# FINAL REPORT FOR PUBLICATION

# ALT-MAT
# Contract No.: RO-97-SC.2238

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**Danish Water Quality Institute (VKI), DK**
**Technical Research Centre of Finland (VTT), FI**
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**Swedish Geotechnical Institute (SGI), SE**
**Swedish National Road and Transport Research Institute (VTI), SE**
**Swiss Federal Laboratories for Materials Testing and Research (EMPA), CH**

**Project Duration: 01 January 1998 to 31 December 1999**

**Date:** **23 January 2001**

**PROJECT FUNDED BY THE EUROPEAN COMMISSION UNDER THE TRANSPORT RTD PROGRAMME OF THE 4th FRAMEWORK PROGRAMME**

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**Report No.: WP6.TRL.003**

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| **Date** | 23/01/01 |
| **Version** | 2.1 |
| **Classification** | **P** |
| **Distribution** | Publicly available |

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# EXECUTIVE SUMMARY

ALT-MAT is a collaborative research project partly funded by the European Commission Directorate General for Transport under Framework Programme IV. The project addresses Task 7.4/23, Improvements to the performance of all highway materials, to their efficient use and reuse, and to the development and use of new materials. The project was intended to encourage the wider use of alternative materials in road construction. This will reduce the consumption of scarce natural aggregates and the environmental impact of the disposal of the alternative materials. The aim of the project was to provide information to bridge the gap between laboratory tests and field behaviour. The objective was to define methods by which the suitability of alternative materials for use in road construction can be evaluated. The methods covered the mechanical properties, functional requirements, leaching potential and long-term stability of the materials and concentrated on unbound granular materials.

The project involved nine research organisations in seven countries and was co-ordinated by the Transport Research Laboratory (TRL) in the United Kingdom. Work commenced in January 1998 and the contract finished at the end of December 1999. Activities carried out during the project included:

- Literature review
- Selection and characterisation of alternative and natural reference materials
- Inspection and monitoring of existing roads constructed with alternative materials
- Lysimeter tests
- Climate chamber tests
- Laboratory tests for mechanical properties, leaching behaviour and hydrodynamic properties
- An end-users workshop held at LCPC, Nantes in March 1999.

This is the Final Report for the project and includes the results of all tests, recommendations for test methods to assess the suitability of alternative materials for use in road construction, an assessment of the suitability of the materials tested and a review of mitigation measures which can be used if the tests indicate possible adverse environmental impacts.

**Literature review**

The literature review showed that there is a general political will to encourage the use of alternative materials in all countries. This is expressed in various ways; sometimes as direct legislation, sometimes as action plans and directives. Most countries have set targets for increasing the amount of recycling. Most countries employ a landfill tax, and in some a tax on natural aggregates has been introduced or is being considered.

Economic factors such as transport costs and treatment costs still limit the use of alternative materials, particularly in countries with large reserves of natural

aggregates. In densely populated urban areas, however, the use of alternative materials is increasingly becoming economic. Usage of alternative materials in roads is fairly small at present, but is expected to increase in all countries.

Technical specifications for road construction in most countries use the same tests for natural and alternative materials. The alternative materials are assessed on the basis of the natural materials they most closely resemble. In some countries, a distinction is made between road by-products, which may be recycled for the same application with minimal testing, and non-road by-products, for which a comprehensive testing programme is required. Tables giving the testing requirements and limiting values for road construction in the participating countries are given in Appendix C.

Concerns about the potential environmental effects of alternative materials are a barrier to their wider use in most countries. There are few well-established procedures. Most cases are decided on a site-specific basis by the regulatory authorities. This leads to uncertainty, delay and increased costs, with the result that contractors are reluctant to propose the use of these materials.

**Mechanical tests**

A programme of inter-laboratory tests showed that alternative materials behave in a different way to natural materials in tests such as the Los Angeles and Micro-Deval abrasion tests. Test results for alternative materials should therefore be viewed with caution. However, the gyratory compaction method shows good results and should be optimised. This test simulates compaction of pavement layers with a heavy steel roller in the field.

Alternative materials often give better mechanical performance in the field than would be expected from the results of tests such as the Los Angeles or Micro-Deval. Design should therefore be based on performance-related tests such as cyclic-load triaxial or gyratory compaction. Work needs to be done to relate these tests to measurements of field performance made with the Falling Weight Deflectometer (FWD) and similar tests.

For alternative materials tests using vibration (e.g. vibrating table) instead of impact (e.g. proctor) are recommended. The nuclear gauge is not recommended for the determination of the in-situ density of MSWI ash. A test method for the self-binding capability of alternative materials is needed, as is an improved method to describe the material composition.

The following existing CEN mechanical tests for granular materials are evaluated to be suitable for alternative materials:

| Test method | Reference |
|---|---|
| Methods for sampling | EN 932.1 |
| Methods for reducing laboratory samples | prEN 932.2 |
| Determination of particle size distribution | EN 933.1 |
| Determination of the resistance to wear (Micro-Deval) | EN 1097.1 |
| Methods for the determination of resistance to fragmentation | EN 1097.2 |
| Determination of water content by drying in a ventilated oven | prEN 1097.5 |
| Determination of particle density and water absorption | prEN 1097.6 |
| Method for determination of loss on ignition | EN 1744.1 |
| One of the standards prEN 13286.2-13286.5 Test methods for laboratory reference density and water content: | |
| Standard proctor | prEN 13286.2 |
| Vibrocompression with controlled parameters | prEN 13286.3 |
| Vibrating hammer | prEN 13286.4 |
| Vibrating table | prEN 13286.5 |

**Leaching tests and environmental impact**

European or international standardisation is less advanced within the field of assessment of the environmental properties of alternative materials. Standardisation work is, however, in progress, and several standard CEN tests for characterisation of alternative materials may be expected to emerge over the coming years. In the meantime, a number of national standards, pre-standard CEN tests or Nordtest recommended leaching test methods are available to assess the leaching properties of alternative materials under different circumstances. Several of these tests were selected and applied in this project. It is recommended that a number of leaching methods are used in order to fully characterise the leaching properties of the alternative materials. Comparison of the results of these tests with lysimeter and climate chamber tests indicates that column tests provide the most detailed simulation of the actual leaching behaviour of the materials under normal circumstances.

If there is any chance that the pH of the material might change significantly in the field, for example by carbonation of oxides/hydroxides or oxidation of sulfides, pH-static tests should be used to estimate the effect of the anticipated pH change. Leaching tests at high liquid to solid (L/S) ratios (e.g. availability tests) are of limited value in road construction applications, unless the road does not have a relatively impermeable surface layer (e.g. gravel roads in rural areas).

Impact assessments and predictions should be based on scenario calculations, i.e. a description of the physical lay-out of the site in question and the flow of water through the site, in conjunction with a description of the composition of the leachate formed as a function of L/S or time. The leachate composition should be derived from laboratory or lysimeter leaching tests.

Among the useful tools for assessment of the environmental properties of alternative materials used in road construction, we particularly recommend the following:

- Draft prENV12920 Characterisation of waste: Methodology guideline for the determination of the leaching behaviour of waste under specified conditions;
- Column leaching test NT ENVIR 002;
- Batch compliance test prEN 12457-3.
- The pH-dependency of the leaching behaviour should be investigated, e.g. using a pH-static leaching test.

Most of these leaching procedures are currently being developed as European Standards by CEN/TC 292.

The purpose of lysimeters and climate chambers is to simulate the effect of climate on a road construction without a pavement. The lysimeters used were large boxes filled with material and left open to the atmosphere, with the drainage water collected. Lysimeters filled with blast furnace slag, MSWI bottom ash and Swedish natural reference materials were already available from earlier experiments, and a new lysimeter was constructed and filled with crushed concrete for ALT-MAT.

Climate chambers allow the simulation of many years of freezing-thawing and wetting-drying cycles in a few months under carefully controlled conditions.. These tests were carried out in Austria, where MSWI bottom ash was used, and Finland, where steel slag was used. Natural reference materials were also used in both cases.

When effects of climate are to be predicted in larger systems, then lysimeters and climate chamber tests can be used. The conditions for lysimeter tests will resemble natural conditions more closely than laboratory leaching tests, since they will be exposed to the natural climatic conditions. In most cases, laboratory leaching tests can be used to give a conservative estimate of environmental effects, since laboratory tests in most cases will overestimate actual leaching. The results from the lysimeter and climate chamber tests suggest that the pH which is developed in the material over time is the most significant factor in the composition of the leachate. It is thus essential to understand the mineralogy of an alternative material and its likely behaviour in a road pavement in order to make sensible predictions about its leaching behaviour. If the pH is likely to change with time, as a result of oxidation, carbonation or hydration reactions, pH-static leaching tests should be carried out at an appropriate range of pH values.

A model has been adopted to predict the impact of leaching from alternative materials in road construction on the quality of groundwater. The model is site specific and is based on the allowable increase in concentration of contaminants in the groundwater. For each contaminant, a critical length of time is estimated based on its relative mobility; highly mobile ions such as potassium are allocated a shorter critical time than less mobile metals such as chromium. The critical length of time can be converted to a critical L/S ratio on the basis of the road geometry, contributing area of the road to the groundwater catchment and the rate of infiltration into the road. The cumulative amount leached at this L/S ratio is derived from leaching test results; if it is less than the allowable cumulative amount leached, the material may be used in the road construction. The model, which is based on flux considerations, is conservative in that it does not account for the attenuation of contaminants during transport from the application through the unsaturated zone and the aquifer to the point of groundwater extraction.

**Hydrodynamic tests**

Unbound granular layers in road construction will generally be partly saturated for most of the year, with limited periods of full saturation. In order to measure the movement of water through road constructions, it is necessary to know the relationship between water content and suction, and the relation of both to the hydraulic conductivity. A number of methods are available, all of which are appropriate in certain circumstances. The choice of method is affected by factors such as the electrical conductivity, chemical composition and heterogeneity of the materials. Alternative materials differ markedly from natural aggregates in this respect, so these properties should be determined at the start of any investigation so that the most appropriate methods can be chosen. Specific calibration curves may be required for alternative materials, especially for nuclear methods.

One of the materials which causes problems for electromagnetic measurements of water content is MSWI bottom ash, because of its high electrical conductivity. A new test method was developed for this material at LCPC, involving vibrocompression and freezing of samples and use of a pressure chamber for suction measurements. The methods worked well, and are recommended for general use on sensitive materials. Two different MSWI bottom ashes were investigated, both as young and aged materials. The MSWI behaved like a silty soil, with high water retention even at high suctions. The water content of both ashes increased with age, but the shape of the water retention curves remained the same.

**Inspection and monitoring of existing roads**

Inspection and monitoring of existing roads showed that alternative materials gave as good and sometimes better support to the road pavement layers as natural reference materials. The sites investigated ranged from the north of Sweden to south-west France, and hence covered a wide range of climatic conditions. Sites were studied in Sweden, Denmark, France and the United Kingdom. The materials studied included crushed concrete, air-cooled blast furnace slag, MSWI bottom ash and demolition rubble (mixture of brick and concrete). In-situ tests and condition assessments were carried out, trial pits excavated and samples taken for laboratory testing. The performance in the field was often better than would have been predicted from laboratory test results. For some materials, notably crushed concrete and air-cooled blast furnace slag, an increase in stiffness with time was recorded, due to the self-binding properties of the material.

Chemical tests revealed that leaching had caused a perceptible increase in the concentration of certain constituents in the subgrade below the alternative materials. This was noted in Denmark and France below MSWI bottom ash and in the UK below demolition rubble. The phenomenon was recorded in both clay and sand subgrade. The increases were limited to a few constituents in each case, and the resulting concentrations were well below national limits for contamination. Leaching tests and groundwater sampling indicated that the alternative materials did not appear to be having any significant effect on groundwater quality.

**Mitigation methods**

Mitigation methods to counter possible adverse environmental effects of the use of alternative materials were considered. These may be either source-based or pathway-based, it being generally impracticable to move the receptors. Source-based methods include ageing of materials such as steel slag and MSWI ash. This allows harmful constituents to hydrate and/or carbonate, avoiding expansive reactions after the material is placed. It also allows the pH of the materials to drop from often highly alkaline values in fresh materials to near neutral in aged materials.

Pathway-based methods include covering the road surface with a layer of dense, impermeable asphalt or placing low permeability materials on the slopes above the alternative material. The aim is to reduce the contact between water and the alternative materials, and hence reduce the leaching of harmful constituents. These measures should be combined with an effective drainage system.

A further way to reduce contact between percolating water and the alternative material is to stabilise it using bitumen or cement as a binder. This may enable the material to be used in a higher value application such as roadbase, for which the unbound material may not be suitable.

**Suitability of materials**

ALT-MAT is principally about test methods rather than material suitability, but the project included an assessment of the materials used in the study. The materials were chosen in each country on the basis of their availability, past use and potential for use in road construction. Natural materials commonly used in road construction, such as limestone, were tested as a control. It should be noted that the conclusions apply only to the samples tested, and cannot be extrapolated to all materials of the same type.

**Austria:** MSWI bottom ashes from two plants were tested. The materials did not fulfil the national requirements for base and sub-base material. The mechanical performance of the materials could be improved by reducing the amount of fine (<0.063mm) material. The ashes also did not fulfil the national requirements for leaching. To meet these requirements, the ash could be subjected to a longer period of storing and washing, and separation of the non-ferrous metals. However, the use of MSWI bottom ash in road construction is not permitted in Austria at present.

**Denmark:** Crushed concrete was suitable for unbound road base. MSWI bottom ash was suitable as unbound sub-base. Under forthcoming environmental legislation, the MSWI would be suitable below the road pavement but not under the shoulders of the road.

**Finland:** Ferrochrome slag and blast furnace slag can be used in most parts of the road construction, but not in the road base of high standard roads. No environmental concerns were found for either material. The concentrations in leachate from climate chamber tests were very low for most metals.

**France:** Two types of MSWI bottom ash were investigated. They gave very high values in Los Angeles and Micro-Deval tests, indicating they were not suitable for high quality end uses. However, inspections of two existing roads in which MSWI ash had been used as unbound sub-base showed that they were giving satisfactory performance 20 years after construction. No environmental problems were reported.

**Sweden:** Crushed concrete and air-cooled blast furnace slags were investigated. Both were satisfactory as unbound sub-base. Crushed concrete may also be satisfactory as a base course material. An increase in stiffness with time was noted for both materials. Use of air-cooled blast furnace slag high up in the road pavement may cause icing on the road surface in cold climates, especially in early winter. In these cases no significant influence on the surrounding environment was encountered with either of the materials.

**Switzerland:** Recycling glass, VRG-slag (glass-like, not crushed) and VRS-slag (mineral-like, crushed) were investigated for use as bitumen-bound materials in the road pavement. The mechanical properties of the materials were satisfactory, but there were some problems with particle shape for the slags. All three materials suffered problems with poor adhesion to the bitumen binder. There were no problems with leaching of contaminants. However, the slags should not be used in the wearing course as they contain metals, which would be released by attrition.

**United Kingdom:** Steel slag from EAF plant and demolition rubble, consisting of a mixture of brick and concrete, were investigated. The steel slag is acceptable as an unbound sub-base material provided it has been aged. The demolition rubble was satisfactory in most respects for unbound sub-base, however it failed to meet the criteria for frost resistance. This test may be too severe for many parts of the United Kingdom, where temperatures are rarely below zero for any length of time. In-situ tests on a site where the demolition rubble was used as a combined sub-base and capping layer indicated that it was performing satisfactorily. No leaching problems were encountered for the demolition rubble, but leaching tests on the steel slag had high concentrations of molybdenum.

**Further research**

Two main areas where further research is needed have been identified:
- performance tests for mechanical behaviour;
- measurement of the movement of water through road constructions.

In addition, there may also be a need to develop a leaching test suitable for conditions where water movement is slow.

The results from several countries show that alternative materials appear to give better performance in-situ than would be expected from the results of standard laboratory tests. Investigation of alternative materials in tests such as the Los Angeles and Micro-Deval show that their behaviour is significantly different from that of natural aggregates. The usefulness of such tests as indicators of in-situ performance must therefore be questioned. Priority should be given to performance-related tests such as cyclic-load triaxial and gyratory compaction. Research is required to develop these tests and relate them to in-situ measures of performance such as the FWD test. The related research project COURAGE, dealing with the mechanical behaviour of unbound granular materials, came to a similar conclusion.

It became apparent during the project that there were very few reliable data on the movement of water into, through and out of road pavements. As a consequence, the fluxes of contaminants are not known and conservative leaching tests and models are used to estimate environmental impact. The new model developed during ALT-MAT will improve this considerably, but it is still based on a number of fairly conservative assumptions on water movement into and out of road construction. Measurement of the actual quantities of water and contaminants is therefore required to calibrate the model and to enable the development of more accurate models in the future. Water movement in roads also affects the mechanical behaviour of the road materials. This area was agreed as a priority for further research by the projects ALT-MAT, POLMIT and COURAGE. A programme of field tests is proposed, consisting of a series of trial road structures for specifying environmental and mechanical functioning. These should be established in several countries with a range of climatic conditions and maintained for a number of years in order to provide fundamental underpinning information on the movement of water in roads.

There may also be a need to develop a leaching test, which is applicable to granular materials under unsaturated conditions with no or extremely slow flow of water (contaminants transported mainly by diffusion). The development of such a test should also address the need to avoid opening new surfaces of minerals by size reduction of larger aggregates.

**Summary**

The results of the ALT-MAT project are very positive and provide support for the use of alternative materials in road construction. The case studies show that the materials perform as well as natural aggregates, and often better than suggested by standard laboratory tests. Methods for testing the mechanical and hydrodynamic properties of alternative materials and their leaching behaviour are listed, and a model for assessing the environmental impact on groundwater quality on a site-specific basis is presented. It is important that highway authorities and environmental regulatory authorities are made aware of this toolkit of methods and apply them in a national context. This can be achieved through the national seminars, publication of the final report in book form and on the ALT-MAT website, articles in technical journals and presentations at suitable conferences and seminars.

# ABSTRACT

This report presents the results of the research project ALT-MAT (ALTernative MATerials in road construction). The project was commissioned by the European Commission as part of the Fourth Framework Programme, and was carried out in 1998 and 1999 by a consortium of nine research organisations in seven European countries. The objective was to develop test methods to assess the suitability of alternative materials in road construction. The project concentrated on unbound granular materials in the road base, sub-base and capping layers.

The report describes the background to the use of alternative materials in roads, presents the results of the project activities and details the benefits to various end user groups. A toolkit of methods for assessing the mechanical, environmental and hydrodynamic performance of alternative materials is presented. A method for estimating the impact of leaching of contaminants on groundwater under a range of scenarios is described. Case studies of the use of alternative materials are given, including inspection of existing roads and monitoring of trial sections. Mitigation methods which can be used to deal with potential adverse consequences of the use of alternative materials are described. All test methods and mitigation measures should be applied in a national context and with reference to the specific conditions of each site. Supporting information is included in Appendices.

The report will help to encourage the use of alternative materials by providing a rational set of decision-making tools and giving case studies of the successful use of alternative materials in road construction.

# 1. INTRODUCTION

## 1.1 BACKGROUND

Throughout Europe there is pressure to increase the use of alternative materials in construction applications such as roads. This is reflected in the hierarchy of waste disposal options set out by the European Commission in the *Community Strategy for Waste Management* (COM(96) 399):

1. Prevention: minimise waste production and the use of natural materials
2. Recovery: recycling of materials at the highest possible technical level
3. Incineration to recover energy and minimise volumes that have to be deposited
4. Disposal in landfills

The use of alternative materials in road construction contributes directly to options 1 and 2, by reducing the amount of natural aggregate consumed and recycling materials that would otherwise be disposed of as waste. It reduces reliance on option 4, and enables the products of option 3 to be recycled in construction instead of being landfilled.

The recommendations of the Commission are enacted in different ways in different countries. Most employ some form of legislation such as taxes on landfill or on the use of natural aggregates to provide economic drivers for the recycling of alternative materials. Some countries have implemented the hierarchy of waste disposal options through national legislation (e.g. Austria, France) and most have set targets for the amount of material to be recycled.

The OECD (1997) considered the application of these principles to road works. Within the road sector, a distinction was made between recycling road products into the road itself – "cleaning up our own house first" – and accepting the by-products of others. Examples were given of the successful use of a number of non-road by-products in road construction. Caution was expressed that by-products, which contain potentially leachable chemicals may present a hazard to the environment and must be tested carefully before use.

## 1.2 BARRIERS

Despite these political and economic drivers, the extent to which alternative materials are used in road construction is generally small. This is partly to do with the perception of such materials as being "waste" and hence inferior, particularly for non-road by-products; partly for economic reasons; and partly because of concerns about the mechanical and environmental performance of the materials. In parts of Europe where natural aggregates are readily available, the use of alternative materials is not economic. Elsewhere, transport costs are the dominant factor. Alternative materials such as blast furnace slag are used close to the source of production, and in urban areas building demolition material and crushed concrete are used.

From the point of view of mechanical performance, uncertainties about alternative materials remain, especially with respect to the long-term performance. The nature and composition of alternative materials is often significantly different from that of natural aggregates, and existing tests for natural aggregates may not be appropriate. However, most national technical specifications use the same test methods for alternative materials and natural aggregates.

The potential environmental concerns about the use of alternative materials were referred to in the OECD report. These present a major barrier to the greater use of alternative materials. A number of leaching tests are being developed by CEN TC 292, and others have been developed by the Netherlands, the Nordic countries and the United States. These tests have generally been developed for assessing the behaviour of materials in landfills, and there is uncertainty as to how they should be applied to road construction. There is little knowledge of the movement of water in road pavements and embankments, and this leads to difficulties in the assessment of the risk posed by leaching of contaminants from roads. A conservative approach is often adopted, based on leaching tests at high liquid to solid ratios, which do not reflect the actual movement of water in road construction. The perception of alternative materials as dirty and inferior, and the great variability which they can exhibit, compound the lack of knowledge and lead to a cautious approach by environmental regulatory authorities. This leads to uncertainty and delay, which discourages designers and contractors from proposing the use of alternative materials.

