimens. With moist, broken stabilised glacial till the modulus value is ca. 21 % and with saturated and broken specimen ca. 13 % of the modulus value of the corresponding intact specimen.

SUMMARY

All the materials tested are in principle capable of producing adequate compressive strength and stiffness to be used in road construction. In practice, some problems may arise especially concerning the choice of parameters for design due to poor environmental durability. In other words, stabilised or self-strengthening materials do not necessarily last intact in repeated freeze thaw cycles. Although the stiffness of stabilised material decreases significantly due to structural failure, it may still possess a reasonable degree of stiffness to be used as sub-base of a road structure.

The second phenomenon strongly influencing the use of such by-products is the internal variability of properties of the by-products. These variations are mainly due to variations /changes in origin and

composition of the fuel used in relatively small power and production plants. This variation in quality causes uncertainty in the properties obtained in the structural layer in two ways. The material used in laboratory test may sometimes differ quite remarkably from the material used in the actual structure. In addition, the variation during construction phase makes it difficult to carry out the compaction control

By-products can be successfully used for road construction as long as special properties of these materials and the precautions governing their use are taken into consideration in testing, planning and construction.

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THE USE OF FLOTATION SAND IN EARTH CONSTRUCTION

by
K. Kujala[1)], M. Ahonen[1)] and H. Koivisto[2)]

Kujala, K., Ahonen M. & Koivisto, H. 2001. The use of flotation sand in earth construction. *Geological Survey of Finland, Special Paper 32, 75–81,* four figures and 5 tables.

Flotation sand, comparable to natural sand in its material properties, is a by-product of calcite flotation. The capillary rise of flotation sand is lower than 90 cm, the material is non-frost-susceptible (SP < 0.5 mm^2/Kh) and its hydraulic conductivity is higher than 10^{-6} m/s. Its friction angle is approximately 44° and therefore a little greater than that of sand with a corresponding grain size. In its technical properties, flotation sand is a suitable material for the filter layer of road construction as well as for filling structures that require a frost resistant material with a high bearing capacity. Refined with mixture materials, such as bentonite, it is also a suitable material as a hydraulic barrier in landfill covers. In addition, flotation sand is greatly strengthened when bound with bark ash, for example, thus fulfilling the quality requirements set for bound materials of road structures. Flotation sand does not contain any materials that are harmful to the environment.

Keywords: construction materials, flotation sand, by-product, engineering properties, earthworks, Finland

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INTRODUCTION

Approximately 70 million tons of natural rock material is used annually in earth construction in Finland. The decline in good quality rock material resources, the need for protection, and the growing distances in transportation have all increased the need for applying substitute materials for sand and gravel. Simultaneously, various fields of industry generate a great number of mineral by-products that can be utilised in earth construction. Also, waste management legislation requires replacing natural materials with waste and by-products. Nevertheless, if these materials are to be utilised in earth construction, certain technical properties and environmental qualifications are required of them.

In the initial stages of using recycled material, the material properties have to be examined more comprehensively compared to traditional materials, whose use is based on results achieved during long-term utilisation. Defining long-term behavior often requires test constructions and monitoring of the structures before actual utilisation.

This article deals with the material properties of the by-product of calcite enrichment at the Lappeenranta mine of Partek Nordkalk Oyj Abp, and its suitability as an earth construction material. A total of 100 000 tons of flotation sand is generated annually.

MATERIALS AND METHODS

Materials

The grain size distribution of flotation sand varies in the different sections of the disposal area. The coarse fraction is deposited close to the discharge pipe, and the finer fraction is carried along in water, further away from the pipe. The grain size distribution of the coarser fraction equals that of sand, and the finer component is equivalent to silty sand (Fig. 1). Both materials are even-grained. The average grain size d_{50} of the fine flotation sand is 0.08 mm and of the coarse flotation sand, 0.16 mm.

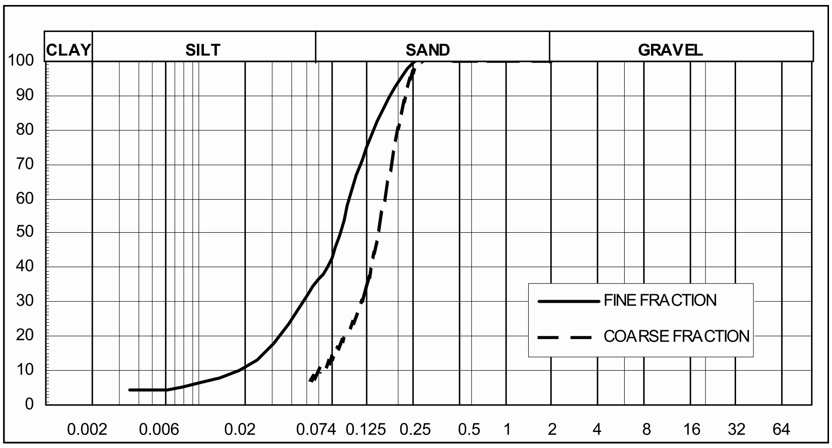

Figure 1. Grain size distribution of flotation sand in the disposal area. Partek Nordkalk Oyj Abp's Lappeenranta mine.

Bark ash from Enso Oy's Imatra works was used to strengthen the flotation sand and calcium bentonite was used to decrease their hydraulic conductivity.

Methods

The material properties of flotation sand was determined by methods commonly used in geotechnical research. Only principles of the most essential test methods used in this research are presented in Table 1.

Table 1. Test methods used in flotation sand research.

Property, parameter	Principle of test method
Environmental validity	
*total elemental content	ICP-AES
Hydraulic properties	
*hydraulic conductivity	*flexible-wall perimeter
*capillary rise	*capillarymeter
*water retention capacity	*pressure plate apparatus
Frost	
*segregation potential	*frost heave test
*freeze-thaw durability	*change of length, compressive strength test
*water durability	*water immersion test
Thermal properties	
*thermal conductivity	*thermal needle probe
Mechanical properties	
*shear strength	*triaxial test
*resilient modulus	*dynamic triaxial test
*tensile strength	*bending beam test
*bearing capacity	*CBR-test

Sample preparation

When using a mixture that includes binding materials, cylindrical test samples of the flotation sand were prepared. Water was added to the mass to achieve the optimum water content. The masses were then mixed together mechanically. The process of mixing was continued until the binding material, based on visual examination, was completely blended with the dry aggregate. Compaction of the samples tested (compressive strength test, freeze – thaw test, water immersion test), using uniaxial compression test equipment was performed using a gyrator compactor into a 4” mold. The target degree of density was 95 %. The height of the compacted samples was 100 ±±2 mm. Compaction of the samples tested using dynamic triaxial equipment and bending capacity equipment was performed with a hand rammer. After the test samples were prepared, they were stored in a closed plastic box on top of a steel grating at room temperature. There were 10 centimeters of water at the bottom of the plastic box.

Calcium bentonite and flotation sand were mechanically mixed together to form a material of uniform quality, after which the target amount of water was added. The degree of density of the samples was set either at 90 % or 95 %. The samples were compacted with a slightly higher water content than the optimum water content.

RESULTS AND DISCUSSIONS

Environmental validity

The mineralogical composition of flotation sand is wollastonite, quartz, calcite, and dolomite. The results of elemental analyses of flotation sand are presented in Table 2. The major elements are Ca, Mg and Fe. Because all trace elements are lower than the proposed threshold values set for materials used in earth construction (Assmuth 1997), the material can be used without limit (Table 1). Only the beryllium content (1.3 mg/kg) of the coarse fraction slightly exceeds the lower limit value (1.0 mg/kg), but it is still clearly lower than the upper limit value (10 mg/kg). The beryllium content of the fine fraction is lower than the defining value (< 0.5 mg/kg). It must be noted that the beryllium content is lower than the background content in Finnish soil.

Table 2. Elemental contents of flotation sand. The table also presents the suggested values for concentrations of harmful materials in soil. The results are reported in milligrams per kilogram of dry matter (mg/kg).

	Flotation sand Fine fraction (mg/kg)	Flotation sand Coarse fraction (mg/kg)	Judgement criteria Upper limit value (mg/kg)	(Assmuth 1997) Lower limit value (mg/kg)
Al	2430	5280		
As	<10	<10	13	60
B	<5	5	5	50
Ba	29.4	39.7	600	600
Be	<0.5	1.3	1	10
Ca	233000	205000		
Cd	<0.5	<0.5	0.3	10
Co	<1	1.8	50	200
Cr	3.2	7.2	80	500
Cu	6.6	8.7	32	400
Fe	1850	3910		
K	361	929		
Mg	4020	4000		
Mn	52.6	99.4		
Mo	<3	<3	5	200
Na	466	899		
Ni	<2	4.0	40	300
P	431	358		
Pb	<5	<5	38	300
S	359	830		
Sb	<15	<15	5	40
Sr	296	277		
Ti	184	354		
V	1.1	4.5	50	500
Zn	8.4	13.6	90	700

Material properties of flotation sand

The physical properties of flotation sand is presented in Table 3. Its values of friction angles correspond to the values of sand. The cohesion of the fine fraction flotation sand is greater than that of the coarse fraction flotation sand. According to the CBR value (CBR = 40 %), the resilient modulus of the materials is appr. 185 MPa, calculated with an empirical formula (Table 3).

$Mr=17.6\ xCBR^{0.64}$ (MPa)

Both fractions are non-frost-susceptible (SP<0.5 mm^2/Kh), and their hydraulic conductivities are (k>10^{-6} m/s). Their capillary rise is lower than the values (0.9 m) set for filter layers in the conditions for quality control of the Finnish National Road Administration. The thermal conductivity of flotation sand is equal to that of sand in the same degree of density and water content (Table 3).

Table 3. Material properties of flotation sand determined by laboratory tests.

Property	Coarse fraction	Fine fraction
Specific gravity ρ (t/m^3)	2.89	2.88
PH	8.6	8.6
Maximum dry density *$_{g*dmax}$ kN/m^3	17.6	17.7
Optimum water content w_{opt}	13	14
Capillary rise h_c cm	78	86
Hydraulic conductivity k (m/s)	$10^{-5.0}$	$10^{-5.6}$
Friction angle ϕ	44.7°	43.7°
Cohesion c (kPa)	3	15
CBR-value	42	51
Segregation potential SP_0 (mm^2/Kh)	0	0.4
Maximum frost heave h (mm)	0.5	0.1
Thermal conductivity λ (W/Km)		
– unfrozen (+22°C)	1.17	1.13
– frozen (–15°C)	1.50	1.41

Material properties of bound flotation sand

Compressive strength and modulus of elasticity

After 28 days of curing, the compressive strength of flotation sand bound with bark ash varies between 1.3 and 5.5 MPa, depending on the grain size of the flotation sand and the amount of bark ash (Fig. 2). As the amount of bark ash increases, the compressive strength increases in a linear manner. After the first 28 days the increase is minor. The modulus of elasticity varies between 76 and 221 MPa. The changes in the modulus of elasticity are similar to the changes in compressive strength.

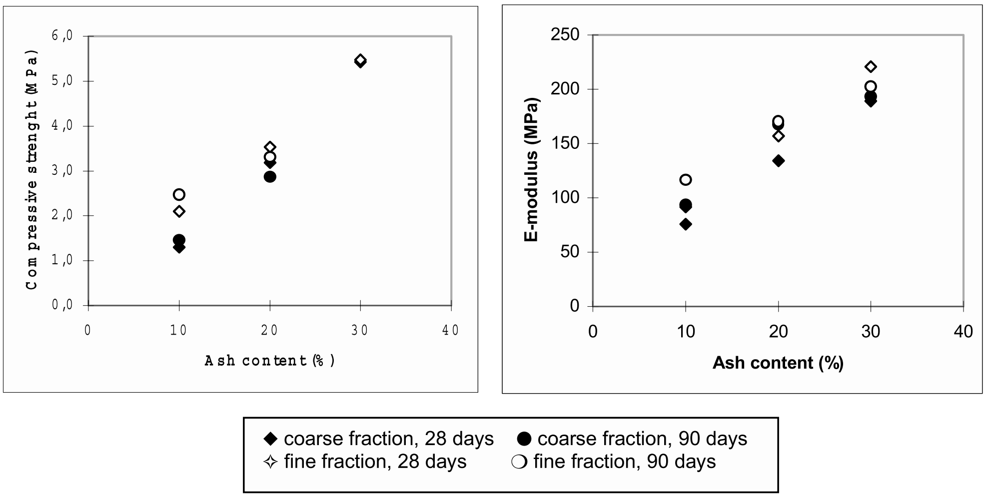

Figure 2. Compressive strength and modulus of elasticity of flotation sand bound with bark ash as a function of time and amount of bark ash.

Resilient modulus

The resilient modulus of flotation sand bound with bark ash increases as a function of the sum of principal stresses, the grain size of the flotation sand, and the amount of bark ash. For example, with the sum of principal stresses of θ = 50 kPa, the resilient modulus varies between 548 and 787 MPa (Fig. 3 and Table 4). The values of the resilient modulus of sand are equal to the values of high quality crushed aggregate.