## 1.3 ALT-MAT

The ALT-MAT project was conceived as a way of addressing the concerns about the mechanical and environmental performance of alternative materials in road construction. The project was commissioned by the European Commission under the Fourth Framework Programme. The full title of the project is ALTernative MATerials in road construction. The project concentrated on unbound granular applications in the base course, sub-base and capping layer of roads. It commenced in January 1998 and ran until the end of 1999. The participating organisations are listed in Table 1.1.

**Table 1.1 Organisations participating in ALT-MAT**

| Organisation | Country | Acronym |
|---|---|---|
| Transport Research Laboratory (Co-ordinator) | UK | TRL |
| Österreichisches Forschungs-und Prufzentrum Arsenal | Austria | ÖFPZ |
| Danish Road Institute | Denmark | DRI |
| Danish Water Quality Institute (Associate Partner) | Denmark | VKI |
| Technical Research Centre of Finland | Finland | VTT |
| Laboratoire Central des Ponts et Chaussées | France | LCPC |
| Swedish Geotechnical Institute | Sweden | SGI |
| Swedish National Road and Transport Research Institute | Sweden | VTI |
| Swiss Federal Laboratories for Materials Testing and Research | Switzerland | EMPA |

## 1.4 OBJECTIVES

The objective of ALT-MAT is to develop methods to assess the suitability of alternative materials for use in road construction. The output from the project, presented in this report, is a toolkit of methods for assessing the mechanical performance, hydrodynamic properties and potential leaching of contaminants under a range of scenarios.

The project had two subsidiary objectives: to assess the suitability of the particular materials tested; and to consider mitigation methods which could be employed where the performance of alternative materials was not adequate to allow their unrestricted use. Consideration was also given to future research which would enable better prediction of the field performance of the materials.

## 1.5 REPORTS

Two publicly available reports, a Literature Review and an Interim Report, have been produced by the consortium. They are available on the ALT-MAT web site at http://www.trl.co.uk. The main conclusions and test results from these earlier reports are included in this report, which is a stand-alone report including all the results from the project.

This Final Report comes in two parts: the main report, which presents the conclusions and recommendations from the project; and the Appendices, which contain the detailed information on the literature reviews, test methods, case studies and test results. The Appendices are included on a CD in the back of the report.

The contents of the main report and the Appendices are listed in the Table of Contents. The main report falls into six sections:

1. Chapters 1 to 3: Introduction, objectives, activities, benefits
2. Chapters 4 to 6: The toolkit; recommended test methods for mechanical, environmental and hydrodynamic tests and guidance on their use in different scenarios.
3. Chapter 7: Case studies of inspections of existing roads and monitoring of trial roads.
4. Chapters 8 & 9: Mitigation measures and an assessment of the suitablity of the particular materials tested in the project.
5. Chapter 10: Areas where further research is required.
6. Chapter 11: Summary and conclusions.

# 2. PROJECT ACTIVITIES

## 2.1 INTRODUCTION

In order to achieve the aims of the project, a number of activities were carried out to investigate the behaviour of alternative materials under actual field conditions or simulated field conditions. The results were compared to the results of standard laboratory tests on the same materials, to establish which laboratory tests gave the best prediction of field performance. The materials selected and the tests carried out are described in the following sections. Full details of all test methods are given in Appendix E.

## 2.2 MATERIALS

Each organisation selected two or three alternative materials for testing and one or more natural aggregates as controls. The alternative materials were chosen on the basis of their availability and potential suitability in each country. The selected materials are listed in Table 2.1.

**Table 2.1 Materials selected for testing**

| Country | Alternative Materials | Reference Materials |
|---|---|---|
| Austria | Municipal Solid Waste Incinerator (MSWI) ash from two different plants | Dolomite |
| Denmark | MSWI ash, crushed concrete | Sand, gravel |
| Finland | Granulated steel slag and air-cooled steel slag | Granite |
| France | MSWI ash from two different plants | Diorite |
| Sweden | Air-cooled blast furnace slag, crushed concrete, MSWI ash (lysimeter studies only) | Till, crushed rock |
| Switzerland | MSWI ash (2 types), glass-like slag | Natural aggregate |
| United Kingdom | Steel slag, building demolition material | Limestone |

## 2.3 LITERATURE REVIEW

A review of the preconditions for the use of alternative materials in roads and the current usage was carried out. The methods available for mechanical and environmental testing of alternative materials were also reviewed. The results formed the baseline for the project and are given in Appendix A. The movement of water in road construction was of crucial importance to the project, so a detailed review of the available information on this topic was carried out and is given in Appendix B.

As part of the literature review, tables were prepared giving the test methods and limiting values for alternative materials in different layers in the road. These national application tables were prepared for the different countries in the consortium and are included in Appendix C. The tables form a useful guide to the requirements for the use of alternative materials at the present time.

## 2.4 FIELD AND SIMULATED FIELD TESTS

These tests fall into four main categories:

1. Inspection of existing roads
2. Monitoring of trial road sections
3. Lysimeter tests
4. Climate chamber tests

### 2.4.1 Inspection of existing roads

The most effective way to assess the suitability of alternative materials is to examine how they have performed where they have been included in existing road constructions which have been subject to traffic for a number of years.

Sites where alternative materials had been used as unbound granular base and sub-base were investigated in the UK, Denmark, France and Sweden. A variety of techniques were used to investigate the sites. Non-destructive tests included visual inspection, Falling Weight Deflectometer (FWD), Profilograph, ground penetrating radar and photographs. Intrusive investigations included excavating trial pits, in-situ density measurements and plate bearing tests (GDPBT). Samples were taken for laboratory analysis for mechanical and environmental properties according to national standard methods.

The results are summarised in chapter 7 and the full national reports are included in Appendix D.

### 2.4.2 Trial road monitoring

In addition to the intrusive investigations described above, two trial sections of road were selected for monitoring. Both sections are in Sweden, one in the south and one in the north. This gives a range of climatic and geological conditions. Crushed concrete had been used in both sections: as sub-base in the south; and as sub-base and base in the north.

The trial sections were constructed in 1997 as part of another project, and the monitoring was continued as part of ALT-MAT. During construction of the roads, sampling, levelling, compaction control etc was carried out. In previous field tests the bearing capacity (deflection) was measured by using the KUAB/FWD91 (FWD = Falling Weight Deflectometer). Rutting as well as other damage was visually inspected in combination with other measurements. The in-situ tests included levelling, Static Plate, FWD, PRIMAL (Swedish Profilograph) and RST (Evenness). The samples taken during construction and field tests were analysed by using sieve-analysis, Nordic Ball Mill, Freeze-Thaw tests and triaxial apparatus. The density of the materials, the moisture content and other mechanical properties were also determined. Leaching tests were carried out on samples of materials and the chemical composition of the groundwater at the south Sweden site was monitored.

The results of the trial road monitoring are given in chapter 7 and Appendix D.

### 2.4.3 Lysimeter tests

Lysimeters are large boxes (2.0m x 2.0m x 1.0m) filled with material and left open to the atmosphere. The purpose is to simulate a field system without a pavement, by allowing precipitation to percolate through the material. The leachate is collected under an inert gas at the base of the lysimeter and samples are analysed at regular intervals.

The lysimeter tests were carried out at SGI in south Sweden. Lysimeters filled with blast furnace slag, MSWI bottom ash and natural reference materials were already available from earlier experiments, and a new lysimeter was constructed and filled with crushed concrete for ALT-MAT.

The rate of percolation of water under natural conditions is relatively slow. The lysimeter filled with MSWI bottom ash took 6 years to reach a liquid to solid ratio of 1.0. In a road situation, with the unbound material covered by relatively impermeable bituminous or cementitious pavement layers, the rate of percolation would be much slower. In the time scale of the ALT-MAT project, the lysimeters can only give information about the composition of the initial leachate from a road. By restarting existing lysimeters, the time scale is extended somewhat. However, this initial leachate often has the highest concentrations of contaminants and is thus of great concern for environmental impact.

The lysimeters represent an intermediate situation between the totally realistic but uncontrolled situation of the trial road sections and the highly controlled but artificial situation of the climate chambers and the standard laboratory tests. They provide useful information with which to calibrate the results of laboratory tests. In particular, many laboratory leaching tests are carried out in saturated conditions, whereas the lysimeters reflect the natural situation of partial or intermittent saturation.

The results of the lysimeter tests are given in Chapter 5 and Appendix F.

### 2.4.4 Climate chamber tests

Climate chambers allow the simulation of many years of freezing-thawing and wetting-drying cycles in a few months under carefully controlled conditions. As with the lysimeters, the aim is to simulate a road structure without a pavement. These tests were carried out in Austria, where MSWI bottom ash was used, and Finland, where steel slag was used. Natural reference materials were also used in both cases. Infiltration boxes, approximately 0.85m x 1.20m x 0.30m were constructed and the materials compacted in them to simulate embankments without a pavement. The boxes were then sprayed with water to which de-icing agents had been added and subjected to a number of freeze-thaw cycles, with temperatures ranging from -20°C to +20°C. Leachate was collected and analysed at regular intervals and the mechanical properties were measured before and after the tests. National standard tests for frost susceptibility were carried out for comparison with the climate chamber tests.

The results of the climate chamber tests are given in Chapter 5 and Appendix F. Details of the test methods are given in Appendix E.

## 2.5 LABORATORY TESTS

The laboratory tests fall into three categories:

1. Mechanical tests

2. Leaching tests
3. Hydrodynamic tests

### 2.5.1 Mechanical tests

National standard mechanical tests were carried out on all materials by all partners. Mechanical tests on asphalt bound glass-like slag were carried out by EMPA to assess its suitability for use in asphalt pavement layers. Inter-laboratory mechanical tests on unbound materials were carried out in Switzerland, France and Denmark. The Los Angeles, Micro-Deval, vibrating table and gyratory compaction tests were carried out on the same materials in different organisations. The extent of breakdown of the materials in the Los Angeles was recorded after 100, 250 and 500 revolutions, and after 3,000, 6,000 and 12,000 revolutions in the Micro-Deval tests to investigate the differences in the behavior of the alternative materials and natural materials.

The use and interpretation of the mechanical tests is discussed in Chapter 4. The results of all tests are enclosed in Appendix F and details of the test methods are given in Appendix E.

### 2.5.2 Leaching tests

All partners participated in the programme of leaching tests. The tests utilised are listed in Table 2.2 below. These tests are generally established tests, which are either national standards (e.g. Nordtest methods) or draft CEN tests. They have been chosen because they simulate a range of environments and leaching scenarios, which can be compared to the data from the climate chamber tests, lysimeters and inspections of existing roads to establish which tests give the best prediction of actual performance.

The use of the tests and their interpretation is discussed in Chapter 5. The results of the tests are given in the national reports on environmental tests in Appendix F and details of the test methods are given in Appendix E.

**Table 2.2 Environmental tests conducted by ALT-MAT partners**

| Test method | Status |
|---|---|
| Determination of pH and alkalinity | X |
| Determination of TOC and LOI (550°C) | X |
| Total analysis of constituents | X |
| Analysis of selected trace elements after partial digestion | Optional |
| Two-stage serial batch leaching test at L/S = 0-2 l/kg and 2-10 l/kg (CEN prEN 12457-3/Nordtest) | X |
| The pH -static leaching test at L/S = 10 l/kg (3 or 4 pH values Determined by its own pH and the scenario) | X |
| Availability leaching test (L/S = 2 x 100 l/kg, pH = 7 and 4, Analysis of both extracts), Nordtest NT ENVIR003 | X |
| Oxidised availability leaching test (L/S = 2 x 100 l/kg, At pH = 7 and 4) | Optional |
| Column leaching tests for L/S = 0 - 2 l/kg Analysis of 5 fractions of eluate for L/S = 0,1 - 2,0 l/kg Nordtest NT ENVIR002 | X |
| Granular tank leaching test NVN 7347 | Optional |

TOC: Total organic carbon
LOI: Loss on ignition
L/S: Liquid to solid ratio in a leaching test
X: Compulsory test

### 2.5.3 Hydrodynamic tests

In order to understand the behaviour of materials in road construction, in particular the rate of movement of water through the layers and the potential for leaching, it is necessary to measure the fundamental hydrodynamic properties of the materials. Detailed hydrodynamic tests on MSWI bottom ash were carried out by LCPC in France. The relationship between water content and suction and between hydraulic conductivity and water content was established for two different MSWI materials and compared with the results for natural sand and silt soils. MSWI ash was investigated to assess whether physico-chemical processes, which occur in the ash, have an effect on their hydraulic properties. This is an example of how alternative materials differ from natural materials in their behaviour, and how this affects their performance.

The use and interpretation of hydrodynamic tests is discussed in Chapter 6. The results of the tests are enclosed in Appendix F and the test methods are described in Appendix E.

# 3 BENEFITS

The project is intended to increase the usage of alternative materials in road construction. It achieves this in three ways:

1. Providing a toolkit of testing methods, which can be used to assess the suitability of alternative materials. The toolkit is intended to allow use of the test methods under widely varying climatic conditions and a range of scenarios relating to methods of road construction and degree of leakage through the road pavement. It is intended that the tests be used in a national context on a site-specific basis, so that the methods chosen and the interpretation of the results are relevant to the particular conditions of the site.

2. Increasing confidence in the use of alternative materials in road construction by describing case studies where they have been used successfully.

3. Describing a number of mitigation methods, which can be employed to enable the use of alternative materials where the toolkit test methods indicate that they would not be suitable. As for the test methods, the mitigation methods should be applied in a site-specific context; measures which are suitable in Nordic countries, for example, may not be appropriate in a Mediterranean climate.

The organisations involved in the project come from countries with a wide range of climatic conditions, and the results are applicable on a Europe-wide basis. The concepts can also be applied to other areas with similar climatic conditions, such as Eastern Europe and the United States. However, in all cases, the methods should be used in a way appropriate to the national and site-specific situation.

Several categories of end user have been identified for the outputs from ALT-MAT:

- **Regulators and specifiers:** national organisations responsible for specifications for highway works, who determine which materials may be used in road construction and the methods for testing them.

- **Policy direction groups:** WERD (West European Road Directors), DERD (Deputy European Road Directors) and other groups who wish to encourage greater use of alternative materials.

- **Standardisation bodies:** CEN and national standardisation bodies who define methods of testing materials.

- **Environmental regulatory bodies:** national organisations who may be concerned about potential leaching of contaminants from alternative materials.

- **Highway designers:** who may require assurance about the mechanical and environmental properties of alternative materials.

- **Engineering contractors:** who may wish to use alternative materials in road construction or other earthworks.

- **Producers of alternative materials:** who may be seeking markets for their products.

- **Scientists and researchers:** in universities and organisations such as FEHRL who may be carrying out research on related topics.

The results from ALT-MAT will be of benefit to all the above, both those who might specify the use of the test methods and mitigation measures and those who would have to carry them out. By providing methods for addressing the uncertainties about alternative materials, the project will encourage greater use of them. This in turn will lead to less use of natural aggregates and reduce the amount of alternative materials sent to landfill sites.

The project was concerned with the use of alternative materials in road construction. However, the conclusions are applicable to other earth structures such as railway and canal embankments and airport runways and taxiways, and should encourage the use of alternative materials in these areas.

# 4. MECHANICAL TESTS

## 4.1 EVALUATION OF TEST METHODS FOR ABRASION BEHAVIOUR OF ALTERNATIVE MATERIALS

### 4.1.1 Introduction

This chapter includes the results of the inter-country tests carried out between the three countries Denmark, France and Switzerland. It is a summary of the individual results which are extensively discussed in the national reports of the participating countries.

### 4.1.2 Objectives

The goal of this investigation was to compare different test methods for the evaluation of abrasion and attrition properties among various currently used alternative materials. Concerns were mentioned on test methods like Los Angeles, which were suspected to give too high abrasion coefficients for softer alternative materials.

### 4.1.3 Materials

In order to guarantee good comparison among the results of all the participating countries some alternative materials[1] and natural aggregates, as described in the national reports, were exchanged (Table 4.1) and tested. Each test method was carried out only in one country. But due to limited financial budgets and restricted time, not all materials have been tested with every test method.

[1] Materials are described in the national reports of the participating countries

**Table 4.1 Overview of materials and test methods used in inter-country testings**

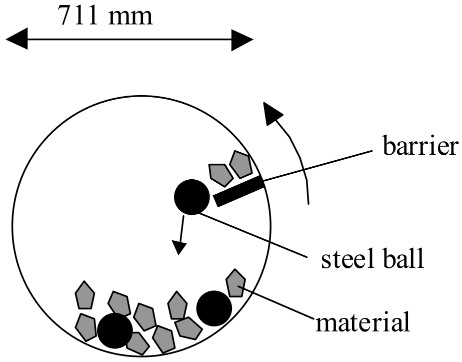
| | **Micro-Deval** | **Los Angeles (CEN)** | **Vibrating table** | **Los Angeles (ASTM-B/C/D)** | **Gyratory compaction** | **Los Angeles (SN)** |
|---|---|---|---|---|---|---|
| **Place of testing** | LCPC France | LCPC France | DRI Denmark | DRI Denmark | EMPA Switzerland | EMPA Switzerland |
| **Danish materials** | | | | | | |
| Natural base aggregate | **X** | **X** | **X** | **X** (ASTM-C) | | |
| Crushed concrete | **X** | **X** | **X** | **X** (ASTM-B) | | |
| Natural sub-base aggregate | **X** | **X** | **X** | **X** (ASTM-D) | | |
| MSWI DK (Municipal solid waste incineration ash) | **X** | **X** | **X** | **X** (ASTM-D) | | |
| **French materials** | | | | | | |
| Natural aggregate | **X** | **X** | **X** | **X** (ASTM-C) | **X** | |
| MSWI Ivry | **X** | **X** | **X** | **X** (ASTM-C) | **X** | |
| MSWI Egletons | **X** | **X** | **X** | **X** (ASTM-C) | **X** | |
| **Swiss materials** | | | | | | |
| Natural aggregate | **X** | | | | **X** | **X** |
| Recycling glass | **X** | | | | **X** | **X** |
| VRS-slag | **X** | | | | **X** | **X** |
| VRG-slag | | | | | **X** | **X** |

### 4.1.4 Test methods

In this chapter, a short overview of all test methods used in this inter-country testing is given with special emphasis on their differences and the mode of stress involved.

#### 4.1.4.1 Los Angeles test (LA)

**Principle**: Rotating drum with steel balls and barrier




The material tested is stressed by a combination of attrition and impacts of the falling steel balls as it is supposed to happen in drums for the production of bituminous hot mix asphalt.

Although this test is widely used all over Europe some parameters may vary slightly depending on the national standard:

**Table 4.2 Variations in different standards for determination of the LA-value**

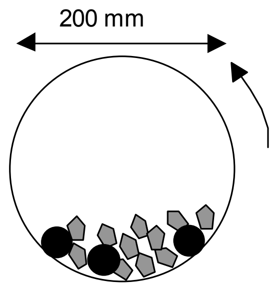
| Standard | ASTM B | ASTM C | ASTM D | CEN EN 1097.2* | Swiss standard SN 670 835b |
|---|---|---|---|---|---|
| Aggregate fractions used | 9.5/19 mm | 4.75/9.5 mm | 2.36/4.75 mm | 10/14 mm | 1/3**,11/16 mm |
| Weight of sample | 5000 g | 5000 g | 5000 g | 5000g | 5000 g |
| Number of balls | 11 | 8 | 6 | 11 | 10 |
| Total weight of balls | 4584 g | 3330 g | 2500 g | 4475 g | 4170 g |
| Fines passing | 1.7 mm | 1.7 mm | 1.7 mm | 1.6 mm | 1.6 mm |

#### 4.1.4.2 Micro-Deval test (French Standard NF EN 1097-1)

* Actually the French Los Angeles test [3] was carried out. But as the French test method differs from the CEN-method only slightly in the total mass of balls the method is referred as CEN-test.

** Due to the small aggregate size of the VRG-slag, Los Angeles test was slightly modified.

**Principle**: Rotating drum with steel balls **without** barrier and smaller diameter

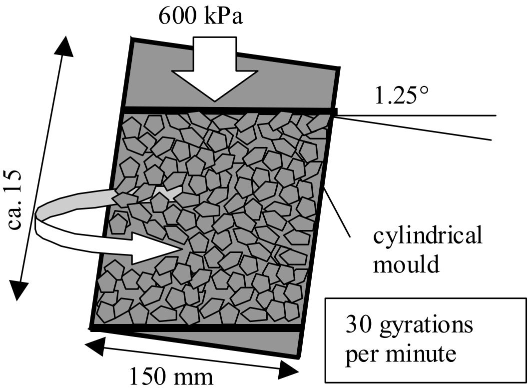



In comparison with the Los Angeles machine the Micro Deval equipment is smaller and has no barrier. Hence there is no impact from falling steel balls, but only attrition produced by the friction of steel balls and sample material.

The Nordic ball mill test, which has not been included in the current test series, is very similar to the Micro-Deval test, but has, like the Los Angeles machine, a barrier inside the drum.

#### 4.1.4.3 Gyratory compaction (AASHTO Standard TP4-97)

**Principle**: Compaction at constant pressure with out of plane rotation



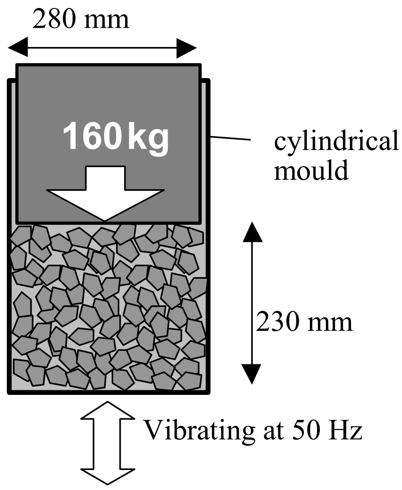

In contrast to both Micro-Deval and Los-Angeles test there is no rolling of the aggregate, but a constant pressure and a kneading movement produced by gyrations at an angle of 1.25°. This is assumed to represent best the compaction process by a heavy roller compactor in the field.

All aggregates were taken as they were delivered and the whole aggregate fraction was used without prior washing. Compaction and sieving was done on dry material because of technical reasons. For the interpretation of the abrasion behaviour, aggregate size distribution is determined before and after gyratory compaction on two test samples.