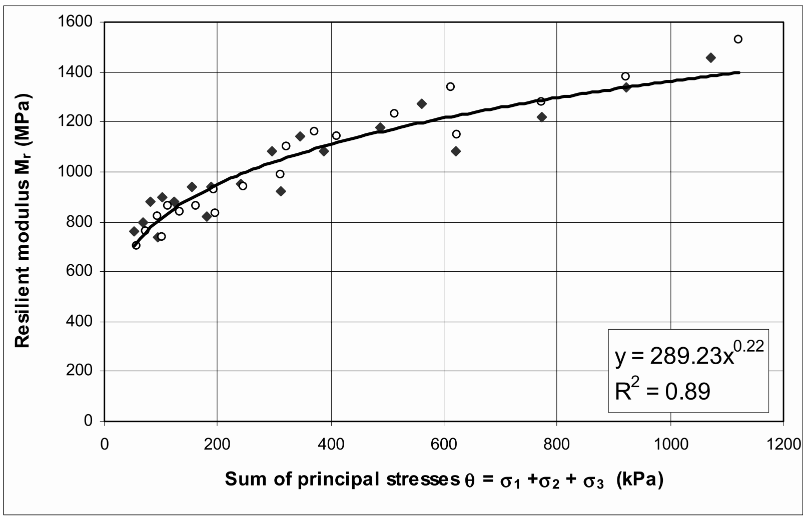

Figure 3. Resilient modulus of flotation sand bound with bark ash as a function of the sum of the principal stresses and the power curve fitted to measurement observations. Curing time 90 days, amount of bark ash 30 %, degree of density D = 95 % ($*_{g*dmax.}$ = 17.6 kN/m^3, $w_{opt.}$ = 14 %).

Table 4. Resilient modulus of flotation sand bound with bark ash as a function of the sum of the principal stresses θ = 50 kPa, θ = 100 kPa and θ = 200 kPa.

Flotation sand + bark ash	R^2	Resilient modulus M_r (MPa)		
		θq = 50 kPa	θq = 100 kPa	θq = 150 kPa
Coarse fraction + 10 % bark ash	0.86	584	660	872
Fine fraction + 10% bark ash	0.91	685	524	623
Coarse fraction + 30 % bark ash	0.85	651	685	734
Fine fraction + 30 % bark ash	0.94	787	540	728

Freeze-thaw durability and water immersion

The compressive strength of flotation sand bound with bark ash does not decrease significantly after freeze-thaw cycles or after immersion in water (Fig. 4). In the samples that were visually examined, there were no signs of ruptures or brittle fractures after freeze-thaw tests and water immersion tests. Also, changes in length were minor in these tests. The test samples absorbed only <10 % water during the tests.

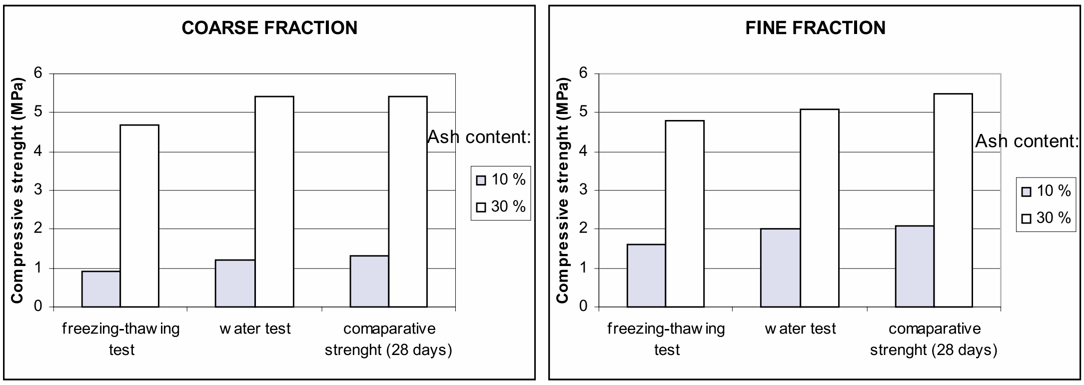

Figure 4. Compressive strength of the test samples after freeze-thaw tests and a water immersion test. The figure presents the compressive strength of the samples without freeze-thaw cycles. Curing time (28 days).

Material properties of flotation sand and bentonite mixture

The frost heave test was repeated as four freeze-thaw cycles. The segregation potential was defined after the first cycle. After the frost heave tests, the hydraulic conductivity of the samples was measured using a flexible-wall permeameter.

The flotation sand was found to be non-frost-susceptible, excluding the material fine fraction flotation sand + 4 % bentonite, which was low frost-susceptible (Table 5). After the four freeze-thaw cycles that were also frost heave tests, the hydraulic conductivity of each samples was < $10^{-9.0}$ m/s.

Table 5. Frost susceptibility and hydraulic conductivity of the mixture of flotation sand and bentonite after frost heave tests.

Material	Number cycles	Degree of density [%]	Water content [%]	Segregation potential [mm²/Kh]	Classification of frost susceptibility	Hydraulic conductivity [m/s]
Fine fraction + 6 % bentonite	4	94.9	16.2	0	Non-frost-susceptible	$10^{-9.0}$
Fine fraction + 6 % bentonite	4	89.8	16.2	0	Non-frost-susceptible	$10^{-9.0}$
Fine fraction + 4 % bentonite	4	94.7	16.1	1.0	Low-frost-susceptible	$10^{-9.1}$
Coarse fraction + 6 % bentonite	4	94.7	16.2	0	Non-frost-susceptible	$10^{-9.4}$
Coarse fraction + 6 % bentonite	4	89.7	16.2	0	Non-frost-susceptible	$10^{-9.9}$
Coarse fraction + 4 % bentonite	4	94.7	16.0	0	Non-frost-susceptible	$10^{-9.0}$

Utilization of flotation sand in landfill structures

The suitability of flotation sand as a filling material for landfill cover was ascertained in a test structure carried out at the factory landfill site of Partek Nordkalk Oy. The test structure was built particularly to study the feasibility of using flotation sand as the hydraulic barrier layer of landfill when its additive materials were bentonite and other commercial additives. Clay was used as a reference material in the hydraulic barrier. Flotation sand was also used on the surface of the waste layer to smooth out inequalities. The follow-up measurements of the test structures includes the amount and quality of the water infiltrating through the cover, the settlement, temperature and volumetric water content. The details of the results are beyond the scope of this paper.

SUMMARY AND CONCLUSION

The concentrations of harmful elements in flotation sand are very low and below limit values used in the evaluation of environmental suitability. Therefore, the material can be used without limit in earth construction.

The grain size distribution of flotation sand is even-grained and equals that of silty sand and sand. The capillary rise is lower than 90 cm, the material is non-frost-susceptible (SP<0.5 mm^2/Kh), and its hydraulic conductivity is greater than 10^{-6} m/s. Its friction angle is approximately 44° and therefore a little greater than that of sand with a corresponding grain size. According to the CBR value, the load-bearing capacity of flotation sand is as good as the material of a good base course. The coarse fraction of flotation sand fulfils the requirements set for a material used in a filter layer in the guidelines for quality control of the Finnish National Road Administration.

Flotation sand bound with bark ash fulfil the quality requirements for the material for the base course layer in road structures, among others.

The hydraulic conductivity of flotation sand can be effectively reduced with bentonite. With a bentonite content of approximately 6 %, the hydraulic conductivity is >10^{-9} m/s, which fulfils the hydraulic barrier requirements set for landfill cover structures, for example. The mixture of bentonite and flotation sand is non-frost-susceptible and at the most, low frost-susceptible. Freeze-thaw cycles do not increase the hydraulic conductivity of the flotation sand-bentonite mixture.

According to the research results, the potential uses of flotation sand are as filter layers of road and street constructions, environmental structures, and pre-filling and surface layers of the landfill covers. Refined with admixture materials like bentonite, flotation sand can also be used in the barrier layer of landfill covers. As a bound material, with binding materials like bark ash, for example, flotation sand is suitable for other pavement structures of road and street constructions. To resolve the long-term behaviour of the material, test structures should be used particularly to find out the environmental and mechanical durability of the bound material.

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THE USE OF PEAT ASH IN EARTH CONSTRUCTION

by
Eero Huttunen [1] and Kauko Kujala[2]

Huttunen, Eero & Kujala, Kauko 2001. The use of peat ash in earth construction. *Geological Survey of Finland, Special Paper 32, 83–90*, four figures and 4 tables.

This paper reviews the results of peat fly-ash utilisation at a peat power plant in Rovaniemi. Peat ash has been tested as a filler material in asphalt pavement, as a sub-base material of a road structure and as layers of landfill cover structures. On the basis of the results obtained, peat ash is suitable for these applications in both technical and environmental aspects. At the moment, peat ash is classified as waste and this retards the progress of extensive use of peat ash in earth construction.

Key words: engineering geology, peat fuel peat, ash, utilization, construction materials, highways, pavements, fillers, landfills, Rovaniemi, Finland

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INTRODUCTION

The Suosiola peat power plant of Rovaniemen Energia uses peat ash as its main fuel. In addition, oil and wood chips are used. In August 1995, a new modern combustion unit was brought on stream. Approximately 13 000 m+ of peat fly-ash is generated annually. At present, the peat ash is disposed 30 km away, at the Suksiaapa swamp.

The utilisation of peat ash in earth construction applications has been studied in several research and development projects, which have proceeded through the classification of material-related properties to designing and constructing test structures. At present in the research, the monitoring phase of the test structures is in progress. Because of the restricted availability of suitable natural raw materials in Rovaniemi and its surroundings, technical and economic needs for the development of the utilisation of peat ash exists. Because of the geographical location, special climate conditions and, especially, the freezing of the soil, has to be taken into consideration in structures and materials.

ENVIRONMENTAL ASPECTS

The basic precondition for extensive use of peat ash is the environmental qualification. In Finland, no such official standards exist which could be applied in evaluating the environmental impact of by-products applicable for earth construction. However, in general a three-step evaluating procedure is followed. In the first stage, the environmental impact is estimated on the basis of composition. If the total concentration exceeds a certain maximum concentration, the environmental impact is evaluated on the basis of solubility and risk analysis.

Table 1. Total concentration and solubility of peat ash in maximum solubility test NEN 7341 and column test NEN 7343. The results are given in milligrams per kilogram of dry matter (mg/kg dm).

Element	Total concentration	Max. leaching test NEN 7341	Leaching test (Column test) NEN 7343	Guideline values for total concentrations	
				Lower Value (mg/kg)	Upper value (mg/kg)
Al	47500	699.4	109		
As	54	20.7	0.04	13	60
B				5	50
Ba	142			600	600
Be				1	10
Ca	106000	29060			
Cd	4.3	0.99	0.004	0.3	10
Co	33	<5		50	200
Hg	–	<0.02			
Cr	212	<5	80	500	
Cu	86	4.93	0.01	32	400
Fe	244000	<100			
K	1410	285.7			
Mg	12500	1132.9			
Mn	1700	51.2			
Mo	<5	<5		5	200
Na	1090	275.8			
Ni	85	<5	0.11	40	300
P	13200	492.6			
Pb	35	<10		38	300
S	9450	9851			
Sb		<50		5	40
Sr	353	89.6			
Ti	815	5.9			
V	356	18.7		50	500
Zn	126	9.9	0.76	90	700

< concentration is below the detection limit

The previously mentioned values are interpreted so that the by-product that has total concentrations below the lower value can be used without limitations for almost any purpose. Material that has total concentrations above lower value, but below the upper value, can be used with some limitations or with some protective precautions, but only in those applications that pose no risk to human beings. If the upper value is exceeded, the use of material requires a detailed risk assessment before use. This procedure is not, however, officially in use.

The total concentrations of the peat ash were determined by extracting it in nitrohydrochloric acid (3:1 hydrochloric acid: nitric acid 90^{o}C). The analysis was performed using ICP-AES- method. The concentration of the leaching elements were examined using maximum leaching test NEN 7341 and with leaching test NEN 7343.

The total concentration and the maximum leaching values and leaching values of peat ash are presented in Table 1. Total concentration of all the elements are below the upper value. The lower value is exceeded by elements As, Cd, Co, Cr, Cu, Ni, V and Zn, but their solubility is slight according to the maximum leaching test. In the leaching test (column test), the concentration of these elements was smaller than the maximum concentration when the placement criteria was group 1, i.e. application in an unisolated form.

THE USE OF ASH AS ASPHALT FILLER

In the laboratory, the material properties of ash as filler, as well as the material properties of the bitumen-filler mixtures, and asphalt pavements that included ash, were studied. On the basis of the laboratory results, a test pavement was constructed, where peat ash was used as filler for a SMA-12 pavement. In this research, PANK-norms (PANK 1995) that correspond the European standards were applied.

Laboratory Phase

The peat ash fulfilled the requirements of the filler, except the void content, which was higher than the maximum value presented in PANK-norms. Because the fine aggregate of asphalt pavement generally includes a mixture of sand and crushed rock as fine aggregate, the void content in the fine aggregate is smaller than that of the peat ash alone. Hence the norm requirement can be achieved. To fulfil the norm requirement, an individual estimation of each case is required. The peat ash that was examined met the PANK-norm requirements in terms of grain size distribution and ignition loss for the additive filler.

The effect of peat ash on the stiffness of the pavement was studied by determining the softening temperature of bitumen (B120) and filler mixtures for aged and unaged samples. According to these results, the softening temperature of mastic that included peat ash as filler was clearly higher than the softening point of the mastic that included lime or a mixture of lime and peat ash. On the basis of the softening temperature, it can be estimated that when using peat ash as additive filler, the modulus of stiffness is greater than when lime filler is used. However, using only peat ash as filler is limited by the void content that can raise the total amount of mineral aggregate voids content in asphalt mass to be too high.

In laboratory experiments, pavement type AB 16 was used. Bitumen B120 was used as binder. In the test pavements, peat ash was used as additive filler. For the reference pavements, lime powder was used as additive filler. According to the determinations, the optimum binder content of those pavements that included peat ash is from 0.6 to 0.8% higher than that in the reference pavements. The increase in binder content is apparently caused by the higher void content in the ash. The modulus of stiffness of the test pavement was higher than that of the reference pavement; for example, at +20 °C, a 1.45 times higher value was achieved. The deformation values of the test pavements represent the deformation class I in 1995 Asphalt norms. All test and reference pavements were easy to compact.

Field Results

The test asphalt pavement is located in the centre of Rovaniemi, on Lapinkävijäntie road. The proportional class that is determined on the basis of the traffic flow, is B. The SMA 12 test pavement included 9% peat ash of the total mass of mineral aggregate. In the reference pavement, lime powder was used as filler. Core samples were taken from the test and reference pavements, and the mass density, void content, indirect tensile strength and sensitivity for deformation were measured. The void values of the test pavement, which included fly ash, varied slightly more than the void values given in the 1995 Asphalt norms. On the basis of the tensile stress (–2ºC), the test pavement is classified in the highest freeze-proof class. On the basis of the cyclic creep stress test, the test pavement is classified in deformation class II, which corresponds to the proportional classification (Table 2).

Table 2. Material properties of the test and reference pavements (SMA 12) at the Lapinkävijäntie road site.

Pavement	Pavement density kg/m³	Mass density kg/m³	Voids %	Indirect tensile strength (kPa) –2°C	Indirect tensile strength (kPa) +10°C	Creep test %
Reference	2410…2566	2566…2604	4,1…5,2	2060…2491	1018…1488	
Test	2460 – 2482	2586 – 2618	0.9 – 6.1	1819 – 2491	1068 – 1163	2.7 – 3.1

THE USE OF ASH IN SUB-BASE LAYERS

Peat ash reacts with water in a pozzolanic manner. This property is viable in structures that require high bearing capacity, such as road, street and yard structural layers. On the other hand, problems caused by the strength gain of the material have to be taken into consideration; for example in municipalities' technical maintenance work. In order to strengthen the structures as far as possible, peat ash should be stored dry and moisturised only immediately before the constructing or during the work. Repeated freeze – thaw cycles decrease the compressive strength of peat ash.

In the test structure (Fig. 1) peat ash replaced the 900-mm thick sub-base layer of crushed rock or gravel crush. The compacting of peat ash was done in November 1997, at a temperature of -7 ºC. Compacting was successful with ash that was still warm after the burning process. Peat ash was moisturised at the power plant immediately before transportation to the construction site. The base course and the pavement layers above peat ash were constructed during summer 1998. At the same time, monitoring equipment was installed and samples were taken from the peat ash layer. More information will be obtained from the freeze-thaw weakening, from the relationship between thermal conductivity and the water content, and from the frost susceptibility of ash, when the behaviour of the structure is observed in situ conditions. This information and other material parameters (Table 3) are essential requisites for establishing instructions for the use of peat ash in the future.

The results of laboratory tests of the samples taken from the test structure are presented in Table 3. Significant in these results is the low frost susceptibility (segregation potential), which indicates that when ash is well compacted and its strength is increased, the material is classified as non-frost susceptible.

The maximum depth of frost during the winter of 1998–1999 was 156 cm, and during the winter of 1999–2000, 138 cm. The freezing index was 36 300 Kh and 30700 Kh, respectively. In reference structures, the frost depth during the winter of 1998–1999 in the Rovaniemi region was approximately 250 cm. The insulation effect of peat ash is clearly illustrated in the temperature gradient (Fig. 2). During wintertime, peat ash retards frost penetration and the temperature decreases in the top part of the base course. On the other hand, in springtime the layer of peat ash slows down the thawing process. Both low thermal conductivity and high heat capacity affect the frost behaviour of ash.

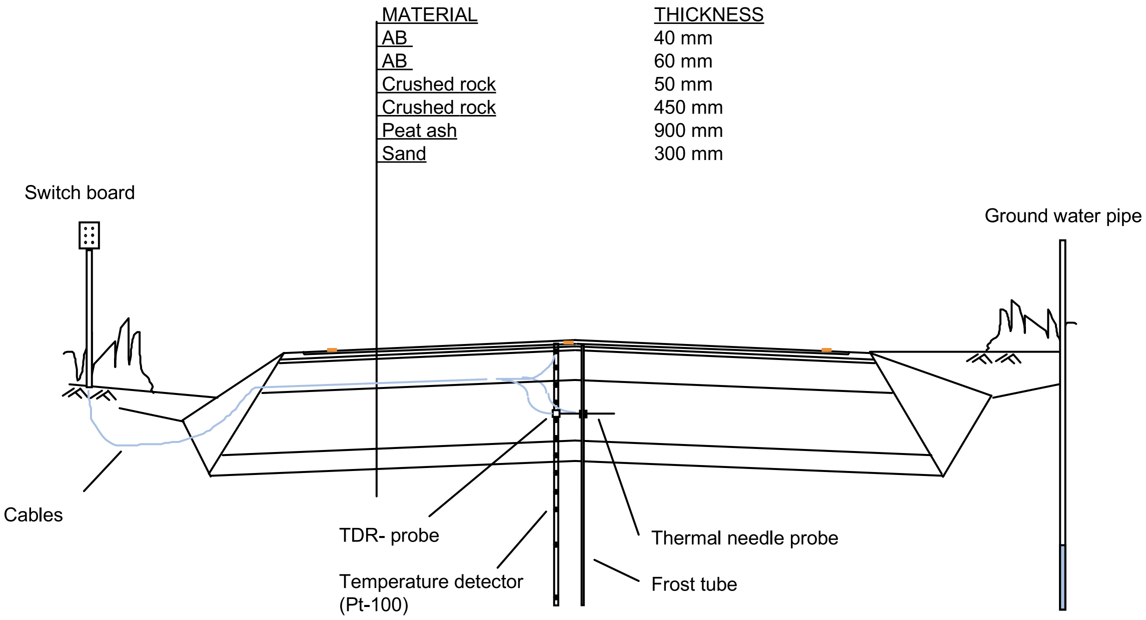

Figure 1. Cross-section of the peat ash test structure of Teollisuustie Road, Rovaniemi.

Table 3. Material properties of peat ash layer of Teollisuutie Road, Rovaniemi.

Properties	Value	Unit
Density*	1.59	kg/m^3
Water content*	35	%
Porosity*	61.9	%
Compressive strength*	1.14	MPa
CBR-value	34.8	%
Segregation potential	0.2	mm^2/Kh
Thermal conductivity (+20°C)	0.75	W/mK
Hydraulic conductivity	$10^{-6.1}$	m/s

* Average values of the samples

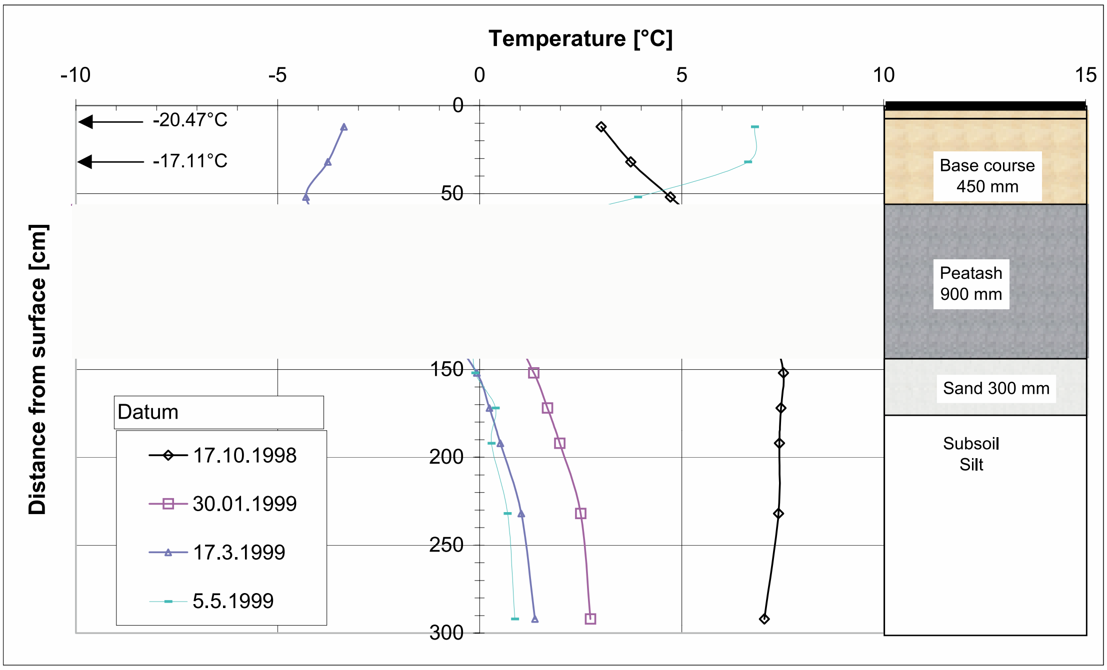

Figure 2. Temperature profiles of the Teollisuustie peat ash structure in Rovaniemi, winter 1998–1999.

UTILISATION OF PEAT ASH IN LANDFILL STRUCTURES

The cover of Mäntyvaara landfill was chosen for test constructing purposes. In the laboratory, the peat ash index properties, compaction properties, frost susceptibility, freeze-thaw behaviour, air permeability and erosion properties, as well as mechanical, hydraulic, and thermal properties, were studied. In addition, the amount of water infiltrating through the test structure was estimated by numerical modelling. On the basis of this research material, a plan for the test structure was made. The plan includes two test structures. In the thinner structure, the idea is to allow the frost to penetrate the hydraulic barrier, and to determine the effects of frost on the material properties of the hydraulic barrier, as well as on the functioning of the whole structure.

The monitoring of the test structure includes measuring the amount and quality of the water infiltrating through the structural layers, settlement, temperature and peat ash water content measurements (Fig. 3).

The settlement of the test structures from June 1999 to May 2000 was between 0.22 and 0.32 m. In both test structures, the greatest settlement was in the middle of the structures. In test structure 1, the maximum frost depth was approximately 0.8 m in February, when 0.6 m of the peat ash surface layer was frozen. During November – April, a significant temperature gradient (approximately 5 – 7°C) in the peat ash surface layer was noticed. The temperature difference is related to the low thermal conductivity, which is about 0.35 – 0.55 W/Km at the present density and water content (Jauhiainen 1999). The temperature of the waste fill during the period varied between 6.5 and 14.4°C (Fig. 4).

In test structure 2, the maximum depth of frost was approximately 0.8 m in February. At the time, the 500-mm thick peat ash surface structure was completely frozen. The temperature of the waste fill in test structure 2 during the period varied slightly more (between 4.8 and 14.1 °C) than the temperature of the waste fill in test structure 1 (Fig. 4).

No significant changes occurred in the volumetric water content of the peat ash layers in test structures 1 and 2. In both test structures, the volumetric water content of the hydraulic barrier (46 to 48 %) was higher than the volumetric water content of the surface layer (32 to 42) during the observing period June 1999 to May 2000.

In December, it was observed that through the surface structure of the test layer 1, about 0.5 l of water had infiltrated. In other lysimeters no water was noticed during the observation period. The rainfall during June-December was 454 mm in total in Rovaniemi. On the basis of the analysis, the pH of the water was high (11.97). The concentration of heavy metal in the infiltrated water were extremely small (Table 4).

Table 4. Results of the analysis of water infiltrated through the surface layer.

Properties	Value	Unit
pH	11.97	
Electrical conductivity	766.0	mS/m
Copper	267	µg/l
Arsenic	0	µg/l
Nickel	45	µg/l
Chrome	649	µg/l
Zinc	4	µg/l
Cadmium	0	µg/l

CONCLUSIONS

On the basis of the results and experience obtained, both technical and environmental properties enable peat ash to be used in the tested applications. In order to determine and ensure the long-term durability, continuing the monitoring of the test structures is essential. The long-term behaviour of peat ash in different applications will finally determine the application-specific life cycle costs, which determine the technical and economical competitive ability of different utilisation alternatives.