The gyratory compaction test was developed in the United States under the HRP-program and is now standardised for bituminous bound mixtures. As part of the inter-country testing, gyratory compaction was carried out in the same way, but with unbound materials.

#### 4.1.4.4 Vibrating table (CEN Draft Standard prEN 13286-5)

**Principle**: Compaction at constant pressure (weight) under vertical vibration




The main purpose of this method is to determine the maximum dry density under saturated condition of cohesionless materials after compaction.

The pressure is about 24 times smaller compared to the gyratory compaction. This compaction is supposed to represent best the compaction process by a vibrator roller in the field.

### 4.1.5 Test results

The amount of fines passing through the 1.7 mm sieve (or 1.6 mm) divided by the mass of the original sample is defined as Los Angeles coefficient or as abrasion coefficient. Hard materials give low LA-coefficients, soft material show high LA-coefficients.

#### 4.1.5.1 Los Angeles tests

**Table 4.3 Results of the LA-testing (Los Angeles coefficients)**

| | **Los Angeles (CEN)** | | | **Los Angeles (ASTM)** | | | **Los Angeles (SN)** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Number of revolutions** | 100 | 250 | 500 | 100 | 250 | 500 | 100 | 250 | 500 |
| **Danish materials** | | | | ASTM-C | | | | | |
| Natural aggregate (base) | **5** | **12** | **22.5** | **5** | **12** | **23** | | | |
| | | | | ASTM-B | | | | | |
| Crushed concrete | **12** | **24** | **38** | **11** | **22** | **36** | | | |
| | | | | ASTM-D | | | | | |
| Natural aggregate (sub-base) | | | | **5** | **12** | **23** | | | |
| MSWI | **25** | **39** | **54** | **19** | **32** | **50** | | | |
| **French materials** | | | | ASTM-C | | | | | |
| Natural aggregate | **2** | **4.5** | **8.5** | **3** | **7** | **13** | | | |
| MSWI Ivry | **19** | **28.5** | **40** | **22** | **32** | **45** | | | |
| MSWI Egletons | **23.5** | **34.5** | **48** | **24** | **40** | **55** | | | |
| **Swiss materials** | | | | | | | | | |
| Natural aggregate | | | | | | | **2.2** | **5.3** | **10.7** |
| Recycling glass | | | | | | | **4.3** | **6.4** | **11.2** |
| VRS-slag | | | | | | | **3.6** | **8.3** | **15.7** |
| VRG-slag | | | | | | | **5.4** | **9.9** | **15.2** |

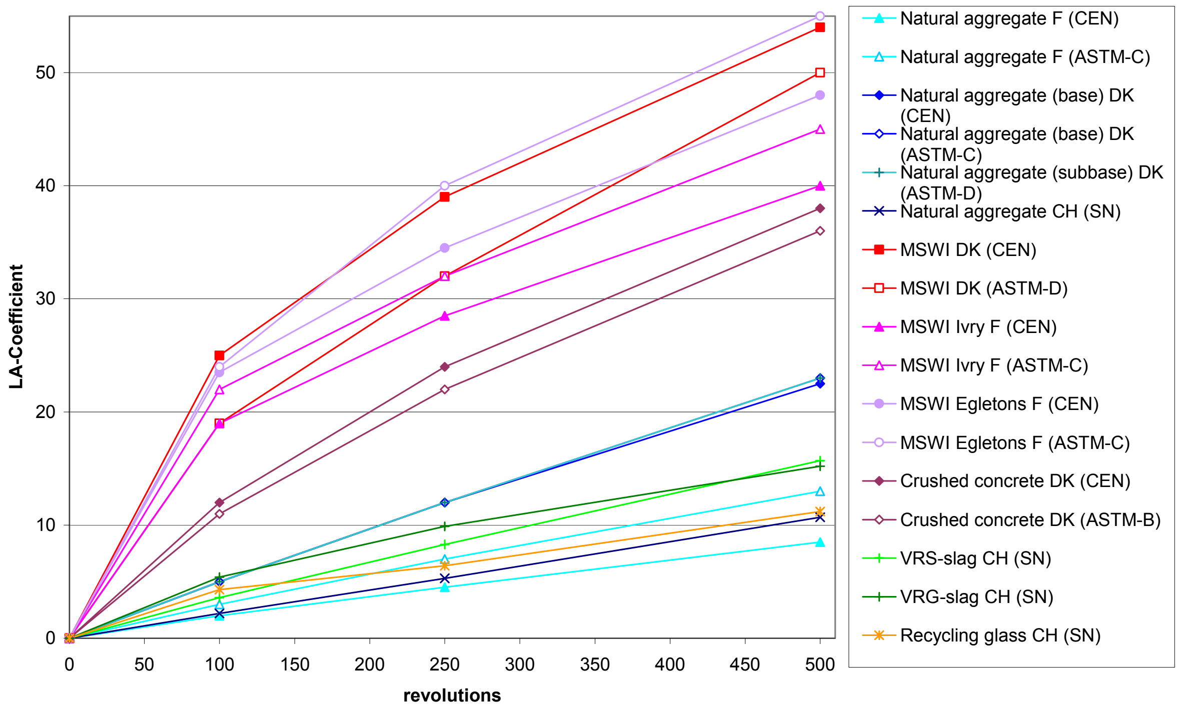



**Figure 4.1 Los Angeles test results for all materials investigated**

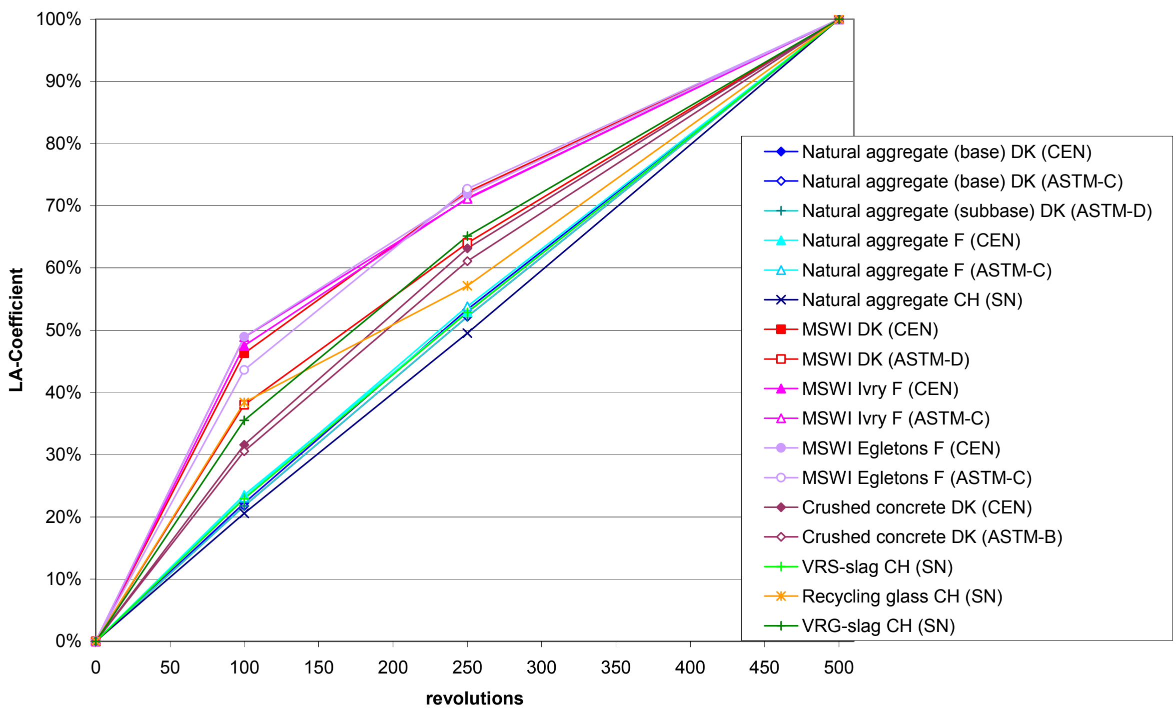



**Figure 4.2 Los Angeles coefficient normalised to 100% at 500 revolutions**

- ASTM-B and CEN-method of the Los Angeles test give approximately the same results for natural aggregates and alternative materials. ASTM-C shows up to 12% higher and ASTM-D slightly lower values compared to the CEN-method. For an ultimate statement the database is too small.

- Natural aggregates show a straight line in Figure 4.1, because the LA-coefficient is independent of the number of revolutions.
- Surprisingly, all MSWI samples tested according to the CEN method give the same curve, independent of the end value and their origin. It might be, that this way of representing the results shows some typical behaviour of certain material groups.
- The experimental Los Angeles test shows a perfect linearity of the response for natural aggregates, regardless of their mechanical resistance. Conversely it shows the non linearity for softer materials like the MSWI bottom ash group. Crushed concrete takes an intermediate position. This differentiation is much stronger at 100 revolutions than at 500 revolutions. A general law has been found for the response of each material to the Los Angeles test. It has the form of the function $\mathbf{y = a \cdot x^b}$. An exponent **b** close to 1 gives a straight line, which is found for natural aggregates. When the exponent **b** is decreasing the slope at the beginning is increasing and a curved line is observed (Figure 4.2). This behaviour is most clearly expressed by MSWI-type material. Thus, **b** can be considered as a material specific constant, describing the abrasion sensitivity at low mechanical stress. Factor **a** together with exponent **b** gives the final Los Angeles abrasion coefficient.

#### 4.1.5.2 Micro-Deval

**Table 4.4 Results of Micro-Deval testing**

| | Micro-Deval coefficient | | |
|---|---|---|---|
| **Number of revolutions** | 3000 | 6000 | 12000 |
| **Danish materials** | | | |
| Natural aggregate | **3.1** | **4.2** | **5.6** |
| Crushed concrete | **8.7** | **11.5** | **14.4** |
| MSWI | **23.9** | **30.9** | **40.6** |
| **French materials** | | | |
| Natural aggregate | **1.8** | **2.5** | **2.7** |
| MSWI Ivry | **23.6** | **26.7** | **28.6** |
| MSWI Egletons | **30.4** | **48.5** | **53.2** |
| **Swiss materials** | | | |
| Natural aggregate | **1.5** | **3.3** | **3.9** |
| Recycling glass | **4.2** | **5.8** | **8.4** |
| VRS-slag | **1.4** | **2.2** | **3.4** |

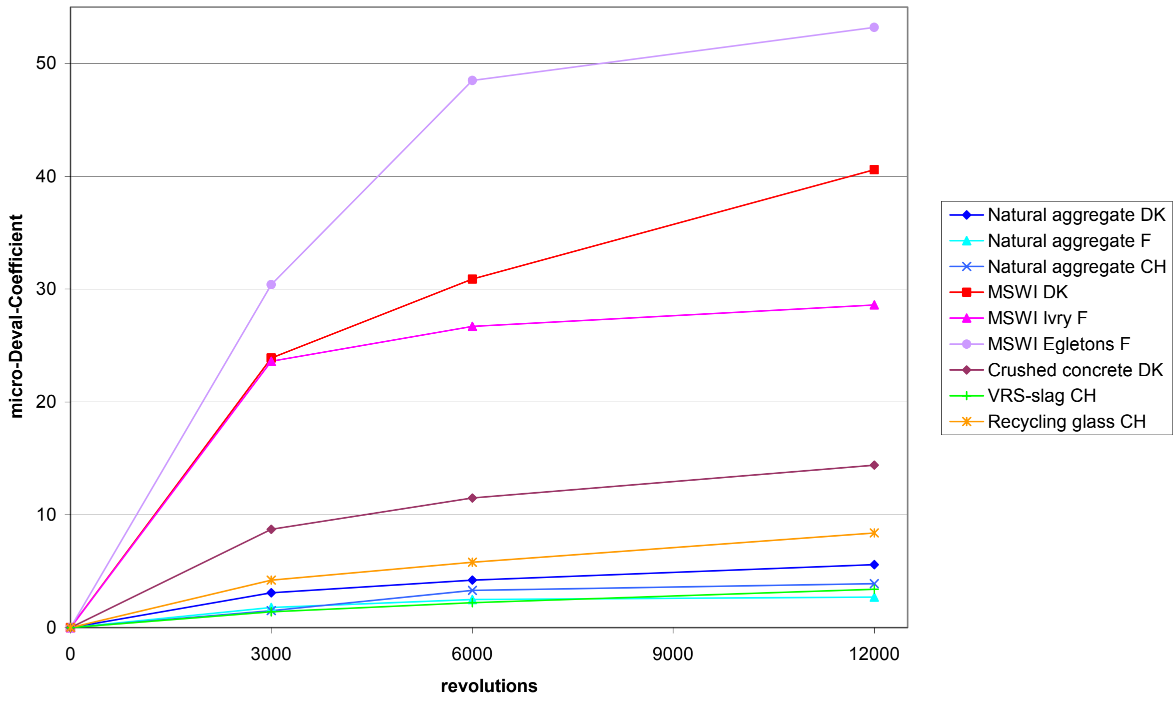



**Figure 4.3 Absolute Micro-Deval coefficients**

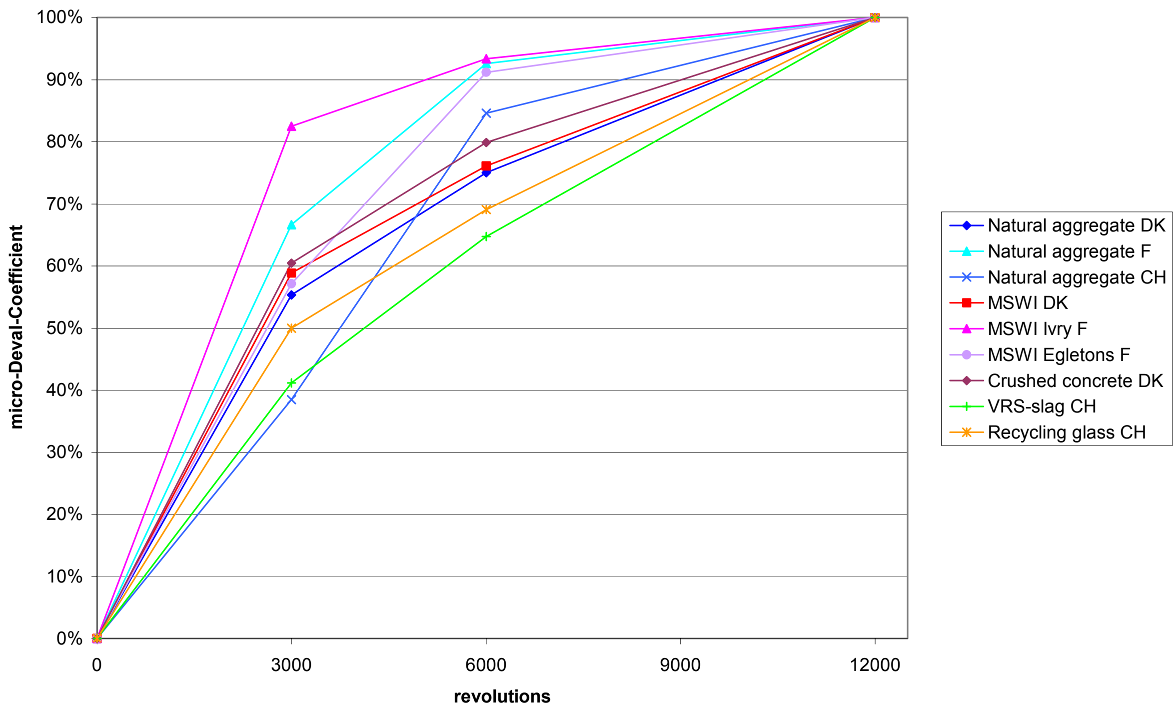



**Figure 4.4 Micro-Deval coefficients normalised to 100% at 12000 revolutions**

- There is a clear classification of the material groups by the Micro-Deval coefficient: natural materials indicate a value below 6, MSWI-bottom ashes are all above 25 and crushed concrete and recycling glass lie in between.
- Similar to the Los Angeles test results, the abrasion at the beginning (3000 revolutions) is much stronger than at the end (12000 revolutions) and lies above 50% of the end value for soft materials like MSWI (Figure 4.4)
- No classification is possible in analogy to Los Angeles coefficients using end values which are normalised to 100%. Natural aggregates do not give straight lines. They are dependent on the number of revolutions. Especially the French natural aggregate shows a high relative Micro-Deval coefficient at 3000 revolutions. But due to the small absolute values this could also be artificial.

#### 4.1.5.3 Gyratory compaction

Aggregate size distribution was determined before and after gyratory compaction on two test samples. Gyratory compaction was carried out with constant pressure and with online detection of the changing sample height. Compaction and sieving was done on dry material because of technical reasons. The same number of gyrations (178 turns) was chosen for the compaction as for the bituminous mixtures.

All aggregates were tested as delivered and the whole aggregate fraction was used without prior washing. The sample amount was determined in a pre-test in order to achieve approximately identical sample height at the end of compaction.

4.1.5.3.1 Compaction curves

There are major differences in the compaction curves of the different materials. Harder materials like natural aggregates show a slower drop than softer slags. Almost identical compaction curves were measured for the EMPA natural aggregate and recycling glass. But the different aggregate size distribution of the materials has also to be taken in consideration, when compaction curves are discussed.

Compaction curves give information about the compactability of a material, but no direct indication of their abrasion sensitivity.

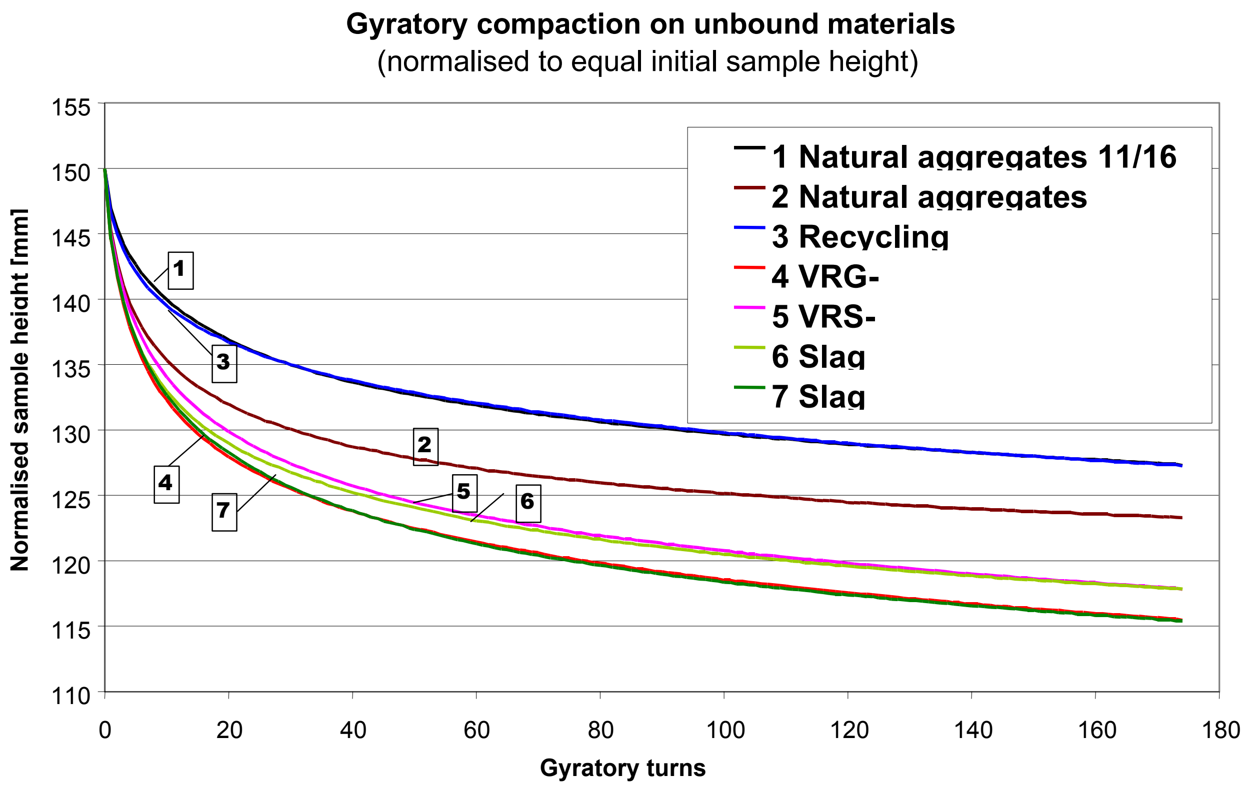



**Figure 4.5 Sample height as a function of the number of gyrations**
Compaction curves were averaged and normalised to the same initial sample height of 150 mm.