According to the present environmental legislation in Finland, peat ash is classified as waste. The research and development projects implemented, as well as the monitoring measurements in progress will enable the analysing the physical and chemical functioning of the structures with numerical models. The analysis of the water infiltrated through the peat ash layer showed that the solubility of heavy metals *in situ* was very low. To help in decision making, risk analysis can be performed on the basis of these preliminary results and experiences.

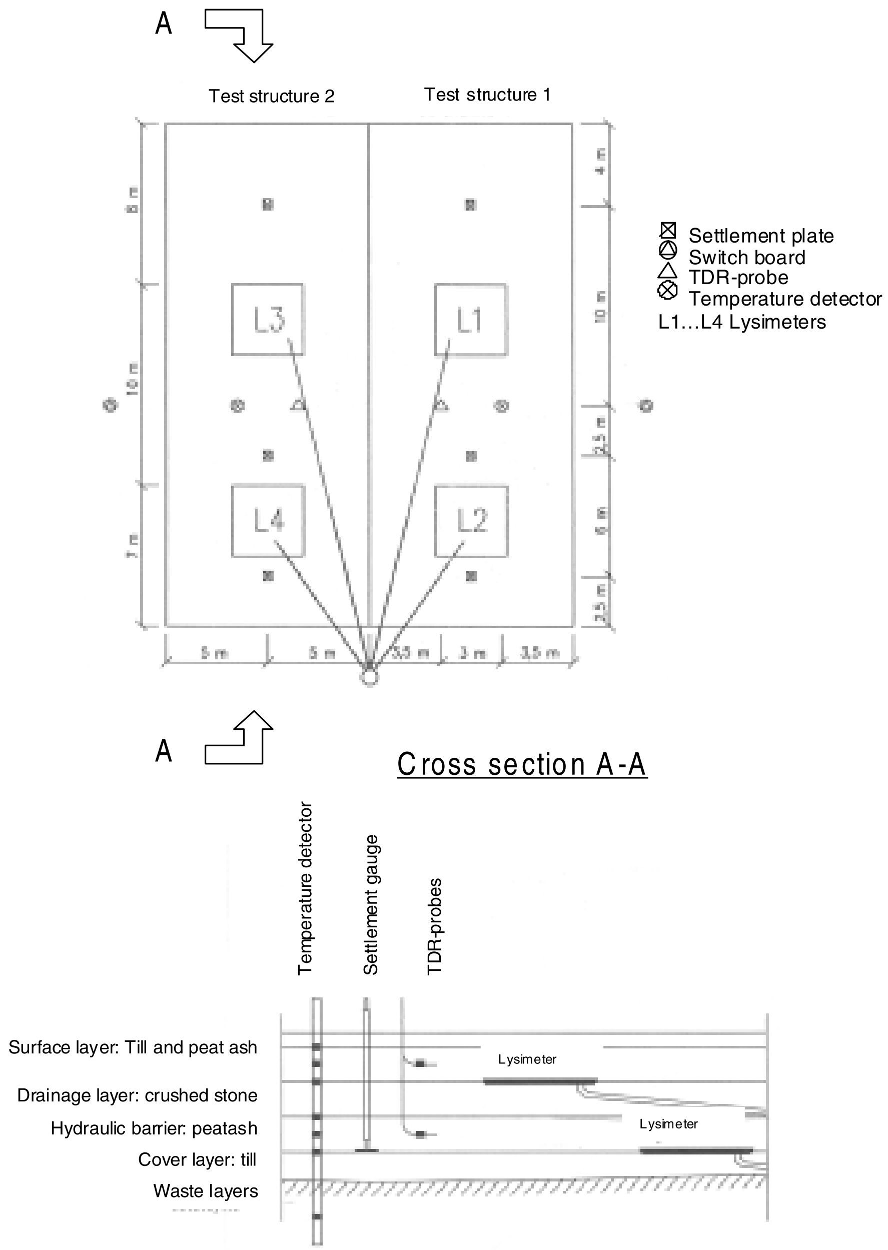

Figure. 3. Instrumentation of the test structure.

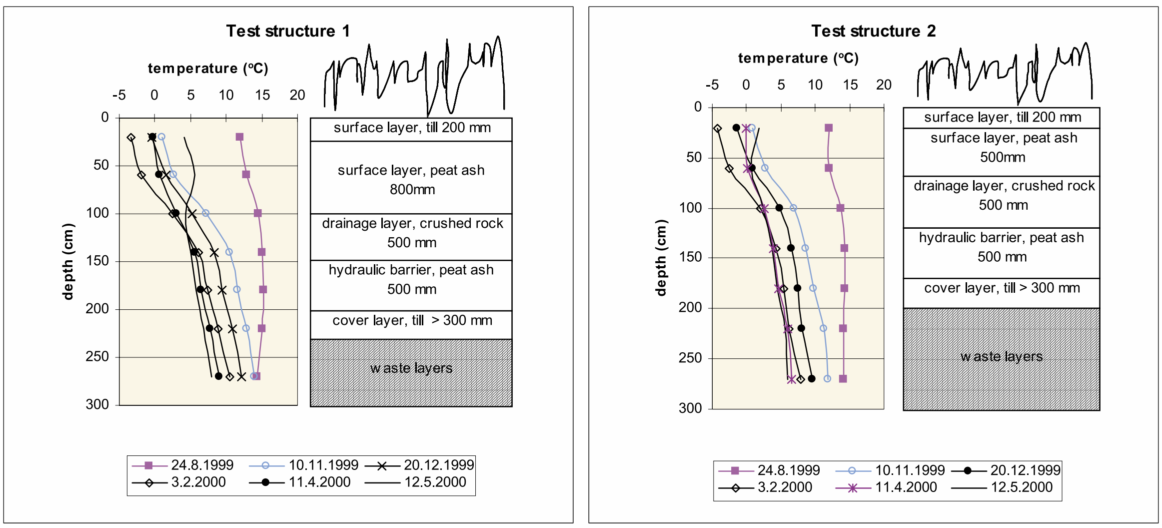

Figure. 4. Temperature profiles of test structures 1 and 2 during the observation period.

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Geological Survey of Finland, Special Paper 32, 91–98, 2001.

DEFINITION OF ENVIRONMENTAL CRITERIA FOR INDUSTRIAL BY-PRODUCTS USED IN EARTH CONSTRUCTION

by
Jaana Sorvari and Jyrki Tenhunen

Sorvari, Jaana & Tenhunen, Jyrki 2001. Definition of environmental criteria for industrial by-products used in earth construction. *Geological Survey of Finland, Special Paper 32, 91–98,* one figure and 2 tables.

At present in Finland, Dutch methodologies and criteria are frequently employed in the environmental assessment of by-products used in earth construction. A study was initiated in order to develop a national code of practice. A hierarchical procedure including composition and solubility standards was elaborated. Derivation of solubility criteria (MPEs) was based on Dutch leaching models and Finnish target values of soil. Conservative risk assumptions were used as a starting point in the definition of parameter values. Different MPE alternatives were created by altering the values of the parameters defining an acceptable load to soil. A risk-benefit analysis was executed by using a decision analysis (the SMART method) in order to identify the best MPE alternative. Land use, uncertainties in analytical methods and non-uniformity of the target values (soil) were considered in the definition of the final MPE values. The proposed solubility standards differ slightly from the corresponding Dutch values. On the basis of the results of previous leaching tests, water-cooled blast-furnace slag and crushed concrete can be considered as readily recyclable, whereas most of the fly ashes from coal combustion could be used only in a monolithic i.e. prefabricated form.

Keywords: construction materials, by-products, earthworks, risk assessment, solubility, standards, Finland

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INTRODUCTION

Significant amounts of natural mineral aggregates such as rock, gravel and sand are used annually in earth construction in Finland. In industrial activities, several wastes having suitable technical properties for use as a substitute for primary materials are produced. Materials employed traditionally in earth construction include blast-furnace slag (BFS), crushed concrete from demolition works and fly ash from energy production. Environmental compliance is a key factor in the assessment of reusability of different by-products.

In Finland, the use and disposal of by-products is mainly regulated by the Waste Act. All industrial by-products are considered to be wastes and normally an environmental permit must be obtained in order to reprocess, reuse or recycle them in a large scale. As an exception to this practice, a simpler notification procedure exists for experimental construction projects. Depending on the amount of a by-product, the permit is granted by a regional environmental centre or by a municipality. The permits have been granted on a case-by-case basis and the process has been regarded as time-consuming and laborious. Since for the time being there has not been any official code of practice concerning the definition of environmental suitability of by-products, practices of acceptance as well as foundations of the decisions have varied. Different leaching tests and environmental criteria based mainly on the 100-fold quality standards of domestic water have been employed. During recent years, Dutch test methodologies and criteria have been widely adopted. The Dutch guidelines and standards are based on the Dutch legislation and environmental conditions and as such are not directly applicable to Finnish conditions. The definition of unified national environmental guidelines has been considered an important development need.

DEVELOPMENT OF A CODE OF PRACTICE

Principles

The basis of the development of environmental criteria was the existing or prospective Finnish legislation. Following the legislation, priority was given to the prevention of ground water contamination. This protection is accomplished by limiting the use of by-products outside the classified aquifer areas. The second principle was the prevention of soil contamination. This is achieved by issuing substance-specific limit values, which define an acceptable, negligible emission to soil.

The primary condition for the reusability of a by-product is that it may not be hazardous, which means that it must be disposable in a landfill designed for non-hazardous wastes.

Structure

A hierarchical procedure has been proposed for the definition of environmental compliance of by-products (Sorvari 2000). According to this model, environmental acceptability can be assessed on different levels depending on the characteristics of a by-product. Numeric criteria have been issued for each of these levels. These criteria are, however, applicable only to non-sensitive areas which receive background load *e.g.* traffic areas, commercial districts and equivalent regions in general.

At the highest assessment level, the composition of a by-product is compared with the composition standards corresponding to the target values characterizing a clean soil. If these values are exceeded, as is normally the case, the solubilities of harmful substances must be examined with leaching tests. The NEN 7343 column test and the NEN 7345 diffusion test should be used as primary test methods. Solubilities in various, relevant pH conditions should be studied as well. The test results are compared with the solubility standards, i.e. Maximum Permissible Emission (MPE) values. If these are exceeded, the by-product in question can be studied further by using a case-specific risk assessment (RA) procedure. In the RA, environmental conditions (*e.g.* transportation and exposure routes, recipients) and the long term stability of the material are taken into account. This study can be material-specific or site-specific. If it can be stated that there is no harm to human health or to the environment, it is allowable to use the by-product at a site equivalent to the one characterized in the RA. The methodologies, methods and contents of risk assessments are not defined in this context since separate national guidance has been prepared elsewhere (Sorvari & Assmuth 1998, Wahlström *et al.*, 1999).

No MPE values are given for organic substances, because there is no consensus concerning suitable leaching test methods. If organic substances are present, environmental suitability can be defined only by a comparison with the target values of soil and a detailed risk assessment procedure.

The composition of a by-product is also compared with the limit values of soil. If these values are exceeded, the definition of environmental suitability should not be exclusively based on solubility, but the stability of the material (possible changes in properties), additional, relevant transportation routes and possible direct exposure routes (*e.g.* inhalation of dust during construction etc.) must be taken into account.

DEFINITION OF SOLUBILITY STANDARDS (MPE VALUES)

MATERIALS AND METHODS

Dutch leaching models presented by Aalbers *et al*. (1996) were used in the derivation of the MPE values for metals. These models are based on extrapolation and interpolation of laboratory scale measurements and the definition of a maximum permissible load to soil (Eqs. 1…4).

Granular materials:

$$E_{max} = E_{soil} + \frac{I_{max}}{d_c \times h \times f_{ext,n}} \quad (1)$$

$$I_{max} = \frac{\alpha}{100} \times T_s \times \rho_s \times h_s \quad (2)$$

$$f_{ext,n} = \frac{1 - e^{-\kappa \times \frac{J \times N_i}{d_c \times h}}}{1 - e^{-\kappa \times 10}} \quad (3)$$

Monolithic materials:

$$E_{max} = \frac{I_{max}}{f_{ext,v} \times f_{temp}} \quad (4)$$

Where

E_{max} = maximum allowable emission (of an individual substance) determined by the NEN 7343 column test (mg kg $^{-1}$) or the NEN 7345 diffusion test (monolithic materials)

E_{soil} = substance-specific correction factor corresponding the leaching of an individual substance from soil (mg kg^{-1})

I_{max} = maximum allowable immission (of an individual substance) in soil during J years (mg m^{-2})

d_c = dry density of a waste material (kg m^{-3})

h = total thickness of a waste material (i.e. the sum of separate construction layers consisting of the same waste material) (m)

$f_{ext,n}$ = factor for the extrapolation from the time representing the duration of the leaching test to J years

α = factor representing the marginal burdening of soil (i.e. acceptable increase in the concentration of an individual substance in soil) (%)

T_s = target value of soil (mg kg^{-1})

ρ_s = dry density of soil (kg m^{-3})

h_s = thickness of the soil layer underneath a by-product structure (m)

J = duration of the emission to soil (yr)

N_i = infiltration through the structure made of waste (mm yr^{-1})

κ = substance-specific slope of the regression line representing the leaching function which has been transformed to a linear model

$f_{ext,v}$ = factor for the extrapolation from the time representing the duration of the diffusion test to J years; wetting period, exhaustion and changes in the diffusion coefficient are taken into account in the definition of the factor

f_{temp} = correction factor for the difference between the temperature in the laboratory and the temperature at site.

The definition of an acceptable load is founded on the target values of soil. Parameter values describing conditions in Finland, *e.g.* soil characteristics, weather conditions and the properties of by-products were employed in the calculations. The information on the variables was gathered from several sources and calculations were performed by using a Monte Carlo technique. Separate MPE values were calculated for different applications (granular vs. monolithic material, unpaved vs. paved structure). The time scale was fixed to 100 years and the thickness of a by-product layer to 0.7 m. MPE alternatives were created by modifying the values of those parameters which describe the "permissible load", i.e. the acceptable increase in the concentrations of contaminants in the soil underneath a by-product structure (á, % compared with the target values of soil) and the depth of a soil layer below a by-product structure (h_s, m). Conservative values such as á = 1 % and h_s = 0.2 m were used as a starting point.

Finnish soil is both horizontally and vertically very heterogeneous. The main soil type is sandy till, which represents 75 % of all tills (Koljonen 1992). Altogether 54 % of the total land area is covered by till in thick layers. Therefore, variables describing the soil type till were selected for the calculations.

A sensitivity analysis was carried out in order to test the sensitivity of the calculated MPEs to the variability of parameters. For some metals, the national target values of soil are defined according to the content of clay and organic matter in soil. For this reason, the sensitivity analysis had to be performed separately for each individual substance.

For those contaminants lacking a soil target value *e.g.* sulphate and chloride, MPE values were derived from the national quality standards issued for domestic water. The target value for chloride is 25 mg l^{-1} and the corresponding quality criteria for sulphate is 150 mg l^{-1}.

Sample size in the Monte Carlo calculations was defined according to an acceptable uncertainty in the medians of the MPE values. Here, the range of +/-2 percentiles was selected, leading to a sample size of 2500.

Decision analysis

For metals, the best alternative of the groups of MPEs was defined by using a SMART method (Simple Multi-attribute Rating Technique) and the methodology employed in a previous study on the selection of a water supply system (Tenhunen & Seppälä 1996). The SMART method has been described in detail by Von Winterfelt and Edwards (1986). Along with the environmental risk, social and economic benefits, i.e. savings in natural resources and landfill space, construction costs as well as social disadvantages were taken into account (Fig. 1).

Indexing (to a range from 0 to 100) of the values given for each decision criterion was executed on the basis of an assumption of linear regression. The sum of each individual indexed value (x_i) multiplied by the criterion-specific weighting factor (w_i), represents the total value of the corresponding group of MPEs. This total value describes the superiority of one alternative compared with the others

The analysis was performed for a 12 m wide road structure containing either natural mineral aggregates (sand, gravel), fly ash from coal combustion or crushed concrete in the base course. Information on the consumption of each by-product was taken from a previous life cycle assessment report (Eskola *et al.* 1999). Several experts representing material producers and waste management and construction companies were interviewed in the collection of the data concerning the costs of construction and landfill disposal.

In the definition of values for the decision criterion "amount of waste ending up in a landfill", it was assumed that all the material which is not environmentally acceptable (i.e. at least one of the substance-specific MPEs is exceeded) is disposed to a landfill. The value of the decision criterion "social disadvantages" was expected to correspond to the amount of the recycled by-product.

The definition of separate MPE alternatives was based on the variability of the parameters á and h_s (see above) and the prognosis of recycling potentiality (% of the total mass of the by-product produced) of the fly ash and crushed concrete in different structures (paved and unpaved structure, granular and monolithic material). The prognosis was estimated from the results of previous leaching tests collected from several information sources around the country.

Weighting of the decision criteria was carried out by representatives of the Ministry of the Environ-

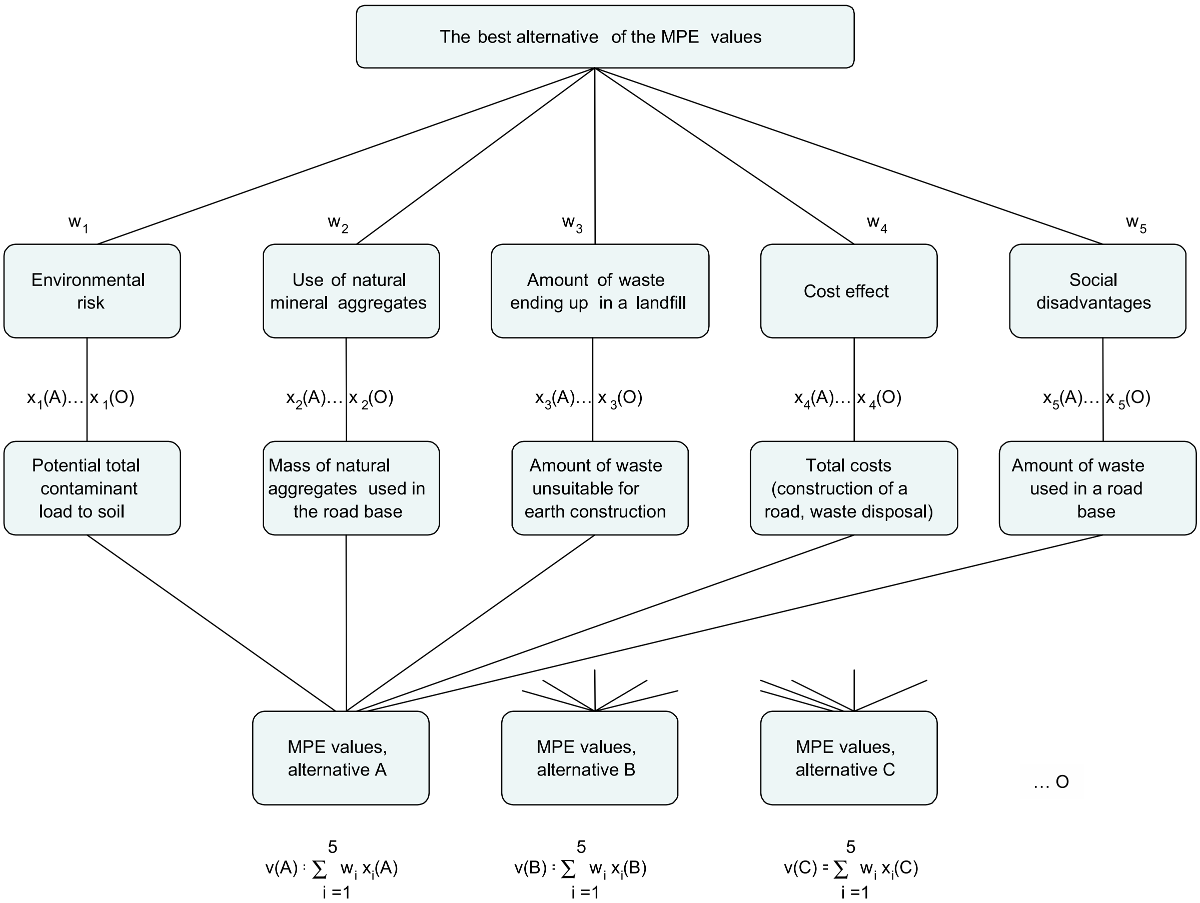

Figure 1. Decision criteria used in the decision analytical study of the different alternatives (A…O) of solubility standards i.e. MPE values (Maximum Permissible Emission). w_i = weighting coefficient of an individual decision criterion i (i = 1…5), $x_i(A)$… $x_i(O)$ = indexed numerical value of a decision criterion i (i = 1…5) corresponding to an alternative representing a separate group of MPEs (A…O), v(A)…v(O) = total value of an alternative representing a separate group of MPEs (A…O).

ment. Since the Ministry is responsible for the prescribing of national environmental criteria, the involvement of other stakeholders such as industrial representatives, users of by-products etc. was considered unnecessary.

Results

According to the results of the sensitivity analysis, the key parameters in the definition of MPE values are those which define the acceptable load to soil underneath a by-product structure that is parameters á, h and h_s. For paved structures, the time scale (J) was also critical and in the case of a monolithic material the density of soil was decisive as well. When all the variables defining the acceptable load (J, á, h, h_s) were fixed, density of soil and by-product, substance-specific constants describing leaching behaviour (ê) and infiltration rate (N_i, mm a^{-1}) were identified to be the key parameters. In the category of monolithic materials, correction factors taking weather conditions into account ($f_{ext,v}$ and f_{temp}) were important. The results of a sensitivity analysis depend significantly on the selection of parameter values (i.e. extreme values, statistical variables and the shape of the distribution).

In the decision analysis, the criterion “environmental risk” received a weighting coefficient of 0.75 and the criterion “use of natural mineral aggregates” a coefficient of 0.25, respectively. Coefficients of other decision criteria obtained the value 0, meaning that they were not regarded as important factors. Aspects such as the type of land use and uncertainties in analytical methods (soil and waste analyses, leaching tests) were considered in the final definition of the MPEs. Furthermore, the non-uniformity of the national target values was also taken into account. The resulting group of MPE values corresponds to the marginal load defined as “a load that can cause a 5 % increase of concentrations (clean soil) in the 1 m thick soil layer underneath a by-product structure”. Due to the non-uniformity of the national target values of soil, the corresponding Dutch guideline values were used in the calculation of the MPEs of Ba, Co, Ni, Sb, and Sn. The final solubility criteria are presented below (Table 1).

Table 1. Proposal for the solubility standards for by-products used in earth construction.

Substance	Granular material Uncovered, mg kg^{-1}	Granular material covered, mg kg^{-1}	Monolithic material mg m^{-2}
As	0.14	0.85	58
Ba	10	28	2800
Cd	0.011	0.015	2.1
Co	1.1	2.5	280
Cr	2.0	5.1	550
Cu	1.1	2.0	250
Hg	0.014	0.032	1.6
Mo	0.31	0.50	70
Ni	1.2	2.1	270
Pb	1.0	1.8	210
Sb	0.12	0.40	36
Se	0.060	0.098	14
Sn	0.85	3.1	280
V	2.2	10	700
Zn	1.5	2.7	330
F	11	25	2800
CN, free	0.060	0.098	14
SO_4	1500	–	–
Cl	250	–	–

CONCLUSIONS

On the basis of this study, new national environmental criteria for the use of by-products in earthworks were proposed. The final solubility standards differ from the corresponding Dutch values and are mainly less strict than the solubility standards issued in some other countries (Table 2). This distinction is due to differences between 1) analytical methods (especially leaching tests) 2) the bases, foundations, methods and principles of the assessment and definition of risks/load and 3) the risk management and waste management policies.

Disparities between the proposed Finnish criteria compared with the corresponding Dutch standards are mainly due to the differences in the national target values of soil, in the definition of an acceptable load and in environmental conditions. Especially the standards issued for paved structures differ from the corresponding Dutch solubility criteria. This is due to the difference in infiltration rates. In this study, a value of 34 mm a^{-1} was employed for paved structures, representing 10 % of the infiltration rate through unpaved structures. In the Netherlands the corresponding value has been 6 mm a^{-1}.

In respect of the proposed solubility criteria, the use of granular fly ash (from coal combustion) will be limited. Especially the concentrations of soluble selenium and molybdenum usually exceed the corresponding MPE values. Further studies are needed in order to determine the significance of Se and Mo loads. However, solubility can be minimized by using a binding material such as cement. On the other hand, according to the results of some previous leaching tests, water-cooled BFS and crushed concrete can be considered environmentally acceptable without any additives.

The Dutch method, which was used for the derivation of MPEs, has the disadvantage of being very sensitive to variables for which it is not possible to define scientifically incontestable and “correct” values (referring to the parameters which specify the acceptable load to soil). The definition of the MPE values for monolithic structures is based on simple equations and the results are very sensitive to the definition of some correction factors which characterize environmental conditions. Furthermore, mixture effects, speciation of contaminants and pH variations are not taken into account. The

Table 2. Some solubility standards issued in different countries (mg kg^{-1}). All values have been transformed to equivalent units by using the L/S-ratio of the corresponding leaching test. a) unpaved b) paved structures. (ÖNORM S 2072 1990, LAGA 1995, Aalbers 1996, Department of Natural Resources 1999, Rasmussen 1999).