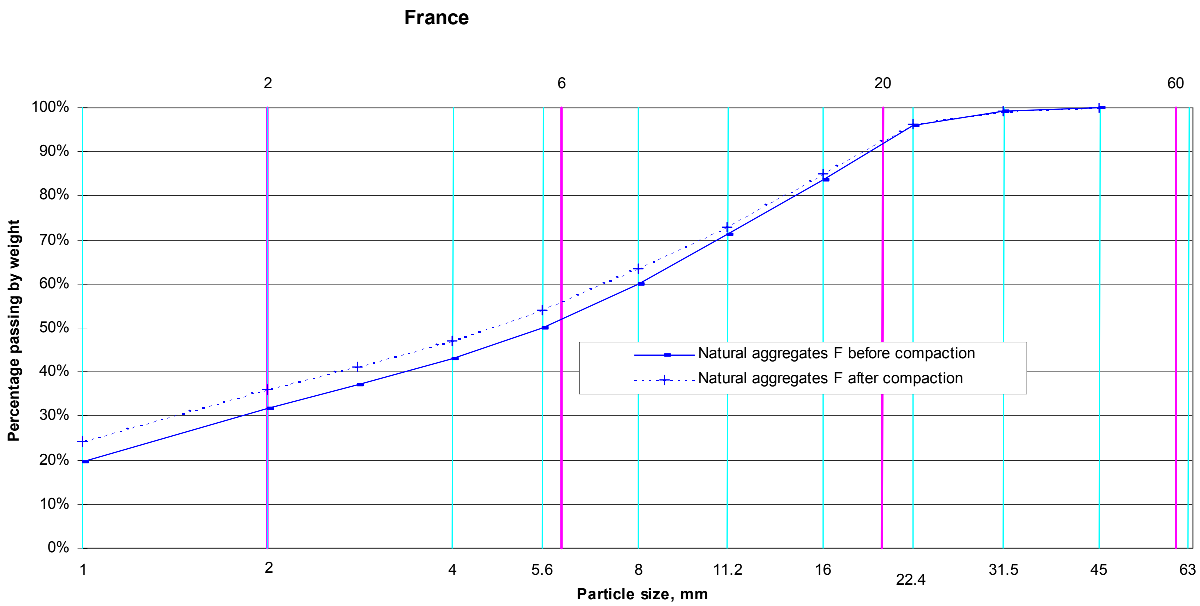
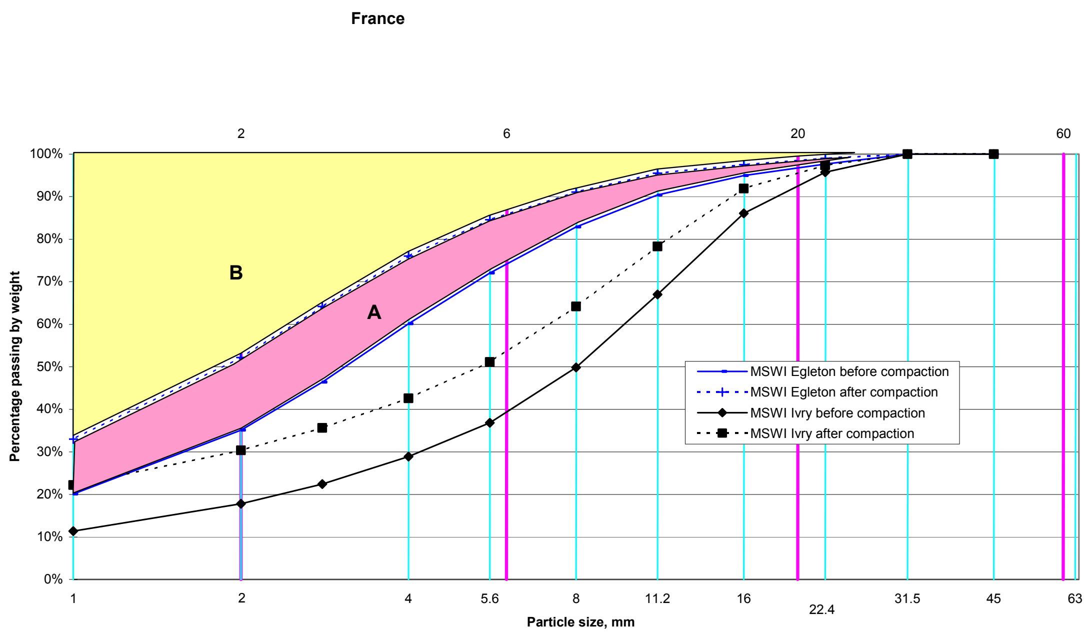
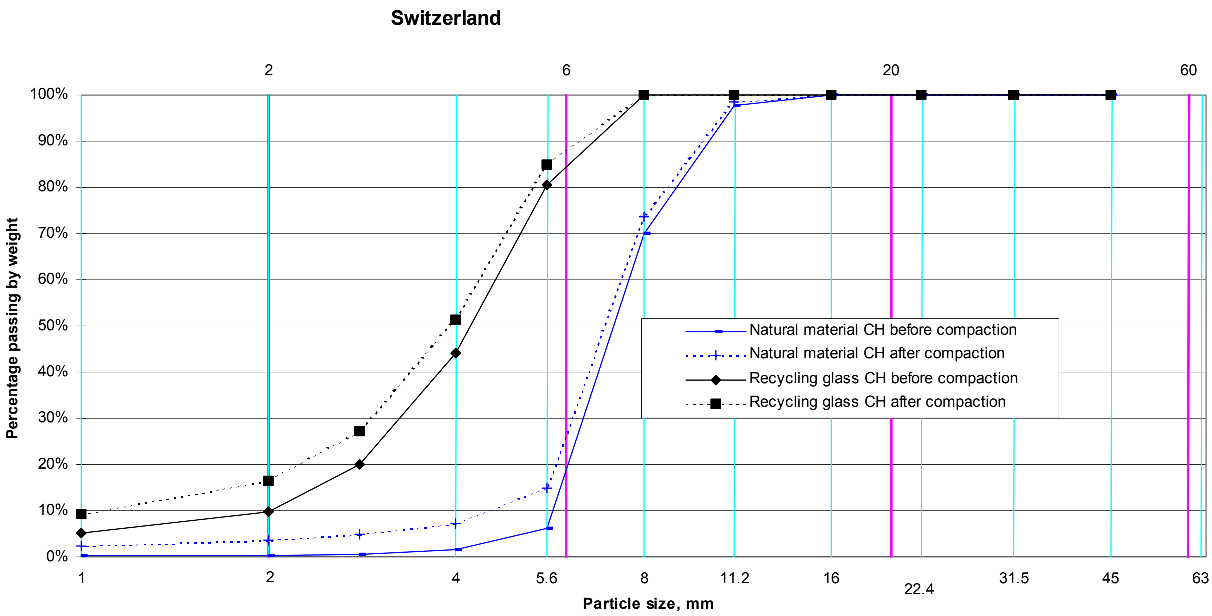



**Figure 4.6 Aggregate size distribution of French natural material before and after gyratory compaction**




## Figure 4.7 Aggregate size distribution of French MSWI before and after gyratory compaction




## Figure 4.8 Aggregate size distribution of natural material and recycling glass before and after gyratory compaction

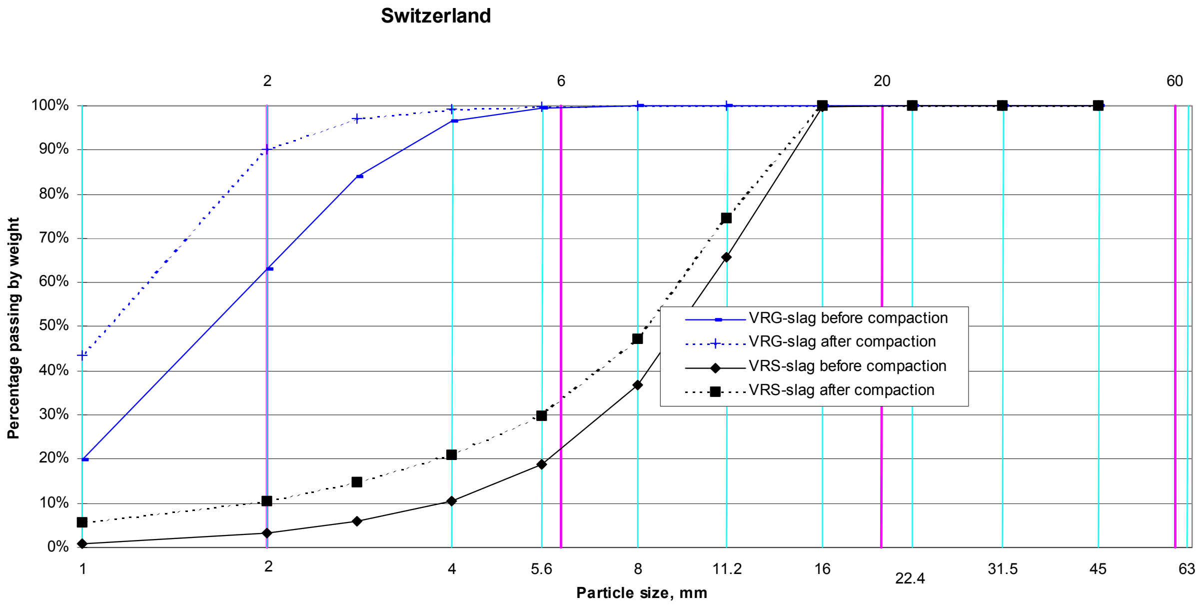



**Figure 4.9 Aggregate size distribution of slag before and after gyratory compaction**

4.1.5.3.2 Calculation

Similar to the Los Angeles and Micro-Deval test, it is possible to determine the fines below 1 mm produced during compaction and then calculate an abrasion coefficient. But this result gives no information about the other fractions. Therefore better results can be received, if the complete aggregate size distribution before and after compaction is determined by sieving. By measuring the area **A** between the two distribution curves and the area **B** above the curve after compaction, a coefficient independent of the aggregate size is obtained (figure 4.7):

$$\text{Gyratory area coefficient } c = \frac{A}{A+B}[\%]$$

For the samples tested the ranking is the same, whether calculating the fines produced or the coefficient determined following the area-method. But this is not necessarily always the case.

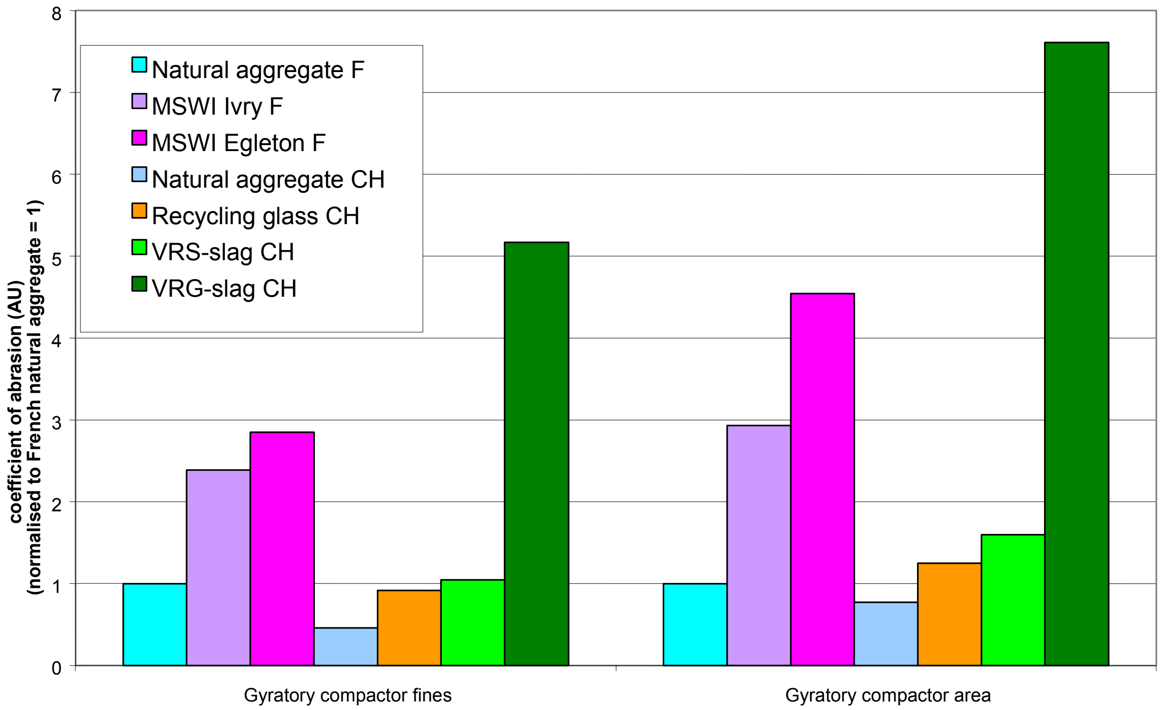



**Figure 4.10 Results of the gyratory compaction** (The French natural aggregate is taken as reference and set to a relative abrasion coefficient of 1. The results of the other materials are scaled linearly.)

4.1.5.3.3 Discussion

- Compaction could be carried out at optimal water content as it is done in the field to get even more realistic results.
- Aggregate size distribution as used for construction can be tested in the gyratory compactor, which is an advantage. Maximum aggregate size is determined by the diameter of the sample mould (150 mm diameter) and should not exceed 50 mm.
- In addition, sample height can be varied to some extent in order to have similar layer thickness as in the field.
- Repeatability is good with gyratory compaction as long as the aggregate size distribution of the two samples is close together.
- The method used to determine the abrasion properties with the gyratory compactor is not standardised for unbound materials. The number of gyrations or the pressure applied (constant 600 kPa) should be optimised in order to give similar results as in the field.

### 4.1.5.3 Vibrating table

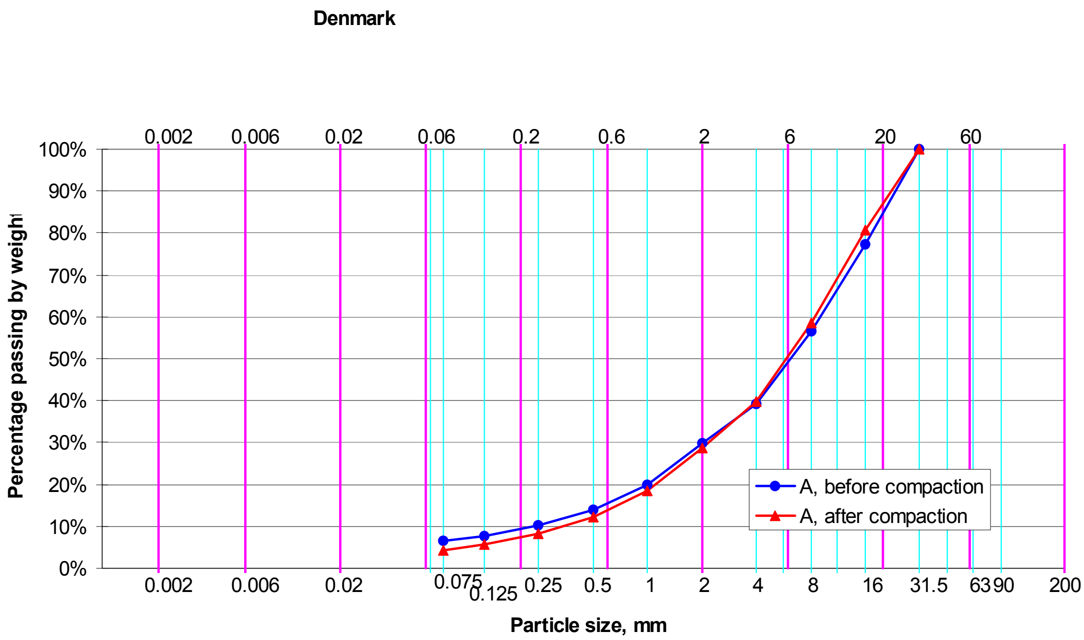



**Figure 4.11 French natural material before and after compaction with the vibrating table**

- The vibrating table is currently used to determine the optimal moisture content for compaction and the maximum dry density of the aggregates.
- Abrasion during compaction with the vibrating table is low and for good natural aggregates not quantifiable from the difference in the aggregate size distribution curves before and after compaction (Figure 4.11).
- Abrasion of soft materials like MSWI-bottom ash during vibrating table compaction lies probably in the same range as abrasion, which takes place during sieving to get the aggregate size distribution.
- The vibrating table compaction method, as it is defined in the European standard (CEN prEN 13286-5), is not suitable to measure abrasion or attrition during compaction.

### 4.1.6 Final conclusions and proposals for future research

Conclusions are based on the materials and tests investigated in this project. Due to the limited number of materials tested all conclusions have to be considered with caution.

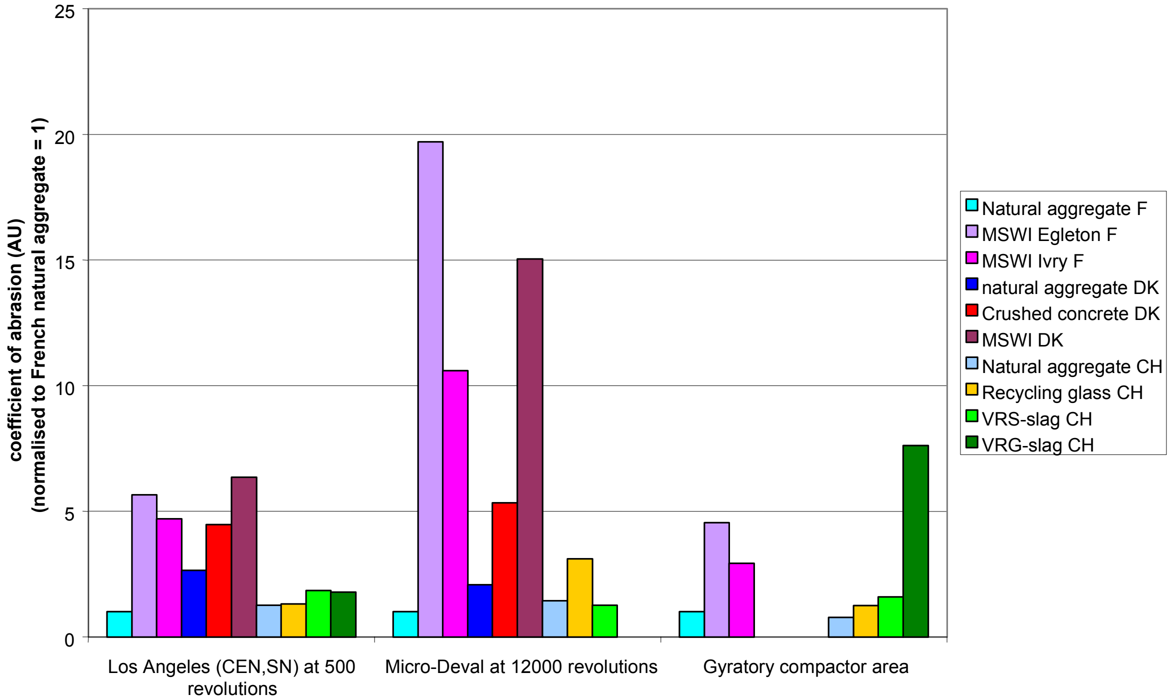



**Figure 4.12 Comparison of different test methods** (The French natural aggregate is taken as reference and set to a relative abrasion coefficient of 1. The results of the other materials are scaled linearly.)

#### 4.1.6.1 Conclusions

**Ranking of the materials by the three test methods for abrasion are roughly the same.**

This statement is correct for about 90% of the materials. Hard materials like all natural aggregates have low coefficients and all MSWI-ashes show high coefficients. For material in between, like crushed concrete, the inference is not so clear. According to the Los Angeles test, crushed concrete is not much better than MSWI-ashes, but in the Micro-Deval test it gives a much lower coefficient than MSWI-ashes.

A special case is the VRG-slag, which has a low LA-coefficient close to natural material, but in gyratory compaction it gives the highest value.

These two examples show that a few materials behave differently in the three tests investigated in the ALT-MAT project.

**Special attention has to be paid to the sieving of weak materials like MSWI-ash.**

Too long or too vigorous sieving could lead to a change of the aggregate size distribution, before it is tested by one of the test methods mentioned. As a consequence, the coefficients measured are too low.

**The number of revolutions for alternative materials in Los Angeles and Micro-Deval test have to be reconsidered.**

Natural materials show a linear relationship between the number of revolutions and the abrasion value for Los Angeles test. This is not true for alternative materials which show higher relative values at low revolutions than at the end. The question arises whether the 500 revolutions for Los Angeles tests and 12000 for Micro-Deval as fixed in the national or European standards are adequate for alternative materials.

**Differences in results using the various modifications of the Los Angeles test are insignificant.**

Results between Los Angeles test carried out according to CEN and different ASTM test options differ not more than 12% for the materials investigated in the ALT-MAT project.

**The Micro-Deval test shows the best differentiation of the materials.**

Figure 4.12 shows that differentiation of the materials is most pronounced in the Micro-Deval test, compared to the other test methods. Hard materials give abrasion coefficients below 2, for MSWI-ash it lies above 10 and values for crushed concrete and recycling glass are in between.

**The gyratory compaction method for unbound materials shows good results and should be optimised.**

Gyratory compaction simulates the compaction of pavement layers with a heavy steel roller in the field. The change in aggregate size distribution taking place during gyratory compaction of unbound aggregate mixtures give valuable information on the behaviour of unbound pavement layers. However, further work has do be done in the optimisation of compaction parameters (pressure, number of gyrations) by comparison of test results from laboratory tests and field experiments.

**The vibrating table compaction method (in wet condition) is a suitable method to determine the laboratory reference density of alternative as well as natural aggregates**

This laboratory compaction method is supposed to represent the compaction process by a vibrating roller in the field. There is almost no difference in aggregate size distribution before and after compaction for natural materials. Abrasion is about the same as during sieving and therefore not usable for soft materials and negligible for hard materials. Therefore the present vibrating table compaction method is not suitable to measure the abrasion or attrition sensitivity of materials.

#### 4.1.6.2 Proposed actions for the future

- **Performance related test methods (e.g. triaxial test) should be introduced.**

  Current test methods often characterise only one of the many properties of a material (e.g. abrasion, gyratory compaction test). That way, some aspects are neglected and others are overestimated. For more realistic statements test methods should take the complete system (pavement) into account. The triaxial test and gyratory compaction test, where the test sample consists of a complete aggregate mixture, are good examples of this kind of test method.

- **Test methods for long-term stability have to be developed.**

  The ageing behaviour of alternative materials is not covered with current test methods, because it was not necessary for natural aggregates. But there exist alternative materials, which undergo chemical reactions in the period of months or years (for example oxidation of sulphides). This often leads to changes of the material's mechanical stability and finally to damages in the pavement structure.

- **Test methods which do not involve a sieving step are needed.**

  As already mentioned, materials with high abrasion sensitivity may show considerable abrasion during sieving resulting in too low abrasion coefficients.

- **A test method for the prediction of the self-binding capability of alternative materials is needed.**

  From field tests it is known, that some materials (e.g. crushed concrete) show good bearing capacities although they have high Los Angeles coefficients. This is due to self-binding properties of these materials and is therefore independent of the abrasion sensitivity. Therefore an additional test to characterise this self-binding ability should be developed and introduced in the standards to assess the suitability of such alternative materials for unbound pavement layers.

- **Test methods should take into account the type of compaction and handling.**

  **and: Instructions for compaction and handling have to be defined depending on the type of alternative material.**

  Alternative materials are significantly influenced by the way they are compacted and handled in general. With special guidelines for the handling of alternative materials proper construction can be achieved even for abrasion sensitive materials.