Substance	Finland		the Netherlands		Germany, dw		fs	Austria	Denmark	USA, Wisconsin	
	a)	b)	a)	b)	a)	b)	b)	a)	b)	a)	b)
As	0.14	0.85	0.88	7.0	0.10	0.50	0.60	1.0	0.016	0.20	10
Ba	10	28	5.5	58	-	–	–	10	0.60	16	40
Cd	0.011	0.015	0.032	0.066	0.02	0.10	0.10	0.05	0.0040	0.020	0.10
Co	1.1	2.5	0.42	2.5	-	–	1.5	1.0	–	–	–
Cr	2.0	5.1	1.3	12	0.30	–	3.0	1.0	0.020	0.40	2.0
Cu	1.1	2.0	0.72	3.5	0.50	2.0	–	10	0.090	5.2	26
Hg	0.014	0.032	0.02	0.076	0.0020	0.020	–	0.020	0.00020	0.008	0.040
Mo	0.31	0.50	0.28	0.91	-	–	1.5	-	–	–	–
Ni	1.2	2.1	1.1	3.7	0.50	1.0	2.0	1.0	0.020	0.80	2.0
Pb	1.0	1.8	1.9	8.7	0.40	1.0	–	1.0	0.010	0.06	0.30
Sb	0.12	0.40	0.045	0.43	-	–	–	–	–	–	–
Se	0.06	0.098	0.044	0.10	-	–	–	0.50	–	0.4	0.10
Sn	0.85	3.1	0.27	2.4	-	–	–	10	–	–	–
V	2.2	10	1.6	32	–	–	6.0	2.0	–	–	–
Zn	1.5	2.7	3.8	15	1.0	4.0	10	30	0.20	100	200
F	11	25	13	100	-	–	–	30	–	32	80
CN, free	0.06	0.098	0.013	0.076	-	–	–	0.20	–	1.6[1]	4.0[1]
SO_4	1500	–	750	22000	1500	6000	–	varies[2]	500	5000	10000
Cl	250	–	600	8800	200	1500	–	varies[2]	300	5000	10000

dw = demolition waste, fs = foundry sand; [1]total cyanide; [2]depends on the electric conductivity

definition of permeability in the case of a paved road structure is problematic because of possible crack formation and infiltration through ramps.

The quantitative data on chemical properties of Finnish by-products was somewhat inadequate. The national target values of soil should be unified. The knowledge concerning adaptation of soil organisms, mixture effects, accuracy of leaching models and long-term behaviour of soluble substances is also insufficient.

The proposed environmental criteria have been used as a basis in the preparation of the Council of State Decree, by which some by-products can be exempted from an environmental permit process. Along with this preparation work, the development of quality assurance procedures is continuing.

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PROBABILISTIC RISK ASSESSMENT OF A CONTAMINATED SITE

by
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Kuusisto, S. M. & Tuhkanen, T. A. 2001. Probabilistic risk assessment of a contaminated site. *Geological Survey of Finland, Special Paper 32, 99–105*, one figure and 5 tables.

The results of deterministic and probabilistic risk assessment at a contaminated site were compared. The deterministic point estimates of the incremental lifetime cancer risk following exposure to dioxin/furan and PCB-contaminated recreational site were 1×10^{-4} for dioxins/furans and 3×10^{-5} for PCBs. The point estimates located at the 99.8 and 97.3 percentiles in the probabilistic range of risk. The distribution means were 4×10^{-6} for dioxins/furans and 4×10^{-6} for PCBs. The point estimates highly overestimated the risk, whereas, the probabilistic approach revealed valuable information regarding the possible distribution of risk. Clean-up levels corresponding risk level of 10^{-6} were also calculated. The point estimates were 5.5 ng TCDD-equivalents/kg soil and 0.5 mg PCBs/kg soil. The 5^{th} percentile values, which are protective for 95 % of the population, were 11.6 ng TCDD-equivalents/kg soil and 0.4 mg PCBs/kg soil. The sensitivity analysis revealed that the soil concentration data is the dominating parameter when it comes to the uncertainty in this assessment.

Keywords: risk assessment, soils, pollutants, dioxins, PCBs, sensitivity analysis

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INTRODUCTION

The traditional way of doing risk assessment is to use single value best estimates for each parameter in risk calculation. This deterministic approach rarely represents the real life situation. Most of the parameters are variable in nature; for example, people who are *exposed* weigh different amounts. Furthermore, many of the exposure assumptions are unknown. The major shortcoming in deterministic approach is the ignorance of the elementary features of exposure parameters, which are the variability and uncertainty.

Because of this variability and uncertainty, most of the input values are really random variables, which can take any value in a range of values, with a certain probability of occurrence. This probabilistic nature of parameters is taken into account in probabilistic risk assessment. (Burmaster 1995)

This paper presents the use of probabilistic risk assessment in a case of contaminated site. Results of the probabilistic approach are compared to the results of the traditional deterministic approach. Carcinogenic risk and risk-based cleanup levels are calculated.

The most commonly used probabilistic method in health risk assessment is the Monte Carlo simulation. In the Monte Carlo simulation, numbers for parameters are generated according to their distributions and risk equation is solved repetitively.

METHODS

The point estimates for the risk where calculated using a deterministic approach recommended by the U.S. EPA (U.S. EPA 1989). Probabilistic risk assessment was done by Monte Carlo Simulation with Latin Hypercube Sampling using Crystal Ball® 4.0 spreadsheet program (Decisioneering). Exposure parameters were approximated by probability density functions (PDFs) found from the literature. PDFs for contaminant concentration data was evaluated using the Kolmogorov-Smirnov goodness-of-fit test and the Maximum Likelihood Estimation in Crystal Ball program.

Sensitivity analysis was done calculating a contribution to variance for each exposure parameter. Contribution to variance is determined by squaring the rank correlation coefficient and then normalizing to 100 % (Decisioneering).

EXPOSURE ASSESSMENT

The contaminated area is a part of a recreational area planned to serve the inhabitants of nearby residential areas. A wide variety of industrial and commercial activities has taken place in the area. The current contamination is mainly due to dumping of fly ash from a waste incinerator. The major contaminants in fly ash are polychlorinated dibenzodioxins and dibenzofurans (PCDD/PCDF), polychlorinated phenols (PCBs), lead (Pb), zinc (Zn), and copper (Cu). Cancer risk following exposure to PCDDs/PCDFs and PCBs is assessed in this case study.

Probability density functions for soil concentration data were approximated from the site data. Soil concentration data from earlier years was used (Paavo Ristola 1988, 1997). A lognormal distribution was chosen to represent concentration data based on goodness-of-fit data and personal judgement. The 95th percentile concentrations were selected as the point estimates. Distribution parameters for soil concentrations are given in Table 1.

Table 1. Point estimates and distribution parameters for soil concentrations.

Chemical	Units	Point estimate	Distribution type and distribution parameters[a]
PCDD/PCDF as TCDD-equivalents	(ng/kg)	643	Lognormal (μ = 174 σ = 392 95% = 643)
PCB	(mg/kg)	12	Lognormal (μ = 3,69 σ = 42,2 95% = 12,16)

[a] Distribution parameters of underlying normal distribution X = ln [X].

The contaminated fly ash is covered with clean sand and gravel. The goal of this paper is to evaluate the usefulness of probabilistic risk assessment compared to the traditional deterministic approach. Therefore, in order to simplify the exposure assessment the risk was assessed as if no clean cover exists.

Ingestion of soil, dermal contact, and ingestion of mother's milk where chosen as possible exposure pathways. Inhalation and ingestion of particles in air contributed less than 1% to the total exposure, and were therefore not included here. The lifetime average daily doses for each pathway was calculated using equations 1, 2 and 3, adapted and modified from the U.S. EPA guidelines (U.S. EPA 1989). The equation for the exposure via mother's milk was adapted from CalTox (CalTox 1993a).

$$DI = \left[\left(\sum_{i=m}^{n} \left(\frac{IR_i}{BW_i} \times \frac{t_i}{10} \right) \times EF_c \times U \times ED_c \right) + \left(\frac{IR_a}{BW_a} \times EF_a \times ED \right) \right] \times CS \times CFS \times \frac{1}{AT} \qquad (1)$$

$$DD = \left[\left(\sum_{i=m}^{n} \left(SA_i \times \frac{t_i}{10} \times FSA_i \right) \times EF_c \times ED_c \times RT \right) + \left(SA_a \times FSA_a \times EF_a \times ED_a \right) \right] \times CS \times CF \times AF \times FC \times \frac{1}{AT} \qquad (2)$$

$$DM = C_{bmilk} \times \left[\frac{IR_{bm}}{BW} \right] \times \frac{EF \times ED}{AT} \qquad C_{bmilk} = I_{mo} \times BW_{mo} \times B_{bmk} \qquad (3)$$

Where

DI = lifetime average daily dose following ingestion of soil (mg/kg-day)
DD = lifetime average daily dose following dermal contact with soil (mg/kg-day)
DM = lifetime average daily dose following ingestion of mother's milk (mg/kg-day)
IR = the soil ingestion rate (mg/day)
BW = the body weight (kg)
ED = the exposure duration (years)
U = the amount of days when the soil is unfrozen (days/year)
CS = the contaminant concentration in the soil (mg/kg)
EF = the exposure frequency (days/year)
CFS = the conversion factor (10^{-12} kg/ng)
AT = the averaging time (days)
SA = the skin area as a function of body weight (cm^2/kg)
FSA = the fraction of skin area exposed
AF = the soil adherence factor (mg/cm^2)
FC = the fraction of soil that is contaminated
C_{bmilk} = the chemical concentration in mother's milk (mg/l)
IR_{bm} = the amount of mother's milk ingested (l/d)
I_{mo} = the mother's total exposure (mg/kg-d)
B_{bmk} = the ratio of chemical in milk and mother's exposure (d/kg-milk)

Subscript *c* denotes a child, and *a* denotes an adult. Input parameters are shown in Table 2.

The results of exposure assessment are shown in Table 3. Only the pathways contributing more than 1 % to the overall exposure are shown.

Table 2. Variables and constant used in exposure assessment.

Parameter	Point estimate	Distribution parameters and type		Reference
IR (mg/d)				
< 6 years	179	μ = 179 95% 208	LN	U.S. EPA 1996
Adult	480	–	–	U.S. EPA 1996
BW (kg)			LN	Burmaster & Crouch 1997
1–2 years	11.8	μ = 11.8 σ = 1.9		
7–8 years	25.1	μ = 25.1 σ = 3.9		
35–44 years	80.9	μ = 80.9 σ = 13.4		
U (d/year)	273	min = 204 max = 355 likeliest = 273	TR	Huttunen & Soveri 1993
EF_c (d/year)	1	min = 0.2 max = 1.0	U	Personal judgement
EF_a (d/year)	40	min = 20 max = 60	U	Personal judgement
ED_c (years)	10	μ = 11.36 σ = 13.76 truncated at 10 years	LN	Israeli & Nelson 1992
ED_a (years)	10	μ = 11.36 σ = 13.76	LN	Israeli & Nelson 1992
AT (years)	75	min = 73 max = 79.5	U	U.S. EPA 1996
SA (cm^2/kg-d)			LN	Burmaster 1998
1–2 years	5.77	μ = 5.77 σ = 1.30		
7–8 years	14.84	μ = 14.84 σ = 2.26		
35–44 years	52.90	μ = 52.90 σ = 9.14		
AF (mg/cm^2)	0.52	μ = 0.52 σ = 0.9	LN	Finley et al. 1994c
FC	1	–	–	–
FSA	0.19		U	U.S. EPA 1996
1–2 years		min = 0.057 max = 0.48		
6–7 years		min = 0.047 max = 0.52		
adult		min = 0.052 max = 0.56		
IR_{bm} (kg/kg-d)	0.11	0.11 CV 0.2	LN	CalTox 1993b
EF (d/a)	365	365	–	–
ED (year)	1	–	–	–
BW_{mo} (kg)	64.2	μ = 64.2 σ = 15	LN	Burmaster & Crouch 1997
B_{bmk} (d/kg-milk)				
(PCB)	0.52	μ = 0.52 CV=10	N	CalTox 1993b
(TCDD)	0.92	μ = 0.92 CV=10	N	

μ, mean; σ, standard deviation of underlying normal distribution X = ln [X]; CV, correlation coefficient; LN, lognormal; W, weibull; U, uniform; TR, triangular

Table 3. Exposure to TCDD-equivalents and PCBs through different pathways. Lifetime average daily dose following DI = ingestion of soil, DD = dermal contact with soil, and DM = ingestion of mother's milk (mg/kg-day)

	TCDD-equivalents		PCB		
	DI (mg/kg-day)	*DM* (mg/kg-day)	*DI* (mg/kg-day)	*DD* (mg/kg-day)	*DM* (mg/kg-day)
Deterministic					
Point estimate	6.68×10^{-10}	5.91×10^{-11}	1.25×10^{-5}	2.35×10^{-6}	6.23×10^{-7}
% of total exposure	91.9	8.1	80.7	15.2	4.0
Percentile [a]	98.73	93.19	98.1	93.4	87.8
Probabilistic					
Mean	6.77×10^{-11}	1.36×10^{-11}	1.40×10^{-6}	5.97×10^{-7}	6.73×10^{-7}
Standard deviation	1.97×10^{-10}	7.01×10^{-11}	1.02×10^{-5}	5.68×10^{-6}	1.05×10^{-5}

[a] The location of point estimate at the probabilistic range of exposure.