## 4.2 EVALUATION OF TEST METHODS FOR FROST RESISTANCE

### 4.2.1 Introduction

This chapter includes the results of several test methods describing the frost resistance of materials used in road constructions. It is a summary of Danish, Finnish, French, Swedish, UK and Austrian results. Frost resistance in this report is the resistance of road construction materials to freezing and thawing.

### 4.2.2 Objectives

A broad variety of test methods describe the frost resistance behaviour. These methods are mainly designed for natural materials. Alternative materials sometimes react differently from conventional ones and in this case the test procedures do not describe the “insitu” behaviour of alternative materials. This is often due to their complex mineralogy. Secondary materials have been used in road constructions successfully though their 'laboratory performance' was rather bad. To get closer to reality it is necessary to bridge the gap between laboratory and field and to adapt the conventional laboratory test to more appropriate field conditions.

### 4.2.3 Test methods

More functional tests like the frost heave test are compared with conventional ones like determination of frost susceptible fines.

Several tests according to the present national standards were performed on the Austrian MWSI bottom ashes (refer to the table below). Frost resistance as a function of the water sensitivity of French MSWI ashes was tested with the methylene blue test (Appendix F4 5.1). Finnish blast furnace slag was tested for its segregation potential (Appendix F3 5. and 6.). Swedish crushed concrete was tested for its frost resistance according to a modified EN 1367-1 (Appendix F5 10.). British demolition rubble and steel slag were tested with a British Standard frost heave test (Appendix F7 4.). Frost heave tests were performed also with Danish crushed concrete and MSWI bottom ash (Appendix F2 5.1.4.). The tests were also performed on natural reference materials.

| Test | Standard | Country | Description |
|---|---|---|---|
| Frost resistance test | ÖNORM B 3123 part 3 | Austria | water saturated grain fractions, sealed in a plastic box to avoid evaporation undergo several freeze thaw cycles, fraction below 1.6 mm is determined, LA-value before and after freeze-thaw cycles |
| Frost susceptibility (weight % < 0.063 after modified proctor test) | RVS 8S.05.11 (Pkt. 3.2.5), ÖNORM B 4418 | Austria | determination of fraction < 0.063 mm after modified proctor compaction, fines must not exceed 4 w-%, if material is well proven in practice 5 w-% fines are allowed without further investigations, if fines are between 4-8 w-% the mineralogy of fraction < 0.020 mm has to be determined and “water sensitive” minerals (e.g. clay minerals, iron oxides) must not exceed certain limits; industrial by-products or reclaimed materials with unknown mineralogy have to be tested with national standard frost heave test |
| Frost heave test | RVS 11.062, ÖNORM B 4412, SN 670 320b | Austria | proctor compacted material in an open proctor mould with thermocouples and water suction from the bottom undergo several freeze-thaw cycles, CBR-values are determined before and after freeze-thaw cycles |
| Frost heaving behaviour in climate chamber | not standardised | Austria | proctor compacted and partly water saturated material in special large plastic boxes undergo several freeze-thaw cycles, surface deformation after each step is measured and compared to those of well proven natural material |
| Frost heave test | not standardised | Denmark | Denmark´s technical university method |
| Methylene blue test | prEN 933-9 | France | determination of potentially water sensitive fines |
| Frost heave test | not standardised | Finland | determination of the segregation potential |
| Frost resistance test | EN 1367-1 | Sweden | water saturated grains sealed in a sheet metal can are exposed to several freeze-thaw cycles, the mass difference before and after the freeze-thaw procedure (after sieving) is measured |
| Frost heave test | BS 812 Part 124 | UK | in principle similar to the Austrian procedure, specification of mean and maximum frost heave |

Due to the fact that the test performed by each country differs from each other only relative comparisons can be made.

### 4.2.4 Results

#### 4.2.4.1 Frost resistance and susceptibility tests

Austria:
The more fragile and porous structure of the MWSI bottom ash investigated leads to a larger proportion of grains smaller than 1.6mm after the freeze-thaw resistance test in comparison to natural materials. The frost susceptibility test resulted in more than 8% (by weight) < 0.063 mm; therefore according to the national standard frost-heave tests had to be performed.

France:
The French MSWI ashes passed the methylene blue test with a value below the 0.2 limit. The methylene blue test indicates the presence of possible water sensitive fines without respect to their mineralogical composition. The French MSWI ashes investigated have less fines than the Austrian ones (France 4.9-6.2 % < 0.08 mm, Austria 7.5-8.6 % < 0.063 mm). See also section 9.5.

Sweden:
The Swedish modification of EN 1367-1 was performed both with deionised water and with a 1% solution of NaCl. The freeze-thaw test with the salty solution gave about 2-3 times higher proportion of fines than the test performed with water (See section 9.6).

#### 4.2.4.2 Frost heave tests

Austria:
The frost heave tests (after RVS 11. 062) showed a mean deformation of about 1 mm. Regarding the frost heave, the Austrian bottom ashes passed the test, but the bearing capacity was decreased far beyond the “normal” decrease of about 20% in CBR. Currently, the criteria for the judgement of materials by frost heave tests are not standardised in Austria but depend on the experience of the official in charge. The climate chamber boxes containing bottom ash materials showed a quite similar frost heave to the dolomitic reference material, which is not frost susceptible (See figure 4.13). No results were obtained for box 4.

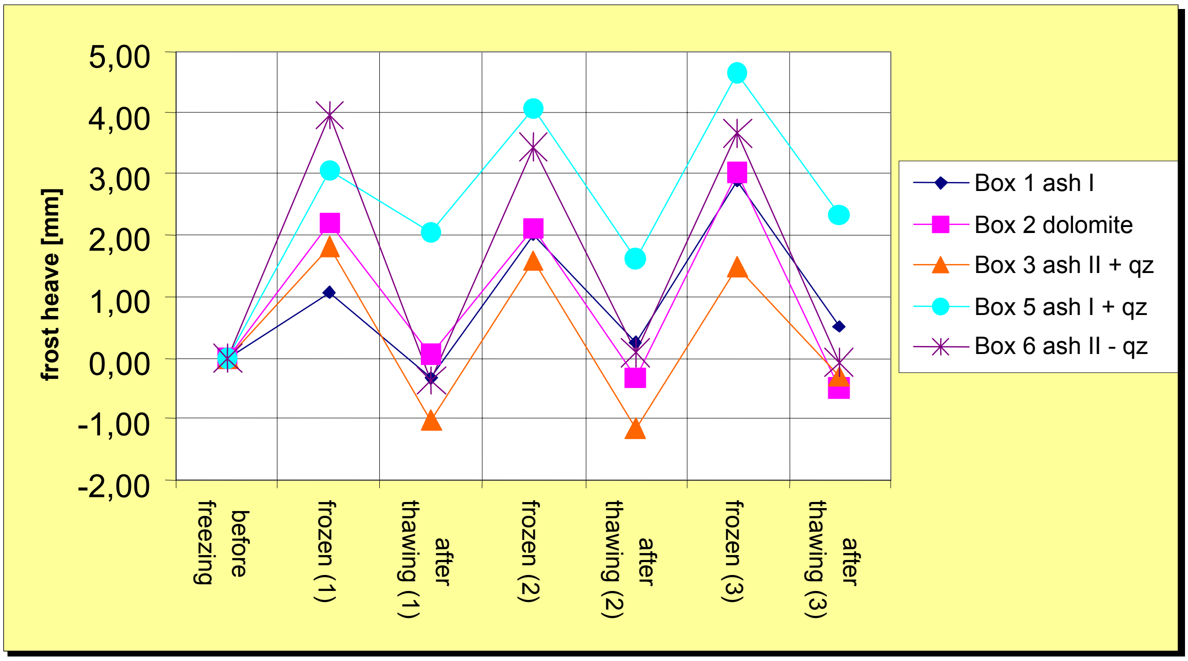



**Figure 4.13 Mean values for frost heave in mm of the climate chamber box materials; qz...quartz gravel**

Denmark:
Crushed concrete material showed similar frost heave behaviour to the natural reference material (sandy gravel). MSWI bottom ash showed less deformation than the natural material (sand).

UK:
The British steel slag showed twice the values of the reference material limestone. Demolition rubble gave about 3 times higher frost heave values than the national reference material. Only the demolition rubble gave values above the national limiting value.

### 4.2.5 Conclusions and recommendations

For testing sub-base and base material the results of the indirect way of testing (frost resistance) are sometimes (e.g. Austria) in contradiction with the frost heave test. Functional methods like the frost heave test simulate the processes of freezing and thawing at small scale and their results are easier to transfer to reality. They also provide information on the restrictions in use.

For well established road construction materials a huge database is available to transfer results of indirect test methods to practical conditions. For alternative materials in road construction such a database is largely lacking.

For a preliminary assessment of material used in pavements, the conventional test methods like EN 1367-1 are appropriate. It would be worthwhile to also take a functional test for this application of alternative materials into account.

Marshal specimens or hydraulic bound specimens could be subjected to similar temperature regimes.

For sub-base and base applications, functional tests, i.e. frost heave tests combined with measurements of the bearing capacity (if possible a functional test measuring bearing capacity), are recommended to assess the frost resistance of alternative materials.

## 4.3 EVALUATION OF TEST METHODS FOR BITUMINOUS BOUND MATERIALS

The mechanical characteristics of bituminous bound materials are a combination of aggregate and binder properties, but in addition the interaction between binder and aggregate is also of crucial importance. Because of this fact, a good quality of both binder and aggregate does not necessarily give a good bituminous bound material. Porosity and smoothness of the aggregate, and also the chemical characteristics of the binder and aggregate, play an important role in the adhesion strength between the two components. Of course, this is also true when alternative materials aggregates are used for bituminous bound materials. Recycling glass, for example, showed a worse performance than natural aggregates when bituminous bound samples were tested with the indirect tensile test (see Appendix F6, Part 2: Swiss national report for mechanical tests on bituminous mixtures). This is a result which is related to the smooth surfaces of the glass particles, which showed an insufficient adhesion strength to bitumen.

In general, test methods for bituminous bound samples and mixtures give valid results for alternative materials, because they are mostly insensitive to the type of aggregate or alternative material. Caution is advised if non-mechanical test methods like tests involving x-rays or other radiation types are used. Alternative materials could behave very differently from natural aggregates in such cases.

## 4.4 OVERVIEW AND EVALUATION OF MECHANICAL LABORATORY TESTS

### 4.4.1 Introduction

This chapter provides an overview and evaluation of the mechanical laboratory tests. A sub-group has reviewed the methods used and has given recommendations for mechanical laboratory tests for alternative materials in road construction.

### 4.4.2 Objectives

The objectives are to give end-users an easily read overview of the laboratory tests for the examination of mechanical properties of alternative materials. The future development of tests, new tests and modified existing tests, should reflect the trends in the European Standardisation Organisation, CEN. The needs for additional information on mechanical testing for alternative materials are given in a brief list.

### 4.4.3 Test methods

This chapter gives an overview of the mechanical tests developed (or under preparation) by the European Standardisation Organisation CEN. The corresponding national test methods are currently used in the ALT-MAT partners' countries. European national standards are expected to be replaced by European standards in 2003/2004.

The test methods are listed in the table below, which also reflects the relevance of the methods for alternative materials in relation to their end use, the time consumption/costs of the method and the purpose of using the test. Unpublished - but planned - European test methods are not in the list.

Only tests usable for aggregates are given in the list. Tests for bituminous bound mixtures are generally evaluated to be more or less independent of the aggregate type.

# Overview and evaluation of mechanical laboratory tests

| Test method title | European Standard no. | Technical relevance | | Time consumption / costs | | Purpose | | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | high | low | high | Low | Compliance testing | Basic characterisation | |
| **Test for general properties of aggregates** | | | | | | | | |
| Methods for sampling | EN 932.1 | x | | x | | x | x | |
| Methods for reducing laboratory samples | prEN 932.2 | x | | | x | x | x | |
| Procedure and terminology for simplified petrographic description | EN 932.3 | | x | | x | | x | An improved method is needed for alternative materials |
| Common equipment and calibration | prEN 932.5 | | | | | | | ) The methods are of general |
| Definitions of repeatability and reproducibility | prEN 932.6 | | | | | | | ) relevance for laboratory<br>) activities |
| **Tests for geometrical properties of aggregates** | | | | | | | | |
| Determination of particle size distribution - Sieving method | EN 933.1 | x | | | x | x | X | |
| Determination of particle size distribution - test sieves, nominal size of apertures | EN 933.2 | | | | | | | The methods are of general relevance for laboratory activities |
| Determination of particle shape - flakiness index | EN 933.3 | | x | x | | | x | Only relevant for aggregates for asphalt |
| Determination of particle shape - shape index | prEN 933.4 | | x | x | | | x | Only relevant for aggregates for asphalt |
| Assessment of surface characteristics - percentage of crushed and broken particles in coarse aggregate | EN 933.5 | | x | x | | | x | Only relevant for aggregates for asphalt and unbound bases |
| Determination of shell content - percentages of shells in coarse aggregate | prEN 933.7 | | x | | x | | x | |
| Assessment of fines - sand equivalent tests | prEN 933.8 | | x | | x | | x | |
| Assessment of fines - methylene blue test | EN 933.9 | | x | | x | | x | |

| **Test method title** | **European Standard no.** | **Technical relevance** | | **Time consumption / costs** | | **Purpose** | | **Remarks** |
|---|---|---|---|---|---|---|---|---|
| | | **high** | **low** | **high** | **Low** | **Compliance testing** | **Basic characterisation** | |
| **Tests for mechanical and physical properties of aggregates** | | | | | | | | |
| Determination of the resistance to wear (Micro-Deval) | EN 1097.1 | x | | x | | x | x | |
| Methods for the determination of resistance to fragmentation (Los Angeles) | EN 1097.2 | x | | x | | x | x | |
| Determination of loose bulk density and voids | EN 1097.3 | | x | | x | (x) | x | |
| Determination of void in dry compacted filler | prEN 1097.4 | | x | | x | | x | Only relevant for aggregates for asphalt |
| Determination of water content by drying in a ventilated oven | prEN 1097.5 | x | | | x | x | x | |
| Determination of particle density and water absorption | prEN 1097.6 | x | | x | | | x | |
| Determination of particle density of filler - Pycnometer method | prEN 1097.7 | | x | x | | | x | |
| Determination of polished stone value | prEN 1097.8 | x | | x | | x | x | Only relevant for aggregates for asphalt wearing courses |
| Method of determination of the resistance to wear by abrasion from studded tyres: Nordic test | EN 1097.9 | x | | x | | x | x | Only relevant for aggregates for asphalt wearing courses |
| **Tests for thermal and weathering properties of aggregates** | | | | | | | | |
| Determination of resistance to freezing & thawing | prEN 1367.1 | | x | x | | | x | |
| Magnesium sulphate test | EN 1367.2 | | x | x | | | x | |
| Determination of volume stability (Sonnenbrand) | prEN 1367.3 | | | | | | | Only relevant for armour stones |
| Determination of drying shrinkage | EN 1367.4 | | x | | x | | x | |
| Determination of resistance to thermal shock | prEN1367.5 | | | | | | | Only relevant for aggregates for asphalt |

| Test method title | European Standard no. | Technical relevance | | Time consumption / costs | | Purpose | | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | high | low | high | Low | Compliance testing | Basic characterisation | |
| **Test for chemical properties of aggregates** | | | | | | | | |
| Methods for determination of chloride content | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Methods for determination of acid soluble sulphate content | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Method for determination of total sulphur content | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Method for determination of impurities that affect setting and hardening of cement | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Method for determination of impurities that affect surface finish | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Method for determination of water solubility | EN 1744.1 | | x | | x | x | x | Only relevant for concrete |
| Method for determination of loss on ignition | EN 1744.1 | x | | | x | | x | |
| Method for determination of slag unsoundness | EN 1744.1 | x | | | x | | x | |
| Method for determination of free lime | EN 1744.1 | | x | x | | | x | |
| **Complementary test for unbound mixtures** | | | | | | | | |
| Test methods for laboratory reference | prEN 13286.1 | x | | x | | x | x | |

| **Test method title** | **European Standard no.** | **Technical relevance** | | **Time consumption / costs** | | **Purpose** | | **Remarks** |
|---|---|---|---|---|---|---|---|---|
| | | **high** | **low** | **high** | **Low** | **Compliance testing** | **Basic characterisation** | |
| density and water content - General | | | | | | | | |
| Test methods for laboratory reference density and water content - proctor | prEN 13286.2 | x | | x | | x | x | Not recommended for weak alternative materials |
| Test methods for laboratory reference density and water content - Vibrocompression with controlled parameters | prEN 13286.3 | x | | x | | x | x | |
| Test methods for laboratory reference density and water content - Vibrating hammer | prEN 13286.4 | x | | x | | x | x | |
| Test methods for laboratory reference density and water content - Vibrating table | prEN 13286.5 | x | | x | | x | x | |

**Specialised laboratory tests**

Apart from the test methods listed above, some specialised tests for alternative materials have been carried out in the ALT-MAT project. These are highlighted in the inter-laboratories cross-testing programme between Denmark, France and Switzerland and are reported in section 4.1: "Evaluation of Test Methods for the Abrasion Behaviour of Alternative Materials."

A number of tests on bituminous mixture have been carried out in Switzerland. Tests for bound applications are being developed by CEN. In general, test methods for bituminous mixture are independent of the aggregate type.

**Field tests**

A number of field tests have been carried out under ALT-MAT WP3. Performance related field tests are not as yet prepared by CEN. The performance related field tests (surface conditions and bearing capacity) are evaluated to be of equal relevance for natural and alternative materials. As to field compaction tests (nuclear gauge and sand replacement), the nuclear gauge test is not always applicable for alternative materials (e.g. MSWI bottom ash).

### 4.4.4 Recommendation for test methods and procedures for the future

The following CEN standard test methods are evaluated to be relevant and usable for alternative materials for unbound applications.

| **Test method** | **Reference** |
|---|---|
| Methods for sampling | EN 932.1 |
| Methods for reducing laboratory samples | prEN 932.2 |
| Determination of particle size distribution | EN 933.1 |
| Determination of the resistance to wear (Micro-Deval) | EN 1097.1 |
| Methods for the determination of resistance to fragmentation | EN 1097.2 |
| Determination of water content by drying in a ventilated oven | prEN 1097.5 |
| Determination of particle density and water absorption | prEN 1097.6 |
| Method for determination of loss on ignition | EN 1744.1 |
| One of the standards prEN 13286.2-13286.5 Test methods for laboratory reference density and water content: | |
| Proctor | prEN 13286.2 |
| Vibrocompression with controlled parameters | prEN 13286.3 |
| Vibrating hammer | prEN 13286.4 |
| Vibrating table | prEN 13286.5 |

For weak alternative materials tests using vibration (e.g. vibrating table) instead of Proctor (impact) are recommended.

Limiting values for the parameters should be set on a national basis, having due regard to the local climate and experience with the relevant materials. In some cases, it may be necessary to determine site-specific limiting values for particular materials.

For alternative materials, the same functional field tests (surface, bearing capacity) as for natural materials are recommended.

The nuclear gauge is not recommended for determination of the in situ density of MSWI bottom ash.

Additional information is needed on:

- an improved method to describe the material composition as to weight proportion of e.g. crushed brick, concrete, asphalt, rock, clay, glass, metals, rubber and plastic,
- an improved method of determination of density grading, e.g. determination of lightweight contaminators,
- an improved understanding of the test results for the sand equivalent and methylene blue test in respect to alternative materials,
- an improved understanding of freeze/thaw resistance of the mixture and particles,
- test methods for long-term stability (ageing behaviour),
- instructions for storing, handling and compaction to be defined depending of the type of the alternative materials, and test methods to take into account the type of compaction,
- gyratory compaction as a "link between laboratory test results and reality",
- performance related test methods (e.g. triaxial test),
- a test method for the prediction of self-binding capability of alternative materials.

# 5 ENVIRONMENTAL TESTS AND THE USE OF SCENARIOS

## 5.1 INTRODUCTION

The primary objective of performing environmental tests on alternative materials used in road construction is to enable assessments of the potential or actual impact on the environment caused by these materials. The results may be used both in a site-specific context and in a more general way to develop a rationale for the setting of criteria for material quality and road design, which will ensure adequate protection of the environment. It is very important to recognise that the testing itself constitutes only part of the impact assessment and criteria development procedures. The test results obtained must be combined with other information (e.g. information on water flow) and placed in the proper context to provide appropriate answers to the questions asked prior to the testing. This implies the use of *scenarios*, i.e. descriptions of the physical situations under consideration.

Environmental tests may also be used for quality control purposes, i.e. to monitor/ensure that materials to be used in road construction comply with regulations and criteria. In this project, environmental tests have further been used to compare the properties of virgin materials, materials that have already been in use for a period of time and reference materials.

This chapter presents the environmental test methods, primarily leaching tests, used in the ALT-MAT project. Selected results are also presented, and their possible application for scenario calculations is addressed. The main objective has been to select, test and recommend reliable laboratory leaching tests suitable for prediction and monitoring of the environmental behaviour of alternative materials used for road construction. Another objective has been to compare and relate the results of laboratory leaching tests, preferably standardised tests, to the results of more comprehensive lysimeter and climate chamber tests, aiming at the simulation of leaching under field conditions. Finally, it has also been an objective to demonstrate the application of leaching data in scenario calculations.

## 5.2 TEST METHODS

### 5.2.1 Information needed on environmental properties

The potentially relevant information on the environmental properties of the alternative materials to be used for road construction may be summarised as follows:

- Total chemical composition/content of selected components;
- Leaching behaviour:

- determination of potential leaching of selected contaminants
- determination of actual or expected leaching of selected contaminants as a function of liquid to solid ratio (L/S) and/or time;
- influence of pH, redox potential, complexing, etc. on the leaching behaviour.

Information on the total chemical composition of the materials or the total content of selected components is important as a basis for further characterisation. The major constituents of the material largely determine its chemical properties and control the leaching conditions when the material comes into contact with water. Potentially harmful components may, even if they are present only in trace amount, be released into the environment and cause unacceptable damage unless specific precautions are taken. From a risk assessment perspective, the chemical composition itself is of limited interest, because the alternative materials used in road construction are usually not accessible for direct contact with humans or other living organisms, the only exception being potential contact and fugitive dust posing potential inhalation/ingestion problems during the construction period. Both of these potential health risks are easily countered by conventional techniques and are not considered further in this context. It is important to note that some of the methods prescribed by regulations for determination of the composition of alternative materials to be utilised for road construction do not necessarily determine the true total content of e.g. inorganic constituents. The results should be interpreted accordingly, and the method of digestion/analysis should always be listed.