RISK CHARACTERIZATION

The risk is characterized by considering the exposure, bioavailability and cancer slope factor. The conservative estimate of oral TCDD bioavailability is 100 %. 0.5 – 50 % of TCDD is found to be absorbed in experimental animals (Copeland 1993). For PCBs the oral absorption is assumed to be 90 % (RAIS 1999). The dermal bioavailabilities are 0.1–3 % for TCDD and 0.6– 6 % for PCBs (U.S. EPA 1992). Bioavailabilities were assumed to be uniformly distributed.

Carcinogenic slope factors (CSFs) were entered as point values, so their effect on variability in the risk estimate was not estimated. The used CSFs were 160 000 kg-day/mg (oral) (U.S. EPA 1997), 300 000 kg-day/mg (dermal) (RAIS 1999) for TCDD-equivalents and 2 kg-day/mg for PCBs (IRIS 1999).

Incremental lifetime cancer risks (ILCRs) were calculated using equation 4. The results are shown in Table 4.

$$ILCR = \left[CSF_o \times (B_o \times (DI + DM)) \right] + [CSF_4 \times B_d \times DD] \quad (4)$$

Where

CSF = the cancer slope factor (kg-day/mg)
B = the bioavailability
DI = lifetime average daily dose following ingestion of soil (mg/kg-day)
DD = lifetime average daily dose following dermal contact with soil (mg/kg-day)
DM = lifetime average daily dose following ingestion of mother's milk (mg/kg-day)

Subscript *o* denotes oral and *d* denotes dermal

Point estimates located at the high end of probability distribution and were therefore conservative and overprotective. Mean and median estimates of risk were smaller than the generally acceptable risk 10^{-6}. The probability distributions of estimated risks were found to be lognormally distributed. Lognormal distribution is a positively skewed distribution, that is most of the values are at the low risk end of the distribution.

Table 4. Risk estimates for TCDD-equivalents and PCBs.

	TCDD-equivalents	PCBs
Deterministic		
Point estimate	1.16×10^{-4}	2.65×10^{-5}
Percentile[a]	99.82	97.33
95th percentile	1.33×10^{-5}	1.28×10^{-5}
Probabilistic		
Mean (μ)	3.51×10^{-6}	4.19×10^{-6}
Median	8.82×10^{-7}	2.58×10^{-7}
Standard deviation (σ)	1.28×10^{-5}	3.83×10^{-5}
Coefficient of variability	3.66	9.14
Range minimum	6.02×10^{-10}	2.72×10^{-11}
Range maximum	6.86×10^{-4}	2.49×10^{-3}
Range width	6.86×10^{-4}	2.49×10^{-3}

[a] The location of point estimate at the probabilistic range of risk.

RISK-BASED CLEANUP LEVELS

Risk-based cleanup levels corresponding to a risk level of 10^{-6} were calculated. One in a million risk is generally though to be acceptable risk. The soil concentration parameter was solved using combined risk and exposure equations. The results are presented in Table 5.

The deterministic estimate of TCDD-equivalent cleanup level is located at the 0.03 percentile, meaning that for only 0.03% of the exposed population the risk will be higher than the acceptable risk of 10^{-6}. The range minimums gives the conservative estimate of soil concentration where the risk is smaller than 10^{-6} in all cases.

Table 5. Risk-based cleanup levels corresponding to 10^{-6} risk.

	TCDD-equivalents (ng/kg)	PCB (mg/kg)
Deterministic		
Point estimate	5.53	0.45
Percentile[a]	0.03	7.56
5th percentile	11.64	0.38
Probabilistic		
Mean (μ)	129.22	1.47
Median	54.56	1.10
Standard deviation (σ)	294.75	1.31
Coefficient of variability	2.28	0.89
Range minimum	2.91	0.12
Range maximum	10 583.30	35.77
Range width	10 580.39	35.77

[a] The location of point estimate at the probabilistic range of risk.

SENSITIVITY ANALYSIS

Sensitivity analysis was done by calculating the contribution to variance for each exposure parameter. Contributions to variance in dioxin/furan risk assessment are shown in Fig. 1. The most important parameter in PCB risk assessment was also the chemical concentration in the soil (contribution 90.7 %). Less important parameters in PCB risk assessment were exposure duration in childhood and adulthood (contributions 4.0 and 1.3 %, respectively).

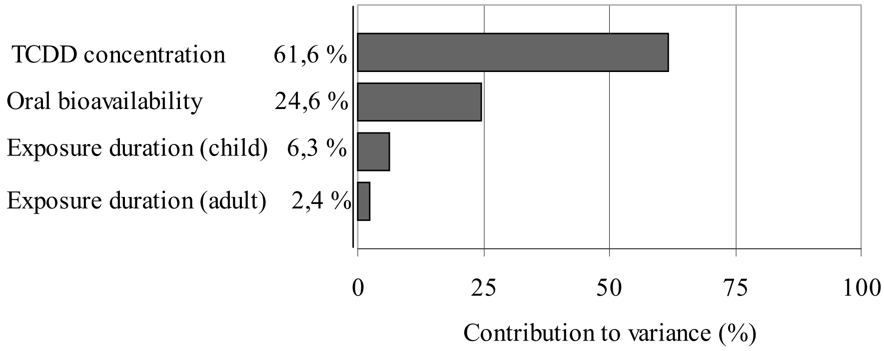

Figure 1. Contributions to variance in dioxin/furan risk assessment. Parameters contributing more than 1% are shown.

CONCLUSIONS

Relatively high deterministic estimates of risk were achieved. However, the probabilistic assessment revealed that these estimates were conservative. The 95th percentiles (for 95 % of the exposed population, the risk is smaller than this value) for both TCDD-equivalent and PCB exposure were 10^{-5}. The medians (50 % of the population experience higher risk) were two orders of magnitude smaller (10^{-7}).

Due to the lognormal shape of risk distribution, majority of the exposed population experience low risk and only a few people are at higher risk. The small high-risk minority will be protected if management decisions are made based on the deterministic assessment. This becomes questionable in cases where resources are scarce but will remain an acceptable approach if resources are not the limiting factor.

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DEVELOPMENT OF SIMPLIFIED PROCEDURES FOR THE SAMPLING OF CONTAMINATED SOILS

by
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Kimura, Takashi, Iwamoto, Hiroshi,Hatanaka, Munenori & O-hara, Junryo 2001. Development of simplified procedures for the sampling of contaminated soils.*Geological Survey of Finland, Special Paper 32, 107–113,* ten figures and 2 tables.

Three simplified procedures for sampling contaminated soils were developed. They are portable, easy to set up and can be operated under space and time restrictions. They are as follows:

a) A sampling method without using drilling mud: A sampler with a spiral cutter on its outside surface like a screw was developed. Compared with a conventional sampler not using drilling mud, this sampler needs about half the time for boring.

b) A shallow depth boring device: An electrical rotary type boring machine using the newly developed screw-type sampler was developed for obtaining soil samples from a depth of about 10 to 15 m below the ground surface without using drilling mud.

c) A simple method for surface soil sampling: This method for surface soil sampling was achieved by attaching a newly developed screw-type sampler with a smaller size to a electric hand drill.

These newly developed tools were successfully applied to investigate a TCE contaminated site together with leaching tests by using PID-gas chromatography.

Keywords: environmental geology, soils, pollution, sampling, methods, samples, drilling, Japan

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INTRODUCTION

In Japan, remedial measures to improve the water quality of lakes, rivers and coastal areas have been in place for several decades; and they have been gradually bearing fruit. However, the recognition for pollution of soil and groundwater has been slow so far. Soil pollution has only recently become a serious social problem. At present, related activity has grown to a fever pitch. In addition, investigations and remedial measures for soil and groundwater pollution are based on trial and error in many municipalities and private enterprise.

Investigations are often carried out at sites that are still in use for other purposes and where space and time are restricted. In such cases, conventional sampling methods may cause problems due to noise and vibration during the operation; they also need considerable space. In order to overcome these disadvantages, three new sampling methods were developed and are as follows.

One basic problem related to the sampling of contaminated soil is to prevent contaminated material from spreading to surrounding non-contaminated areas. For this reason, the drilling mud usually applied in conventional sampling methods should not be used. A second problem consists in the generation of heat caused by the drilling. In the case of sampling soils contaminated by volatile organic compounds (VOCs), the generation of heat should be kept to a minimum in order to prevent volatilisation. This led to the development of a sampler with a spiral cutter on its outside surface like a screw. In this way, the drilling ability was improved, and the generation of heat was decreased as the friction of the periphery surface of the sampler was decreased.

For contaminated areas, it is necessary to determine the distribution of contaminated zones with respect to depth. Soil samples have usually to be collected and analysed down to a drilling depth of several tens of metres below the surface of the ground. In this case, a rotary-type boring machine (see Fig. 3) is typically used. This method allows deep sampling in any kinds of soil, and all-core sampling is possible if an appropriate sampler, e.g. a triple tube sampler, is used. Soil samples obtained by this method have excellent quality showing neither disturbance nor shrinkage of the sample. However, since the main body of the boring machine is large and heavy, it cannot operate on narrow sites and the mobility of the machine is not good either. Moreover, the required drilling time and costs per site are high. Therefore, percussion style boring methods like the SCSC (Yamamoto 1994) and Geoprobe (PB Reports 1998) used in Europe and America for the investigation of contaminated soils have been introduced in Japan. However, because they are percussion style, problems of noise and vibration of hammer and compression of the soil samples have been reported (Suzuki 1999). To counter these problems, a simple electrical rotary-type boring machine was developed for investigation of contaminated soils. Using the newly developed screw-type sampler, soil samples from a depth of about 10 to 15 m below the ground surface can be obtained at an excellent quality without using drilling mud.

Initial investigation of contaminated sites usually requires specification of the areas of contamination by taking a large number of soil samples at shallow depths of about 1 to 2 m below the surface. It would therefore be convenient to have an easy and quick method for surface sampling. By attaching the newly developed screw-type sampler with a smaller size to an electric hand drill, such a method for easy collecting was developed.

Finally, a case study using these new tools for a soil contaminated by VOCs (TCE) is reported, together with soil leaching tests and analysis using the photo ionisation detector-gas chromatography (PID-GC) and gas detecting tubes.

SAMPLING METHOD WITHOUT USING DRILLING MUD

The drilling mud used for usual boring method has the function of preventing a collapse of the bored wall. Other functions are to remove and discharge the drilling chips, to reduce the friction resistance force, to cool of drilling bit and so on. However, drilling mud cannot be used in the case of contaminated soils, so it is necessary that there is a substitute for the drilling mud. A casing pipe with an inner diameter larger than the sampler's outer diameter may be installed in order to keep the bored wall stable. In order to compensate for the other functions of the drilling mud, a spiral cutter was added to the surface of the soil sampler, as shown in Fig. 1. With this spiral cutter, discharg-

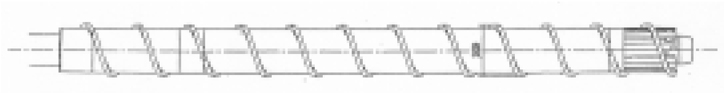

Figure 1. Sampler with a screw-like spiral cutter on its outer surface.

ing and removing of the drilling chips become easy and the generation of heat is decreased. Moreover, the penetration ability in the ground is improved by converting rotary forces into axial forces like a screw nail.

The features of this newly developed screw-type sampler without drilling mud was then tested and compared to those of a conventional sampler. The sampler was improved on the basis of a triple tube sampler system with 99mm outer diameter designed for general use. Because the height of the spiral cutter adds 5mm to either side, the outer diameter of the improved sampler is 109mm. The diameter of the collected soil sample is 71mm. The boring machine used in this sampler test is an oil feed type usually used in boring investigation, and its 100m class of boring ability is a popular type. The test ground is composed of a Kanto loam layer with an N-value of about 5 and a Narita sand layer with an N-value of about 10, shown in Fig. 2, which makes it a typical ground in the Greater Tokyo area. In the test, it was drilled to GL-10m. The situation of the test is shown in Fig. 3.

The length of sampled soil per process is basically 500mm, but lengths of 700mm and 900mm were also tested. 15 soil samples were collected in total. As a result of the test, the length of time required for drilling is only 5 minutes on average for a 500mm sampling length. In the case of 700mm and 900mm sampling lengths, the time required almost doubled. The silty clay with a gravel layer from GL-4.3m to GL-5.7m required about twice the time, but it was still possible to drill to GL-10m. However, below GL-8m the power of the boring machine proved insufficient for the casing pipe of 149.8mm outer diameter that was used to prevent the bored wall from collapsing. This indicates that the outer diameter of sampler and casing pipe should be reduced to make drilling more efficient. There was no temperature increase observed in freshly collected soil samples.

From previous boring investigation carried out near this test site using drilling mud, it was known that conventional boring using drilling mud requires about the same time for soil sampling as the screw-type sampler. Without drilling mud, it takes about the twice the time. It was further assumed that sampling lengths over 500mm would not work because of the friction resistance getting too large.