Determination of total composition of a material would also include determination of total organic content (TOC), loss on ignition (LOI) and alkalinity. Most alternative materials used in road construction are largely inorganic, mineral materials, but some of them, e.g. MSWI bottom ash, may have a largely undesired residual content of organic material.

Although the information on total composition forms an important background for the characterisation of a material, the major property of interest in relation to an assessment of the environmental impact of the material when used in road construction is its leaching characteristics. The leaching test(s) used in a given situation depend(s) upon the nature of the question(s) to be answered, and it will in many cases be necessary to perform more than one test. The major aspects of leaching to be considered in this context are potential leaching, actual or expected leaching as a function of time or L/S and the influence of various factors such as pH, redox potential, complexing, etc. on the leaching behaviour. Consideration should also be given to whether the material must be considered granular or monolithic, and whether the leaching is controlled primarily by equilibrium or steady-state like conditions or by diffusion from a solid body into the water phase. Most of the materials studied in this project are granular, and most of the tests methods used are performed under total or local steady-state like conditions. However, the water flow regime in a road may impose leaching conditions under which the transfer of contaminants is controlled by diffusion processes rather than convective transport. An experimental pre-standard method, the granular tank leaching test, for determination of leaching under these conditions exists, but has not been applied in this project.

### 5.2.2 Selection of leaching tests

A first step in the determination of the leaching properties of a material will be to determine the potential leachability, i.e. the total amount of various components, usually expressed in mg/kg, that can be leached from the material even over a very long period of time. In this project, the so-called availability test is used for this purpose. The availability test is a two-step batch leaching test carried out at 2 x L/S = 100 l/kg under pH-static conditions on material which has been size-reduced to < 0.125 mm in order to remove obstacles to solid phase diffusion. In the first step, pH is maintained at 7.0 and in the second step it is maintained at 4.0. The contact time is 3 hrs in both steps. The two extracts are filtered, combined and analysed for the components of interest. An availability test may be used as a screening tool to determine which components should be analysed in the eluates from subsequent tests performed under “milder” conditions which may to a larger extent resemble field conditions. A special variation of the availability test, performed under strongly oxidising conditions, is included as an option. The purpose of this test is to disclose whether the leaching properties of a reducing material will change dramatically if it is oxidised, e.g. as a result of exposure to ambient conditions.

For granular materials it will be of interest to determine the actual leaching, which under certain assumptions could be expected to occur in a road. It is generally useful to describe the composition of the eluate or the accumulated amounts leached of the components of interest as a function of the L/S. For a given physical scenario and flow regime the L/S scale can be transformed into a time scale. Which test method should be chosen depends on the question to be answered and the degree of detail needed. If interest is focused on the initial leachate from the material, which often carries the highest loads of contaminants, the test should be carried out at a relatively low L/S ratio. This would imply the use of a column leaching test, which in many ways simulates field conditions quite closely, although it is an accelerated laboratory leaching test. If less degree of detail is needed and/or average results representing longer time periods are acceptable, a single or multiple batch leaching test may be performed at higher L/S ratio(s). In this project, column tests are being performed for L/S = 0–2 l/kg, and the proposed European two-stage standard batch leaching test, CEN prEN 12457-3, is performed at L/S = 0-2 l/kg and 2-10 l/kg.

Large scale lysimeter leaching tests and climate chamber leaching tests are, in principle, column leaching tests performed under conditions which more closely resemble field conditions or simulate aspects of field conditions, which are not normally addressed by more routine laboratory tests. In this project, both lysimeter and climate chamber leaching tests were used to evaluate the results of routine laboratory tests simulating leaching behaviour.

The influence of pH on the leaching properties of the materials is investigated by performing a series of pH-static extractions over a range of pH-values at an L/S of 10 l/kg on material, which has been size-reduced to < 0.125 mm.

### 5.2.3 Testing at different levels

In order to facilitate the testing of materials in a regulatory and scientific framework, it is recommended that the approach of testing at different levels developed by CEN/TC 292 is adopted:

**Level 1: Basic characterisation**

Basic characterisation tests are used to obtain information on the short and long term characteristics and leaching behaviour of materials. The effect of varying L/S ratios, leachant composition and factors controlling leachability, such as pH, redox potential, complexing capacity and physical parameters, are addressed in these tests. These tests include column tests, pH-static tests and availability tests (Table 5.1).

**Level 2: Compliance testing**

Compliance tests are used to determine whether the material complies with specific reference values. The tests focus on key variables and (leaching) behaviour identified by basic characterisation tests. These tests include batch leaching tests and determination of pH, alkalinity, TOC and LOI (Table 5.1).

**Level 3: On-site verification**

On-site verification tests are used as a rapid check to confirm that the material is the same as that which has been subjected to the compliance test(s).

A new alternative material should always be characterised at Level 1 before it is considered for utilisation in road construction or for any other applications. Once a material is well characterised at Level 1, quality control and monitoring can be carried using simpler routine compliance tests at Level 2.

### 5.2.4 Overview of tests applied in the ALT-MAT project

In the ALT-MAT project, the methods shown in Table 5.1 were chosen for the laboratory testing of the environmental properties of the alternative materials. In addition, the national regulatory tests were performed in those countries where such tests exist (see appendices).

**Table 5.1 Overview of laboratory test methods used and recommended for granular alternative materials**

| ***Test method*** | **Test level (in general)** | **Tests that to some extent simulate actual leaching behaviour** |
|---|---|---|

| | | |
|---|---|---|
| Determination of pH (in contact with water at L/S = 100 l/kg) and alkalinity | 2 | |
| Determination of TOC and LOI (at 550 °C) | 2 | |
| Total content of major and trace constituents | 1 | |
| Availabilitiy leaching test (L/S = 2 x 100 l/kg, pH = 7 and 4, analysis of both extracts), Nordtest NT ENVIR 003 | 1 or 2 | |
| Oxidised availability test (optional), Nordtest NT ENVIR 006 | 1 or 2 | |
| Two-stage serial batch leaching test at L/S = 0-2 l/kg and 2-10 l/kg, CEN prEN 12457-3 or Nordtest NT ENVIR 005 | 2 | X |
| Column leaching test to L/S = 2 l/kg, analysis of 5 eluate fractions, Nordtest NT ENVIR 002 | 1 | X |
| pH-static leaching test at L/S = 10 l/kg, 3 or 4 pH values (determined by the own pH of the material and the scenario considered). Method under preparation by CEN/TC 292 WG6 | 1 | |

On a few materials, lysimeter and climate chamber leaching tests were also carried out.

The chemical analyses to be carried out on the materials and/or the eluates from the leaching tests were the following:

First priority: pH, conductivity, chloride, sulphate, Na, K, Ca, Mg, Fe, Mn, Si, Al, As, Cd, Cr (total), Cu, Mo, Ni, Pb, Zn, V, alkalinity, LOI, NVOC/TOC

Second priority: Ba, Se, Sb, Hg, Total N, redox potential.

## 5.3 EVALUATION OF LYSIMETER AND CLIMATE CHAMBER TESTS

The purpose of the climate chamber and lysimeter tests is to simulate field conditions of road structures. This gives opportunities to overlap the difference in scale between experiments performed in the laboratory and full-scale trial embankments. The lysimeters are open to the atmosphere and the actual precipitation is collected, while the climate chambers record the release of contaminants due to accelerated climatic cycles.

### 5.3.1 Lysimeters

The materials used were an air-cooled blast furnace slag (ACBF slag). The slag studied in the lysimeter tests originates from Luleå and is of the same type as the slag from Oxelösund used for the leaching tests.

The MSWI bottom ash originated from a plant of mass burn type with moving grates and a capacity of 200000 tonnes/year. Grate siftings were combined with the ash. The ash was stored for about two weeks before it was put into the lysimeter. The concrete originates from several projects and was sorted to get a clean concrete fraction, the exact origin is not known. An outline of the lysimeter system is shown in figure 5.1.

The crushed concrete had been stored before put into the lysimeter and the L/S reached during the storage was about 0.1 based on reached L/S in crushed rock during the same time. The lysimeters with ACBF slag and MSWI bottom ash were already present, with previous series of measurements available, and the installations for measurements of percolating water were restarted. Two lysimeters filled with till and crushed rock respectively have been in operation since 1993 and was used as reference materials. The crushed rock is a conventional base course. The till originates from the area of Norrköping, Sweden.

For ACBF slag and MSWI bottom ash it was only possible to take three samples. From the lysimeter with crushed concrete nine samples were taken. Complete results of the leachate analysis from the alternative materials and reference materials are presented in Appendix F5. Results from earlier investigations on ACBF slag and the same MSWI bottom ash have been included (Fällman, 1997). Results are given in tables as accumulated leached amounts (mg/kg) and diagrams of different elements.

#### 5.3.1.1 Comparison with reference materials

Leached amounts from the *ACBF slag* of S, Cu, Co and Ni exceeded the leached amounts from the reference materials by ten times or more. The differences between leaching methods for these potentially harmful elements were examined further below, see Table 5.2. The elements Fe, As, Cd, Cr, Hg and Mo and also Pb for the last three samples, were below the detection limit. Leached amounts from the *crushed concrete* exceeded leached amounts from the reference materials for K, Na, Cr, Co and Cu, while Fe, Mg, As, Cd, Hg, Mn and V were below the detection limit. From the *MSWI bottom ash* leached amounts of the most of the main components and Co, Cr, Cu and Ni exceeded leached amounts from the reference materials. Fe, As, Hg and V were below the detection limit.

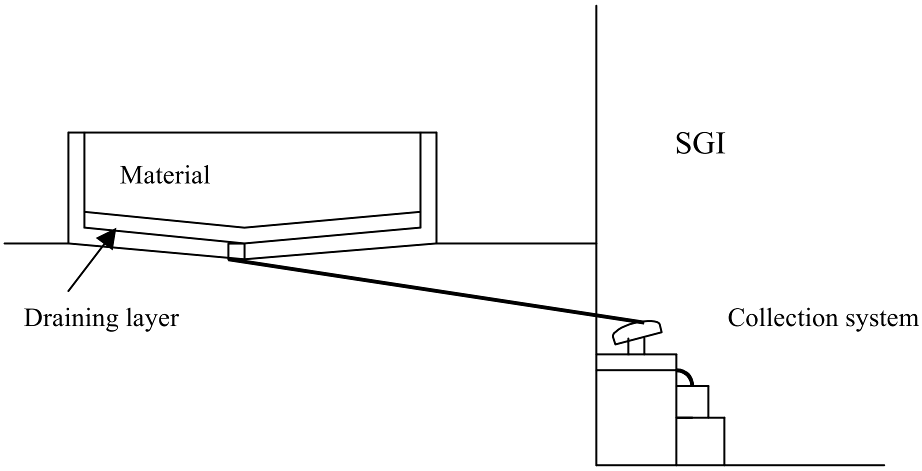



**Figure 5.1 An outline of the SGI lysimeter system**

The pH-value for ACBF slag and MSWI bottom ash is in the same range as for the crushed rock but higher than the till. For crushed concrete the pH-value is higher than both the reference materials.

### 5.3.1.2 Comparison with laboratory leaching tests

In Figure 5.2 the pH-values of the column test, the two- stage batch test and the lysimeter test performed on the *ACBF slag* are shown. The ACBF slag samples were taken from different levels in a road; the numbers in the legends refer to these levels. The pH-values fluctuate strongly in the lysimeter test, and the values are lower than for the leaching tests. Leached amounts of sulphur and Co, Cu, Ni and Zn were found to be higher in the lysimeter test than in the leaching tests (Table 5.2). In Figure 5.3 the leached amounts of Ni are shown.

The initially low pH in the lysimeters was most probably the cause of the increased leaching of the potential harmful elements (exceeding reference materials). It seems that laboratory tests cannot satisfactorily predict leaching in a field situation. Such a low pH was not reproduced in any of the laboratory tests.

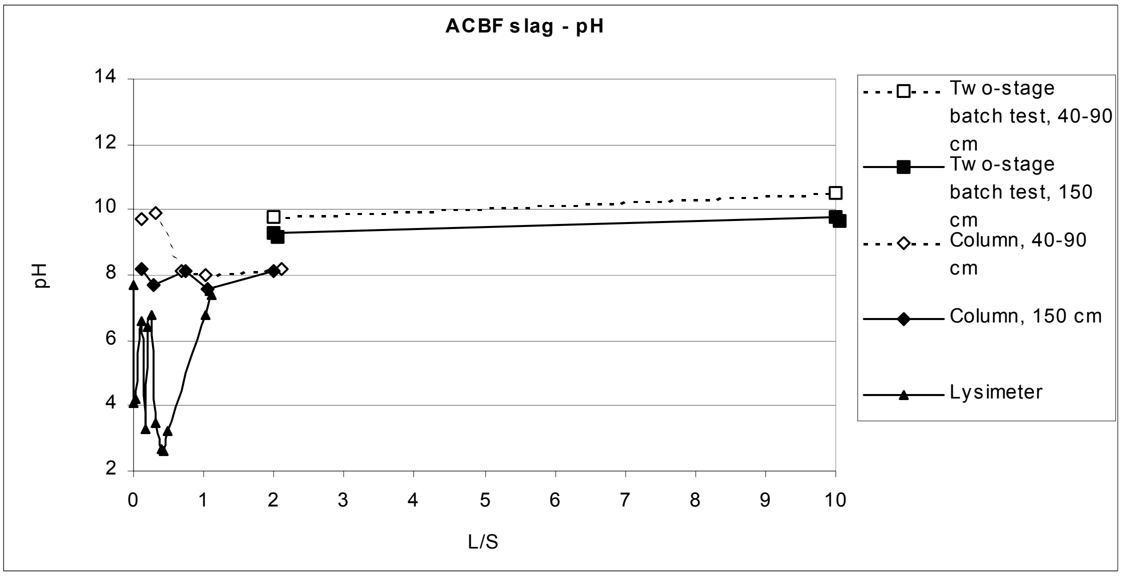



**Figure 5.2 The pH-value in the column test, two-stage batch test and lysimeter test on ACBF slag**

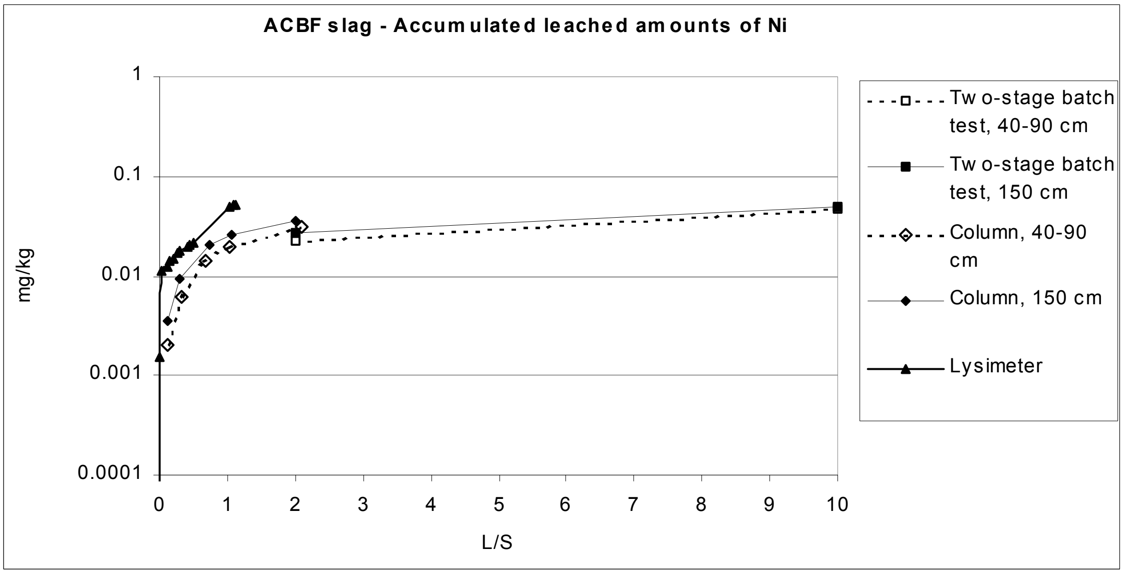



**Figure 5.3 Leached amounts of Ni in the column test, two-stage batch test and lysimeter test on ACBF slag**

The low pH-value is believed to be caused by the oxidation of sulfides. A special test was set up to enhance the sulfur oxidation (modified column tests Appendix F5), but no extreme pH-values were found. Two explanations are possible: either the duration of the modified column tests were insufficient for an acid release, or the buffering capacity of the material placed in the road will in the long run be sufficient to prevent the release of acid.

The pH-values in the column test, the two-stage batch test and in the lysimeter test performed on *crushed concrete* are shown in figure 5.4. At the beginning of the lysimeter test the pH-value is in the same range as the leaching tests. In the last sample in the lysimeter test however the pH dropped considerably, though remaining on the alkaline side. This might be due to carbonation of the material, producing carbonate of the slaked lime that is a constituent of the crushed concrete. In the modified column tests (not presented here) the decrease of pH was even more pronounced.

**Table 5.2 Comparisons of column tests with lysimeters for ACBF slag**

| Element | Acc. Leached amounts from *lysimeters*, L/S = 1 (mg/kg)[1] | Acc. Leached amounts from *ordinary column tests*, L/S = 1 (mg/kg) | Concentration in leachates from *lysimeters*, L/S = 1 (µg/l) | Concentration in leachates from *ordinary column tests*, L/S = 1[1] (µg/l) | Concentration in leachates from *modified column tests* (max. value)[2] (µg/l) |
|---|---|---|---|---|---|
| Co | 0.0062 | 0.0024 | 3.14 | 1.97 | 0.255 |
| Cu | 0.31 | 0.042 | 62.4 | 18 | 3.86 |
| Ni | 0.036 | 0.026 | 27 | 17 | 0.709 |
| V | - | 0.36 | <50 | 337 | 160 |
| S | 2881 | 426 | 666000 | 291000 | 256000 |

[1] The maximum value of two replicates is shown
[2] The maximum concentration during the wetting –drying cycles is presented

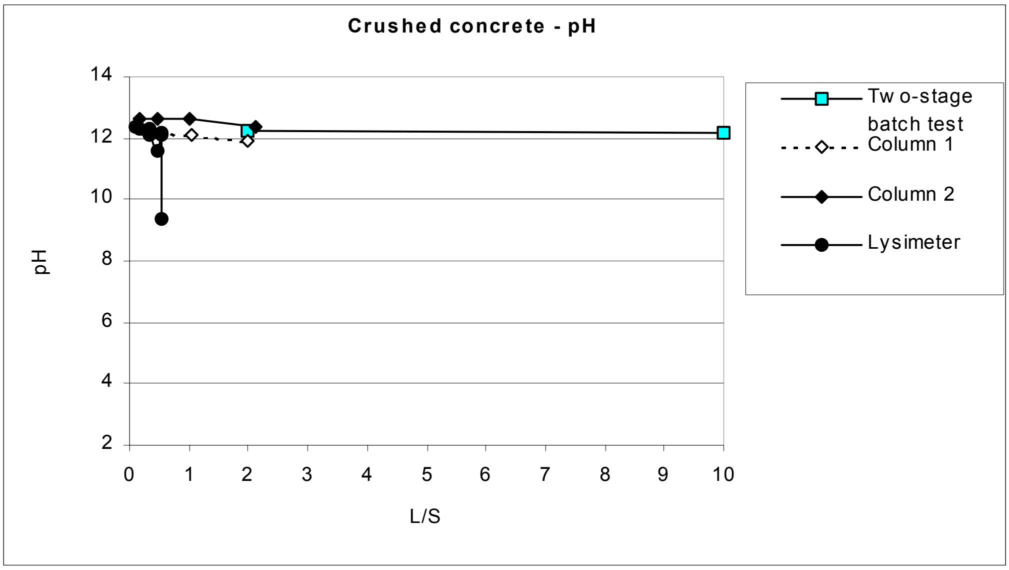



**Figure 5.4 The pH-value in the column test, two-stage batch test and lysimeter test on crushed concrete**

For crushed concrete, other substances than for the ACBF slag were found to have a higher leaching or higher total content compared to the natural reference materials. These (Cr, Cu, Ni and Pb) are examined below to see if there are contradicting results from the different applied test methods, see Table 5.3.

For the crushed concrete it is the modified column test that gives the highest concentrations of Cr and Cu, while Pb and Ni have the highest concentrations in the ordinary column test. The lysimeters have lower accumulated leached amounts of the trace elements than the column tests. Column tests would thus be appropriate to use since it would not underestimate the leaching in a field situation for these potentially harmful elements.

**Table 5.3 Comparisons of column tests with lysimeters for the crushed concrete**

| Element | Acc. Leached amounts from *lysimeters*, L/S = 0.44[1] (mg/kg) | Acc. Leached amounts from *ordinary column tests*, L/S = 0.5[2] (mg/kg) | Concentration in leachates from *lysimeters*, L/S = 0.44[1] (µg/l) | Concentration in leachates from *ordinary column tests*, L/S = 0.5[2] (µg/l) | Concentration in leachates from *modified column tests* (max. value)[3] (µg/l) |
|---|---|---|---|---|---|
| Cr | 0.012 | 0.098 | 33 | 176 | 330 |
| Cu | 0.014 | 0.020 | 33 | 24.5 | 38.7 |
| Ni | 0.005 | 0.010 | 7.31 | 21.7 | 8.69 |
| Pb | 0.00044 | 0.021 | <0.2 | 45 | 0.22 |
| Sulfate | 27.6 | 19 | 15000 | 35000 | 420000 |

[1] During the operation of the lysimeter a L/S of 0.44 was reached
[2] The maximum value of two replicates is shown
[3] The maximum concentration during the wetting –drying cycles is presented

### 5.3.2 Climate chambers

Climate chambers allow the simulation of many years of freezing-thawing and wetting-drying cycles in a few months under carefully controlled conditions. These tests were carried out in Austria, where MSWI bottom ash was used, and in Finland, where steel slag was used. Natural reference materials were also used in both cases.

Illustrated below is a comparison of different leaching methods for the analysis of chromium on the ferrochromium steel slag. For several of the investigated elements analytical results were below detection limits. As can be seen in the example (Figure 5.5), concentrations of chromium are extremely low in comparison with total amount and availability, and the amount leached in the climate chamber test is much less than in the two-stage batch test.

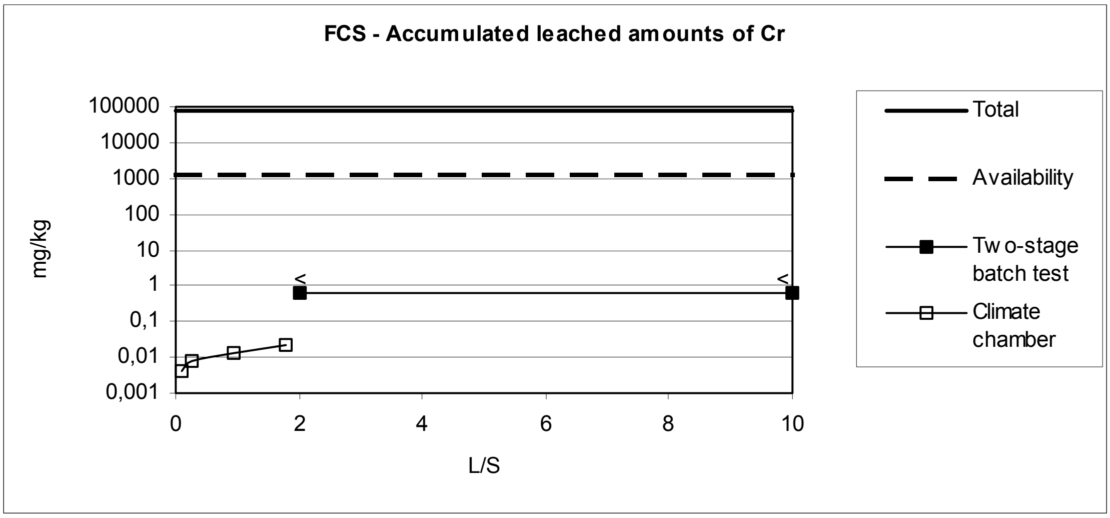



**Figure 5.5 The concentrations of chromium as a function of L/S- ratio for climate chamber tests and batch leaching tests (rewritten from Appendix F3)**

A slight difference was found between pH-values of the CEN batch tests and climate chamber tests for the steel slag. In the batch test pH was 9.7 and 9.2 for L/S = 2 and L/S = 10 respectively while in the climate chamber tests the pH-values were initially at 8.5 decreasing to 7.7 at a reached L/S of 1.81. The laboratory test thus gives a conservative estimate of the impact on the environment due to leaching from the material. Comprehensive information on comparisons of climate chamber tests with other leaching tests on ferrochrome slag is found in Appendix F3, together with comparisons for blast furnace slags.

In the climate chamber tests performed on *MSWI* bottom ash the pH-values were initially very high (up to 11.8) but decreased slightly after approximately 4 months of wetting-drying by about 0.5 to 1 pH-units (Figure 5.6). Tests were performed on a number of boxes filled with varying mixtures of ash and inert natural material, with two boxes of dolomite as a reference material. The natural reference material, dolomite, gave an initial pH of about 9.2. This also decreased with time to between 8.0 and 8.5 (Figure 5.6).

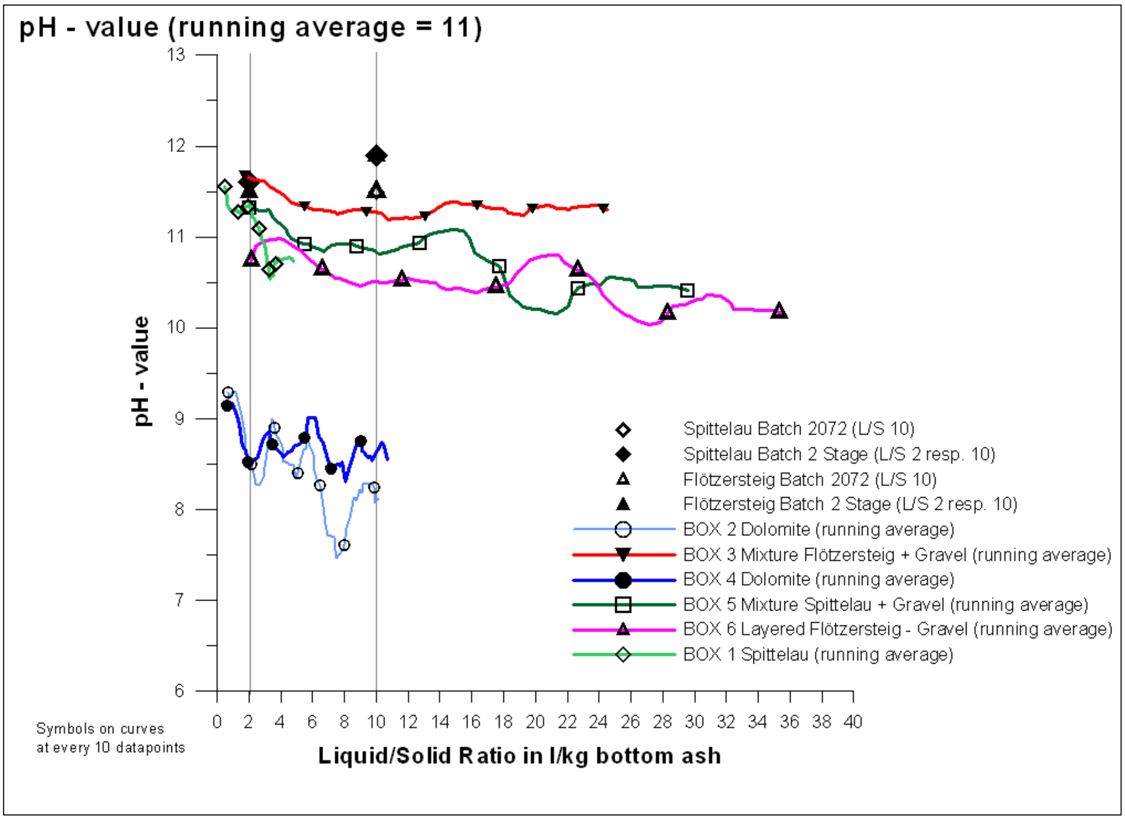



**Figure 5.6 Austrian MWSI bottom ashes – development of pH-value with increasing L/S-ratio during the climate chamber tests**

The reason for a change in pH could be carbonation when the alkaline slag reacts with carbon dioxide from the air. These reactions will occur as a function of exposure time. This has been noticed in the ALT-MAT project. During the inspection of existing roads in France, at a field site with MSWI bottom ash (Le Mans), a mean pH-value of 8.2 was found in contrast to the newly produced bottom ash at Egleton with a mean pH-value of 10.6 (Appendix F4). Similar results were found in Denmark where a lowered pH was noted on batch leaching tests performed on material excavated in 1998 compared to the testing that was done in 1993 on the same material (Appendix D). Such carbonation reactions will also have important implications on the leaching behaviour. It was observed in the studies from the site in France that both Pb and Zn were less leached when pH decreased from 12.3 to 10.7 and 12.3 to 11.5 respectively. Below is an illustration of the effect of the pH-value on concentrations of aluminium (Figure 5.7). Data are taken from the national testing of MSWI of material from Ivry, France and from Austrian testing of MSWI (MVA Spittelau).

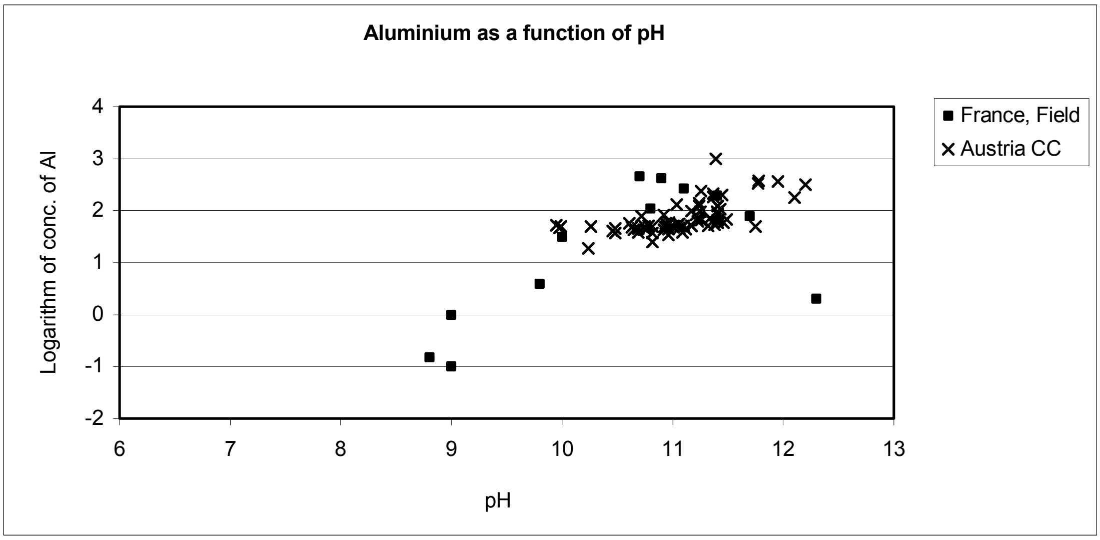



**Figure 5.7 Concentrations of aluminium (logarithm of mg/l) as a function of pH**

Generally a decrease from pH-values of over 10 will be beneficial since it will decrease the leaching of several of the potentially harmful elements such as Zn, Pb and Al and often also others. This means that storage of alkaline material in some instances may be advantageous for the leaching properties of the materials.

In the following, the results concerning the Austrian MSWI bottom ashes will be discussed in more detail.

Climate chamber tests (CCT) and two kinds of batch tests were performed on the Austrian MSWI bottom ashes (ba). For the climate chamber tests two reference boxes containing dolomite gravel (grain size 8/32 mm) and four boxes with MSWI ba (grain size 0/32 and 0/8 mm) were employed. Pretests showed that pure MSWI ba boxes had a very low permeability, which decreased with test duration due to the self-compacting properties of the ashes (from $10^{-7}$ to $10^{-9}$ m/s within 4 weeks). Therefore only one box was run with pure bottom ash, the others contained bottom ash in a mixture with inert quartz (grain size 8/32 mm) and a layered structure MSWI ba – inert quartz. The reason for the mixture of the inert was on one hand to collect a representative amount of leachate, and on the other hand to comply with the national standards concerning the grading of (sub)base material. The total weight of the samples ranged from 80 to 180kg.

A brief test description is given in Table 5.4.

**Table 5.4 Test methods for Austrian tests on MSWI bottom ash**

| *test method* | *brief description* |
|---|---|
| **climate chamber test** | 4 boxes containing MSWI bottom ash and bottom ash with quarz gravel to enhance the permeability; 2 boxes containing dolomite as reference material |
| | **9 wetting-drying cycles** (each consisting of 1 day wetting, 2 days drying, 1 day wetting and 3 days drying) |
| | **3 freezing-thawing-wetting cycles** (each consisting of 3 days freezing, 3 days thawing and 1 day wetting) |
| | **10 wetting-drying cycles** (each consisting of 1 day wetting, 2 days drying, 1 day wetting and 3 days drying) |
| **ON S2072 - single stage batch test** | L/S = 10; 24 hours of leaching; grain size < 10mm |
| **ON EN 12457-3 - two stage batch test** | L/S = 2 and 8 (cumulative: 10); 6 and 18 hours of leaching; grain size < 4mm |

A comparison between the various tests was performed on the basis of the cumulative loads (mg/kg bottom ash) at L/S=2 and L/S=10. The main components in the leachate of the different tests were Cl, $SO_4$ and Na, followed by Ca, K and Al. Out of the minor and trace elements Mo, Cu, Cr, Zn and Pb were the highest concentrations in the leachate.

During the CCT, the loads of the major elements were within the same range for all boxes except those of Mg and Al. The differences might be due to material inhomogeneities and/or differing permeabilities of the box materials. The results of the minor and trace elements were heavily influenced by the detection limits of the analysis. Therefore only a restricted number of elements are applicable for a comparision between batch tests and CCT.

After the end of the CCT only Na and Cl showed plateau values concerning the cumulative loads. All other elements were still dissolved in comparably high amounts even after approx. 4 months of testing (pH 10.5 – 11.5). For Na, Cl, Mo, $SO_4$ and Cu a major portion of the total dissolved amount was released in the first stages of the CCT (L/S approx. 2-5), whereas Ca, Sb and V showed an opposite behaviour. Al, K, Cr and Pb lie in between these two extremes. The conductivity, as a measure for the total amount of dissolved matter, decreased very quickly with increasing L/S-ratio.

Concerning the batch tests, in nearly all cases the one-stage batch test resulted in higher cumulative loads at L/S = 10 than the two-stage batch test. This might be due to inhomogeneities in the material.

For a comparison between the 2-stage batch test and the CCT, See Table 5.5 and Figures 5.8 and 5.9.

**Table 5.5 Summary of leaching test results on MSWI bottom ash**

| *Major elements* | *at L/S 2* | *At L/S 10* |
|---|---|---|

| | | |
|---|---|---|
| Highly soluble elements (Na, K, Al, $SO_4$) | climate chamber > 2-stage batch | Climate chamber >= 2-stage batch |
| Solubility controlled by pH-value (Ca, Al) | climate chamber >= 2-stage batch | Climate chamber < 2-stage batch |
| Mg | climate chamber >> 2-stage batch | Climate chamber >> 2-stage batch |
| ***Minor & trace elements*** | ***at L/S 2*** | ***At L/S 10*** |
| Loads of climate chamber test higher than 2-stage batch test | V, Cr (ash II), Cu, Zn, Mo, Sb, Pb | V (ash II), Cu, Zn, Mo (valid for 2 out of 3 boxes) |
| Loads of climate chamber test lower than 2-stage batch test | Cr (ash I) | V (ash I), Cr, Sb, Pb |

At L/S = 2, the cumulative loads of the CCT exceed those of the two stage batch test in most cases.

At L/S = 10, a distinction has to be made between highly soluble elements and elements of lower, pH-dependent solubility:

- The cumulative loads of the highly soluble elements like Na, Cl, K, $SO_4$ and Mo are slightly higher and in the same range with both tests (CCT and two stage batch test).
- Elements with a heavily pH-dependent solubility like Al, Ca (and partly sulfate) are overestimated by the batch test at L/S = 10. To some extent this holds also for Sb, Cr and Pb. This might be due to the pH-decrease ($pH_{L/S=10}$ ~ 12 for the two stage batch test compared to ~ 10.5 to 11.5 for the CCT) and recrystallization and carbonation processes during the CCT. The above processes did not take place in the batch test and diminished the rates of dissolution of these elements.
- Magnesium had much higher cumulative loads in the CCT than in the batch tests. This could be due to the presence of slowly hydrating magnesium oxide and the pH-differences between CCT and batch tests.

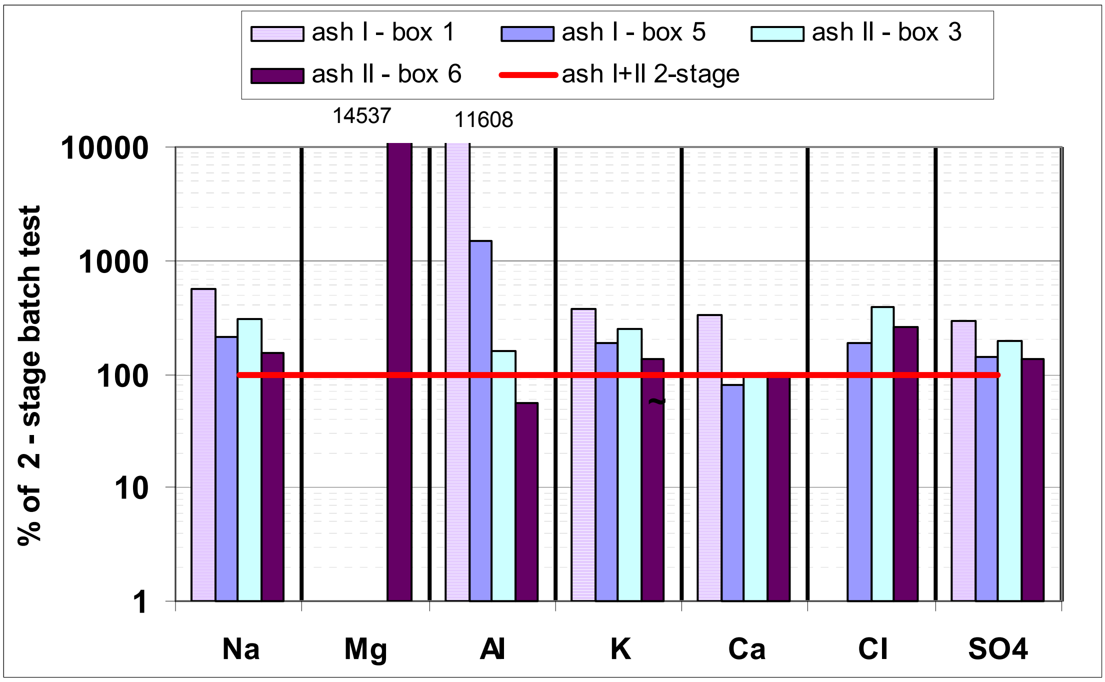



**Figure 5.8 Comparison for the major elements between batch tests and CCT in % of the 2-stage batch tests at L/S = 2**

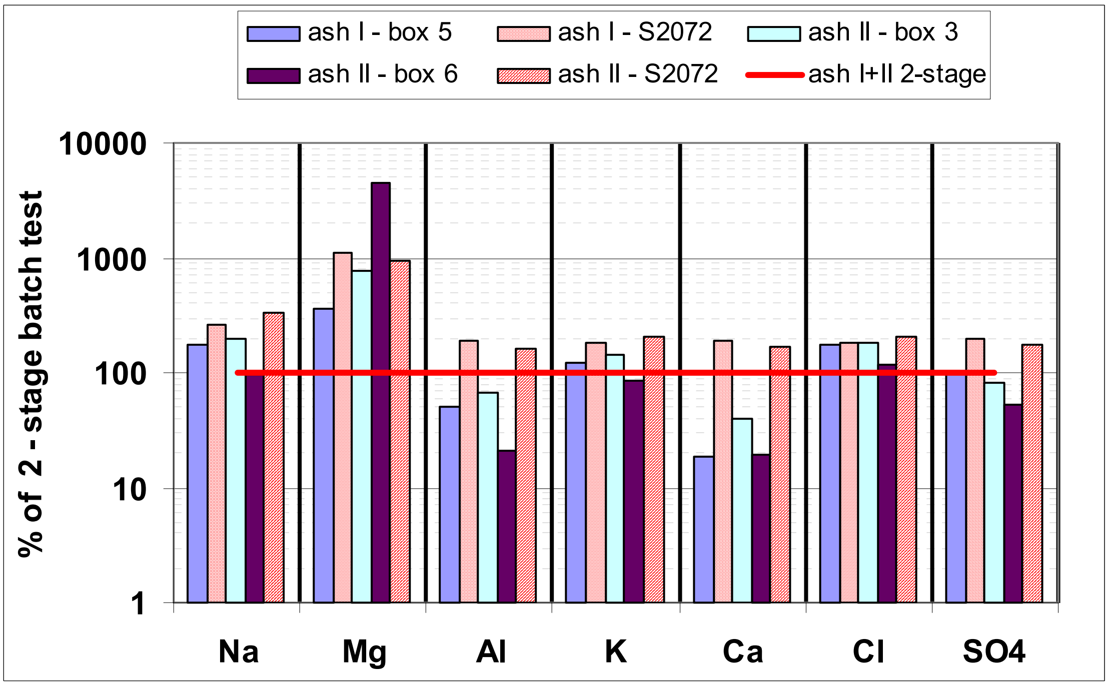



**Figure 5.9 Comparison for the major elements between batch tests and CCT in % of the 2-stage batch tests at L/S = 10**

Summing up, the various tests applied on the Austrian MWSI bottom ashes (CCT, one and two stage batch tests led to markedly differing results. It has to be kept in mind that during the CCT several steps of elution were carried out up to a certain L/S – ratio while during the batch tests just one or two of these steps were performed. Secondly, the amount of material tested was much larger in the CCT than in the batch tests (approx. 140kg vs. 100g); therefore material inhomogeneities can have a large impact on the results of the batch tests. Thirdly, ageing processes like carbonation, phase transformation and reprecipitation during drying are unlikely to be present during the batch tests.

For the above reasons none of the batch tests was able to predict the behaviour of the MSWI bottom ashes during the CCT. In general the results of the two stage batch test were closer to the CCT than those of the one stage batch test. As in the CCT, highly soluble elements e.g. Na, Cl (and partly $SO_4$) were removed to a large extend during the first step of elution. The high concentration of these elements over the whole testing period might be the reason for the higher amount of dissolved matter within the one stage batch test. Nevertheless, the pH-dependent elements like Ca, Al, (Sb, Cr, Pb) were overestimated by the two stage batch test as well.

During the CCT the freezing-thawing cycles (FTC) had a significant impact on the leaching properties of the Austrian MSWI bottom ashes.

- High rates of dissolution during the FTC wetting operations were found for Fe, Zn, Pb and Mn. Possibly the “sudden” release was due to an increased contact time between leachant and bottom ash material during the FTC (Figure 5.10).
- Ca and in some boxes also Al, Cr and Sb showed higher dissolution rates after the freezing cycle than before (Figure 5.11). At the present stage this behaviour cannot be properly explained; for example the pH-changes should have resulted in diminished dissolution rates and not in increased ones as measured. Possibly new penetration paths of the leachant or changes in grain size by freezing-thawing are responsible for this effect.