In order to assess disturbance and shrinkage of

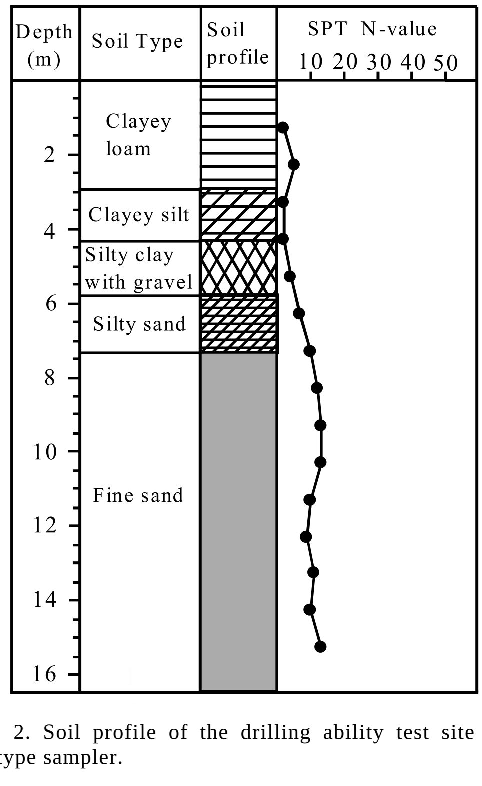

Figure. 2. Soil profile of the drilling ability test site of the screw-type sampler.

Figure. 3. Drilling ability test using the screw-type sampler (Example of a rotary-type boring machine).

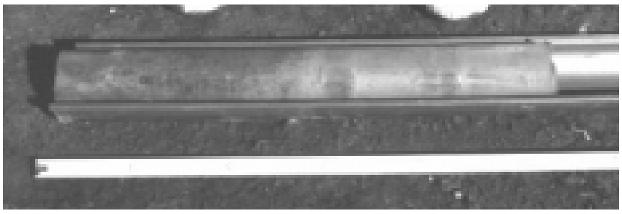

Figure. 4. Example of a soil sample collected by the screw-type sampler.

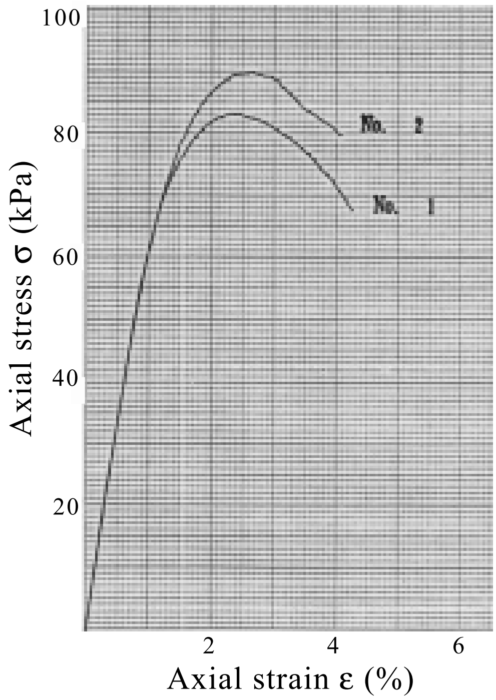

Figure. 5. Example of the uniaxial compression test result for the soil sample collected by the screw-type sampler.

the soil samples, the ratio of the sampled soil length to drilling length was calculated. In the case of the 500mm sampling length, this sampling ratio remained 100% and hence showed no signs of shrinkage. Fig. 4 shows the example of a collected soil sample. But, in the case of the 700mm and 900mm sample lengths, the ratio varied between 93% and 100%. This smaller ratio is assumed to be caused by the inner tube rotating together with the outer tube. One reason may be that the drilling chips fill in the void between both tubes, causing greater friction than with the usual drilling mud in the void. Furthermore, the drain hole in the sampler was disturbed by the drilling chips; this may have hampered the progress of the sampling tube. This problem was solved by installing a sealing mechanism between the inner tube and the outer tube at the top of the sampler.

Several soil tests were carried out using soil samples collected by the screw-type sampler. For the clayey soil, a uniaxial test, consolidation test, and physical test were carried out. In the case of the sand, a liquefaction test, dynamically deformation test and physical test were carried out. On the basis of these test results and the data of ealier tests, it was confirmed that the soil samples collected by the screw-type sampler were undisturbed. An example of the uniaxial compression test result is shown in Fig. 3.

By installing the spiral cutter on the surface of the soil sampler it could be shown that boring without drilling mud, which is the optimum method for investigation of contaminated soils, could be efficiently carried out. Furthermore, it was confirmed that no disturbance occurred, and that soil samples of excellent quality could be obtained. In addition, this sampler makes drilling more efficient and can also be employed in conventional boring using drilling mud.

SHALLOW-DEPTH BORING MACHINE

For the purpose of investigating contaminated soils, a simplified rotary-type boring machine was developed that allows sampling at shallow depths but with excellent mobility. The drilling rod mounted on a metal table moves up and down along a frame as shown in Fig. 6. For the trial, rotation of the rod as well as lifting of the table were powered by two electric motors of 1.0kW and 0.4kW, respectively. The inverter motor allows for smooth regulation of rotational frequency and upward/downward velocity. Noise impact during the drilling was very small, and there was absolutely no vibration either. The machine can be handled by one person because of the wheels attached to the frame. With the described features, the overall weight of the machine was about 160kg.

Drilling tests were carried out on the loam ground with an N-value of between 3 and 5. The drilling depth was 4m. Instead of drilling mud, the newly developed screw-type sampler was used. Because of the small N-value of the sampling ground, there was no problem for drilling using only the dead

Figure. 6. View of the shallow-depth boring machine.

Figure. 7. Shallow depth boring machine mounted on a mini caterpillar.

weight of the boring machine. Soil samples at 600mm sampling length took about 3 minutes. Total time for drilling up to 4m depth required about 90 minutes.

However, once the ground became harder or the drilling bit hit small gravel, it became apparent that the counterweight of the machine's dead weight was insufficient and the boring machine bounced up. Also, although the boring machine was equipped with wheels, the moving of the boring machine was difficult on uneven grounds. To solve these problems, the boring machine was mounted on a compact caterpillar, as shown in Fig. 7. This improvement prevented the machine from bouncing; and operating on uneven grounds became easy. The result of the drilling test under these improved conditions is shown in Table 1.

Drilling mud was not used until a depth of about 6m was reached. Since there was gravel at the depth of from 6m to 7m, the drilling was changed to using drilling mud below this depth, but boring and sampling of soils was possible down to about 15m depth even at N-values of over 10. As Table 1 shows, it took about 3 to 4 minutes to collect soil samples of 700mm length, and there was no shrinkage of the sample. Two persons were sufficient for handling the drilling operation.

This confirmed that the newly developed boring machine was suitable for the purpose of the contaminated soil investigation.

Table 1. Drilling test results of the Shallow Depth Boring Machine.

Sampling Depth (m)	Soil Type	N-Value (estimated)	Sampling Time (minutes)	Sampling Ratio (cm/cm)
0.0 – 0.7	Loam	5	4	65/70
0.7 – 1.4		5	2	65/70
1.4 – 1.8	Clay	5	1	40/40
1.8 – 2.1		5	1	30/30
2.1 – 2.8		5	2	70/70
2.8 – 3.5	Clayey sand	8	2	70/70
3.5 – 4.2		11	3	70/70
4.2 – 4.5		12	5	30/30
4.5 – 5.2		12	9	60/70
5.2 – 5.5		12	6	30/30
5.5 – 5.8		14	5	25/25
6.0 – 7.0		9	6	40/100
7.0 – 7.7		10	3	50/70
9.0 – 9.7		12	5	60/70
11.0 – 11.6		9	4	60/70
14.5 – 14.9		39	3	40/40

Note: sampling ratio = sampling length/boring length

A SIMPLE METHOD FOR SURFACE SOIL SAMPLING

During initial investigation of contaminated sites, identifying the zones of contamination requires that rather large numbers of soil samples be taken at shallow depths of about 1 to 2 m below the ground surface. Hand augers, for example, have been in use for this purpose. However, drilling by man-power requires much time per sampling point as well as considerable input of labour. To overcome this, a simple method for collecting soil samples was developed by making the diameter of the screw-type sampler small enough to be installed on an electric hand drill. The sampler for trial was the improved triple tube sampler, the outer diameter being 50mm and the diameter of the soil sample 23mm. The length of the soil sample was 400mm. This sampler was installed on a 100V electric hand drill, as shown in Fig 8. Drilling and soil sampling was possible as long as the ground was not hard. However, it was impossible to drill through small gravel, and handling below a depth of 1m demanded increased efforts. However, the sampler proved effective for collecting soil samples in the initial stage of investigation. Further improvements are planned to render this sampling method more convenient.

Figure. 8. Surface soil sampling with electric hand drill.

CASE STUDY ON TCE CONTAMINATED SOILS

An investigation of a ground contaminated by volatile organic compounds (TCE) was carried out as the flow chart shows in Figure 4. Since the scope of the contamination had been previously determined by other methods, this part deals with the detailed investigation of the site.

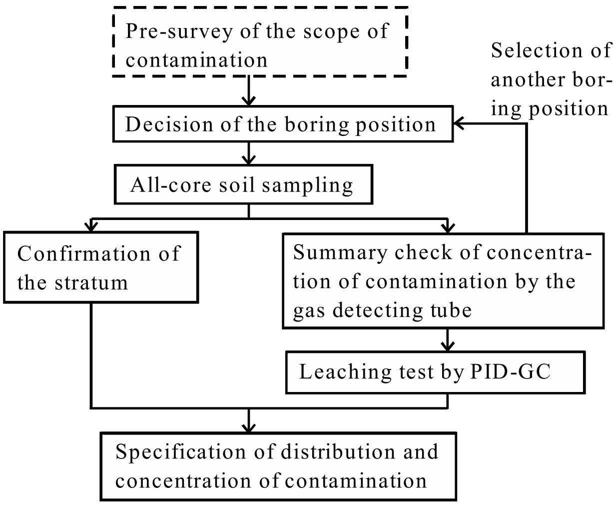

Figure. 9. Flow chart of the investigation of the ground contaminated by TCE.

First, the stratum condition was determined from all-core samples using the above-mentioned boring machine and the screw-type sampler. Simultaneously, gas-detecting tubes were used to check whether or not TCE was present in the soil samples. If soil samples were found to be contaminated, contaminated parts of the soil were picked up and subjected to leaching tests using PID-GC set up in a working hut near the site. Boring positions are displayed in Fig. 5 and the results of the leaching tests are shown in Table 2. It can be concluded that soil parts with higher concentrations found by the gas detecting tube also resulted in high values with the PID-GC analysis. At this site, the concentration of TCE exceeded the standard for environmental quality (0.03mg/l leachate or less from soils) in Japan. Because the boring machine was able to be moved easily from boring point to boring point, this site investigation could be accomplished in just one day.

Table 2. Leaching test results using Photo Ionisation Detector-Gas Chromatography (PID-GC).

Boring Number	Sampling Depth (m)	TCE by PID-GC (mg/l)	TCE by Gas Detecting tube (ppm)
B-1	0.8	n.d.	n.d.
	1.3	0.002	n.d.
	1.7	0.358	10
B-2	0.7	n.d.	n.d.
	1.5	0.230	9
	1.8	0.170	7
	2.3	1.374	42
	3.0	0.129	7
	3.6	0.002	n.d.
B-3	1.2	0.007	n.d.
	1.8	0.052	2
B-4	1.3	0.733	23
B-5	1.5	0.240	14
B-6	1.4	0.333	18
	1.8	0.009	0.5

Note: n.d. – not detected

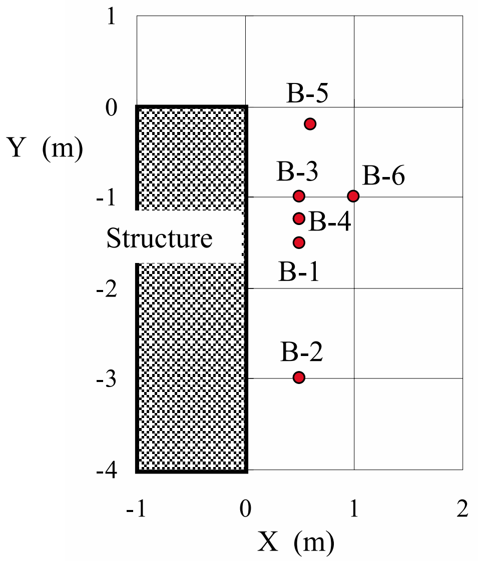

Figure. 10. Position of boreholes at the investigated site.

CONCLUSIONS

The three newly developed methods for investigating contaminated soils reported here have proven to be very effective tools. Future improvements remain to apply these methods to various kinds of ground, e.g. sandy ground and harder ground, and to further rationalise their handling.

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