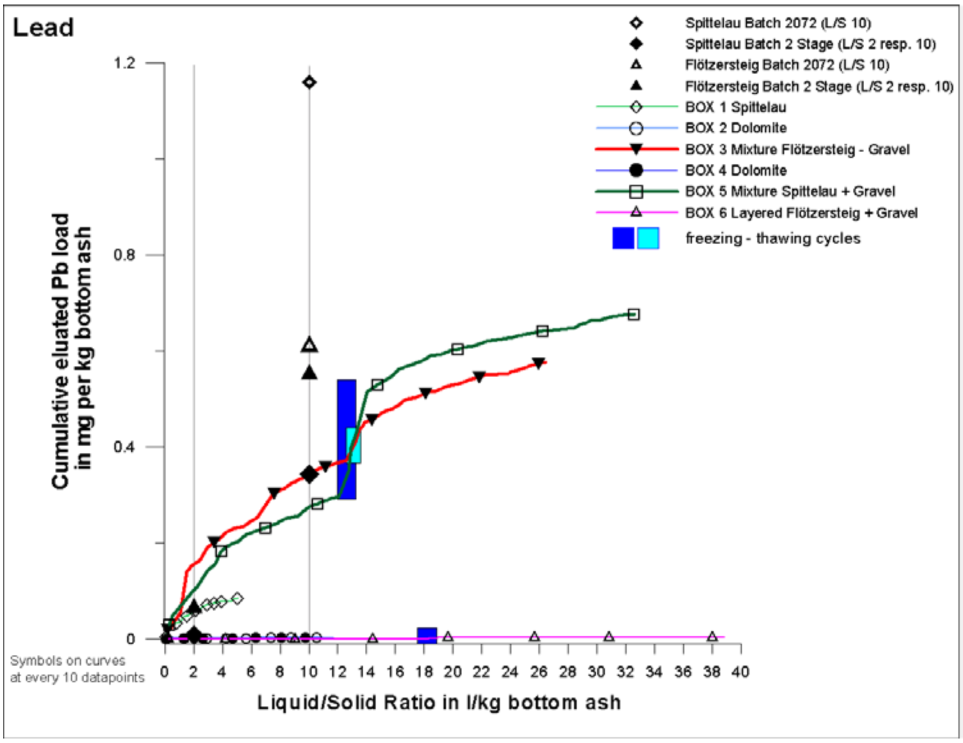



**Figure 5.10 Cumulative Pb-load (mg/kg) during the climate chamber tests**

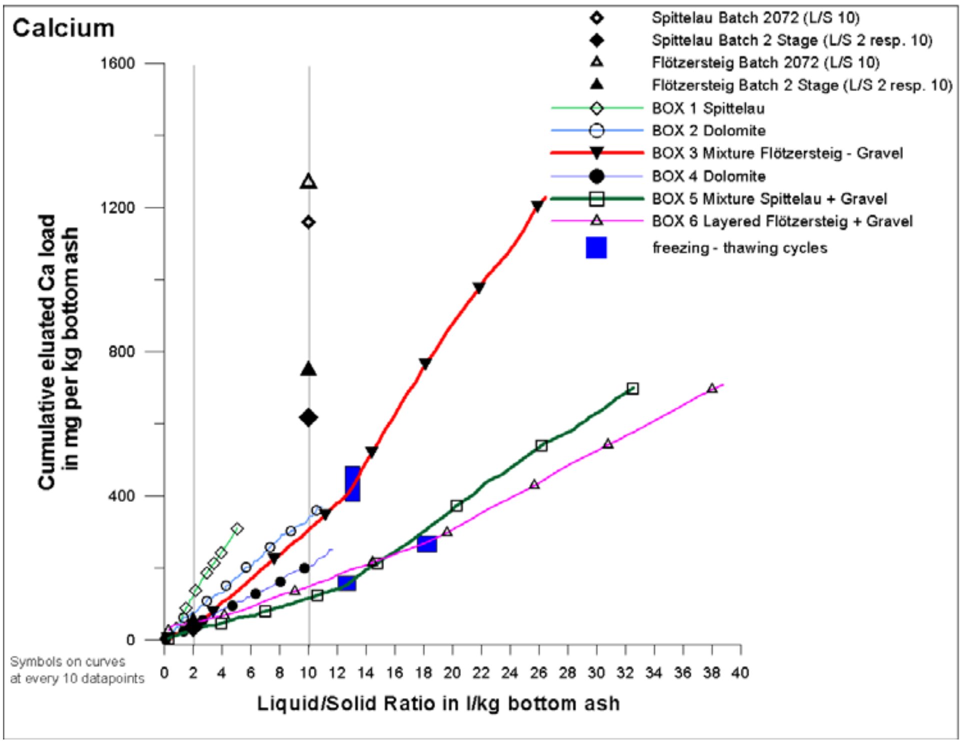



**Figure 5.11 Cumulative Ca-load (mg/kg) during the climate chamber tests**

## 5.4 EVALUATION OF LABORATORY LEACHING TESTS

The laboratory leaching tests performed on the alternative materials are listed in Table 5.1 in section 5.3.4. All the results are listed and discussed in various appendices to the report. In this section, only a few examples of results of testing of MSWI bottom ash are presented to illustrate the different types of results obtained from different types of tests.

Table 5.6 shows the results of the determination of the total contents of selected components in MSWI bottom ash from a stockpile in Denmark together with results of the availability test, the column leaching test (accumulated leached amount at L/S = 2 l/kg) and the two-stage batch leaching test (accumulated leached amount at L/S = 2 and 10 l/kg, respectively) for the same components. All results are expressed as mg/kg of bottom ash on a dry matter basis. For Cd, Cu, Pb and Ni the same results are illustrated graphically as a function of L/S in Figure 5.12. In Figure 5.13, pH of the eluate is shown as a function of L/S for the column and batch leaching tests.

Table 5.7 shows the results of column leaching tests (accumulated amounts leached at L/S = 2 l/kg) performed on MSWI bottom ash from a stockpile, MSWI bottom ash and crushed concrete excavated from two Danish test roads and a reference material (gravel) excavated from the same test road as the MSWI bottom ash.

Results of the pH-static leaching test on Danish MSWI bottom ash from a stockpile are presented in Figure 5.14 for Cd, Cu, Pb and Mo.

**Table 5.6 Results of different environmental tests performed on Danish MSWI bottom ash from a stockpile (all results are mg/kg)**

| Parameter | Total content | Availability test | Column test | Two-stage batch test | |
|---|---|---|---|---|---|
| | | | L/S = 0-2 l/kg | L/S = 0-2 l/kg | L/S = 0-10 l/kg |
| Ca | 50000 | - | 2100 | 1400 | 2000 |
| $Cl^-$ | | 2600 | 3300 | 2100 | 2100 |
| $SO_4^{2-}$ | | 8800 | 8400 | 4000 | 5600 |
| As | 24 | 0.2 | < 0.06 | < 0.004 | < 0.02 |
| Cd | 6.9 | 0.8 | 0.00046 | < 0.0004 | < 0.002 |
| Cr | 500 | 1.7 | 0.0024 | 0.002 | 0.006 |
| Cu | 8400 | 1400 | < 0.007 | 0.004 | 0.02 |
| Mo | 12 | 0.8 | 0.48 | 0.18 | 0.43 |
| Ni | 190 | 19 | < 0.0022 | 0.002 | < 0.006 |
| Pb | 1900 | 300 | < 0.0008 | 0.06 | < 0.22 |
| Zn | 4200 | 800 | < 0.0041 | 0.02 | < 0.1 |
| TOC/NVOC | 49000 | - | 30 | 12 | 32 |

**Table 5.7 Results of column leaching test (cumulative leached amounts at L/S = 2 l/kg) performed on different materials. All results except pH are mg/kg.**

| Parameter | MSWI bottom ash | | Crushed concrete | Gravel (reference material) |
|---|---|---|---|---|
| | From stockpile | From test road | From test road | From test road |
| Ca | 2100 | 1900 | 1100 | 85 |
| $Cl^-$ | 3300 | 2500 | 370 | 70 |
| $SO_4^{2-}$ | 8400 | 7500 | 16 | 76 |
| As | < 0.06 | < 0.06 | < 0.019 | 0.013 |
| Cd | 0.00046 | 0.00069 | < 0.0002 | < 0.0002 |
| Cr | 0.0024 | < 0.0032 | 0.088 | < 0.0002 |
| Cu | < 0.007 | 0.096 | 0.026 | 0.0044 |
| Mo | 0.48 | 0.34 | 0.038 | 0.036 |
| Ni | < 0.0022 | 0.098 | 0.020 | < 0.002 |
| Pb | < 0.0008 | < 0.0008 | 0.0029 | 0.001 |
| Zn | < 0.0041 | 0.41 | < 0.0052 | 0.007 |
| TOC/NVOC | 30 | 31 | 46 | 31 |
| pH range | 7.2 – 8.5 | 7.8 – 8.2 | 12.2 – 12.5 | 7.8 – 8.4 |

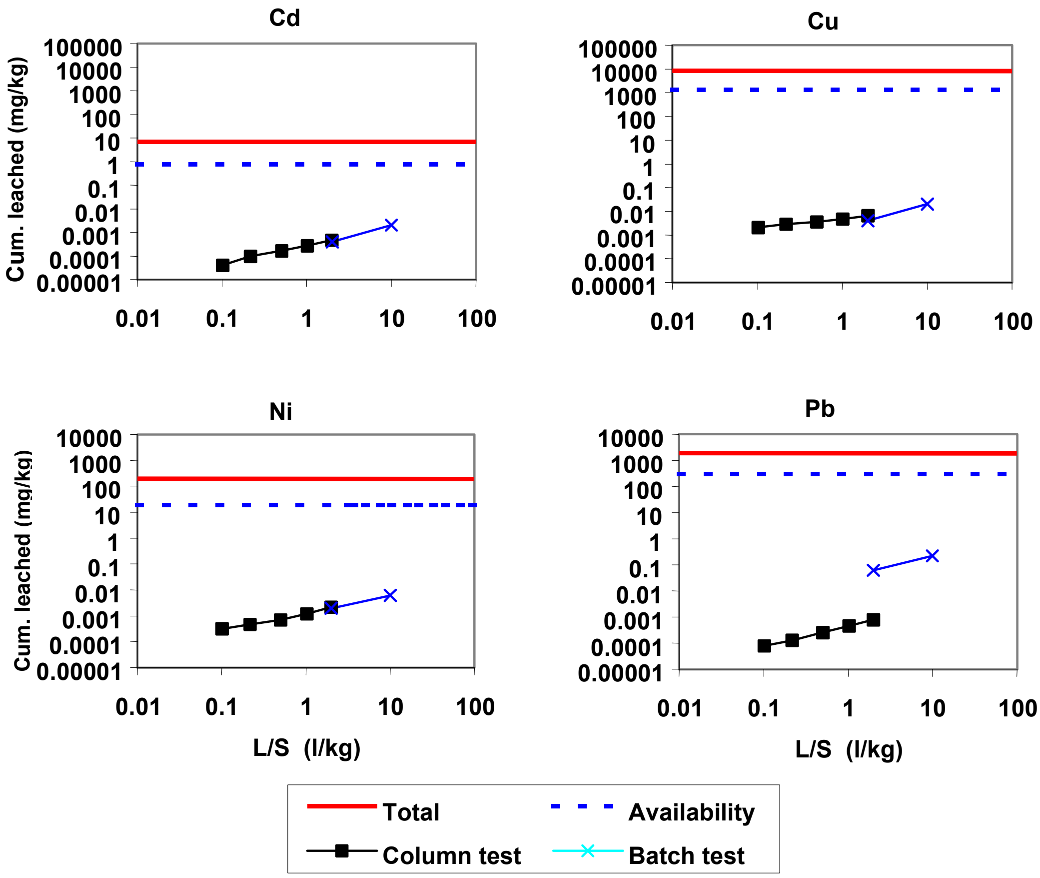



**Figure 5.12 Total content, availability and leaching as a function of L/S for Danish MSWI bottom ash from a stockpile**

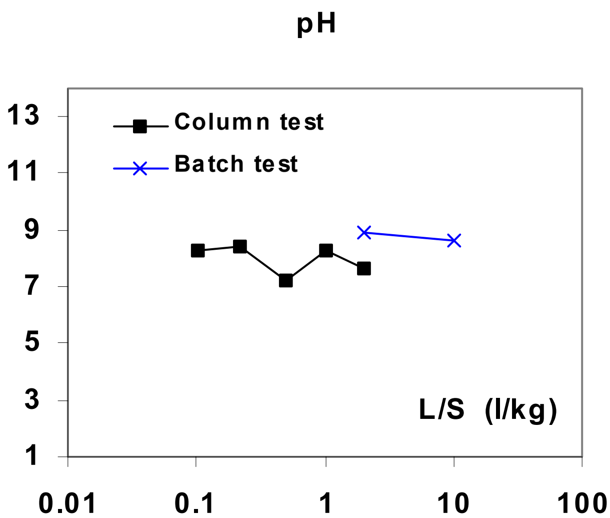



**Figure 5.13 The development of pH in the column and batch leaching tests described in table 5.4 and figure 5.6**

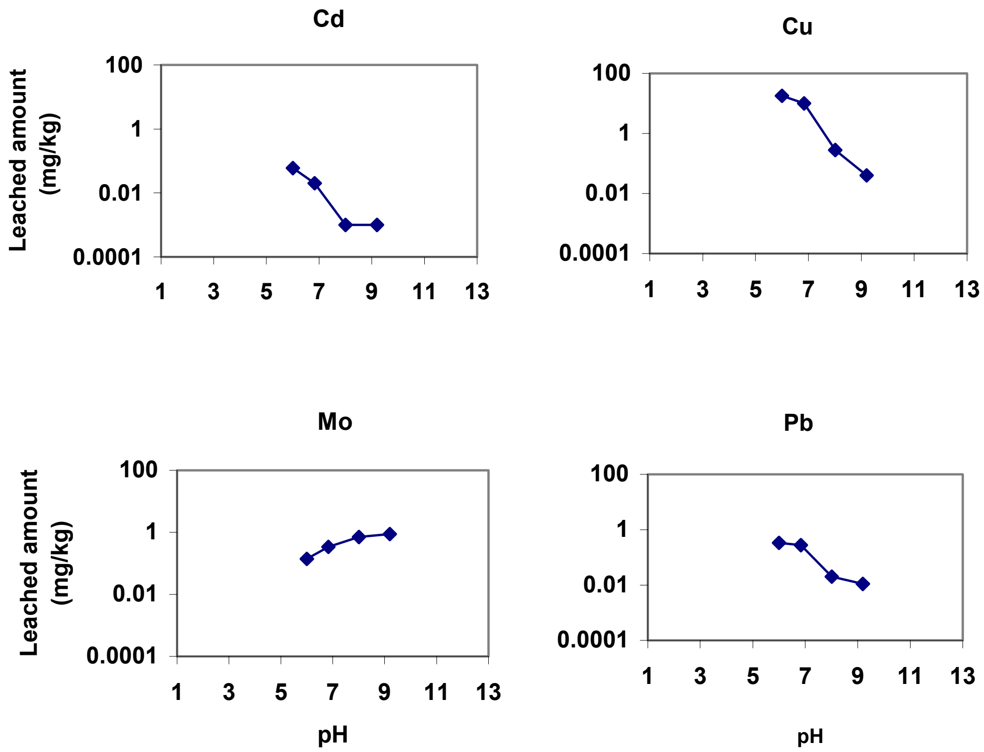



**Figure 5.14 Results of pH-static leaching tests performed at L/S = 10 l/kg on MSWI bottom ash from stockpile**

The results in Table 5.6 and Figure 5.12 illustrate the relationship between the total content of a component, the amount of the component potentially available for leaching and the actual amounts of that component which could be expected to leach under normal conditions. The latter are represented by the column and batch test results, which are shown as a function of the L/S ratio. For a given physical scenario, the L/S scale may be converted to a time scale (see below). It is seen that although a substantial proportion of several of the components, e.g. heavy metals like Cu, Pb and Zn, in principle are available for leaching, only minute fractions of these heavy metals may be expected to leach from the bottom ash under normal conditions. In contrast to this, practically all the major chlorides and sulphates present may be expected to leach relatively quickly. Among the parameters shown in Table 5.6, Mo is the only trace element which is leached significantly. As shown in Figure 5.13 and Table 5.7, the pH of the eluates from the column test varied between 7.2 and 8.5, whereas the eluates from the batch leaching test varied between 8.6 and 8.9. This shows that the bottom ash has been extensively carbonated in the stockpile. Freshly produced MSWI bottom ash is strongly alkaline and will normally produce eluates with pH in the range of 11.0 – 12.5. Strongly alkaline conditions favour the solubility and hence the leaching of oxyanions and of amphoteric elements such as e.g. Pb and Zn. At the prevailing neutral to slightly alkaline environment in the field, these elements leach very slowly.

The data in Table 5.6 exhibit a few discrepancies. The amount of chloride leached in the column test is larger than the amount found in the availability test. This may be due to the heterogeneity of the bottom ash and/or to the uncertainty associated with the leaching procedure and analytical determination. In Figure 5.13 the amounts of Cd, Cu and Ni leached in the column and batch leaching tests fall on the same curve, whereas the amount of Pb leached at L/S = 2 l/kg is much larger in the batch test than in the column test.

The pH static leaching tests have been performed for a relatively narrow pH range, namely between pH = 6.0 and the materials "own" pH. This is relevant for an evaluation of the materials under the expected future pH conditions they will be subjected to in a road-base environment. It can be seen that the leachability of Cd, Cu and Pb is increased substantially if pH moves from approximately 9 to 6, whereas the leachability of Mo, which forms an oxyanion, is reduced. Other elements which forms oxyanions, such as e.g. As and Cr may be expected to behave similarly to Mo. If the ash had been fresh with a high pH, the leachability of e.g. Pb would have been seen to rise steeply at higher pH values. These sensitivities to changes in pH must be taken into consideration when longer term risk assessments are carried out for the use of bottom ash and other alternative materials in road construction. An imposed change of pH may shift the leaching curves obtained from column and batch leaching tests.

The results in Table 5.7 show that the MSWI bottom ash, which has been placed in the test road for 5 years, has retained most of its leaching potential, i.e. the leaching that has occurred has been limited and has probably taken place primarily during the construction period. The pH of the bottom ash from the stockpile and the test road are very similar, indicating that the ash from the stockpile is fully carbonated. The results in Table 5.7 also show that the leaching of both salts and most trace elements/heavy metals from crushed concrete and the reference material, gravel, are relatively low. It may be noted that the high pH of the eluate from the crushed concrete has caused the leaching of Pb to be higher from this material than from the others.

It is evident from the above that a full characterisation of the environmental behaviour of an alternative material under field conditions will require the application of several different test methods. However, once the material has been adequately characterised, more simple routine tests may be applied for compliance purposes, e.g. to test the fulfilment of utilisation criteria based on characterisation data.

## 5.5 THE USE OF SCENARIO CALCULATIONS

The European Standardisation Committee CEN/TC 292 "Characterisation of waste" has developed a guideline for the proper use of leaching tests for various purposes. This guideline (Methodology Guideline for the

Determination of the Leaching Behaviour of Waste under Specified Conditions, ENV 12920) from November 1997 emphasises the need to formulate precise questions concerning the leaching behaviour of a material before choosing a test method, and it prescribes the use of scenarios as part of this process. The guideline provides a stepwise methodology which includes consideration of the following issues:

1) Formulation of the question(s) to be answered
2) Description of the scenario considered
3) Description of the waste
4) Determination of the leaching behaviour and the influence of various parameters on the leaching behaviour
5) Modelling of the leaching behaviour
6) Model validation
7) Conclusions

Following this sequence of steps will not in itself ensure a good result, but it will help in creating a rational and scientific background for the selection and performance of leaching tests for characterisation of waste materials and for the subsequent interpretation of the results. The use of scenarios is necessary both for case by case risk assessments and for the development of criteria for utilisation.

## 5.6 A MODEL FOR ASSESSMENT OF THE ENVIRONMENTAL RISK OF THE USE OF ALTERNATIVE MATERIALS FOR ROAD CONSTRUCTION

### 5.6.1 Methodology

The methodology presented in this section, establishes a relationship between the result of a leaching test carried out on a granular waste product/alternative material and the environmental risk posed by a particular civil engineering utilisation application scenario of that material to downstream groundwater. Only the potential impact on the groundwater quality in terms of elevation of the concentration(s) of one or several leached contaminant(s) in the groundwater at a downstream point of extraction for drinking water purposes is considered. However, the model, which has been developed by Hjelmar et al. (1996) may be generalised to include the potential impact on surface water bodies as well (Hjelmar et al. 1998). The methodology allows the setting of limit values to be divided into two parts: a series of practically objective calculations and a few decisions based on environmental policy. In the case considered, the policy decisions consist of setting maximum allowable values of the increases of the concentrations of various contaminants in the groundwater at the point of extraction (at the well). The more objective calculations consist of using a series of connected scenarios to establish a relationship, firstly between the result of a leaching test and the potential flux of contaminants out of the utilised material, secondly between the flux of contaminants and the elevation of the contaminant level in the groundwater.

**The physical scenario**

The alternative material, which is utilised e.g. as a filling material in an embankment or a road ramp is described in a simplified manner as a box with surface area A ($m^2$), height H (m) and bulk dry density d ($t/m^3$). The material is placed on top of or below the surface of the ground above an aquifer. The general annual rate of infiltration of precipitation in the geographic area is I (m). See Figure 5.15. The maximum acceptable concentration ($C_V$) of a given component in the leachate, which appears at the bottom of the box as a result of the percolation of infiltrated precipitation through the material, is defined as follows:

$$C_V = GE \times D \times P \times IR$$

where :

**GE** is the maximum acceptable elevation of the concentration of the contaminant in question in the groundwater from the aquifer below the site at the point of extraction;

**D** is the ratio between the surface area of the groundwater catchment area considered and the surface area of the utilised material or, alternatively, a dilution factor indicating how many times the leachate from the utilised material is diluted from the point of entry into the groundwater to the downstream point of extraction of drinking water from the aquifer;

**P** is a priority factor which provides the option of placing higher priority on some aquifers than others, e.g. based on its value as a drinking water resource;

**IR** is an infiltration reduction factor, which expresses the ratio between the general rate of infiltration, **I**, in the geographical area in question and the rate of infiltration into (or percolation through) the utilised material which may be reduced by a top cover (increased surface run-off, increased evapotranspiration). The amount of water percolating through the material will thus be I/IR.

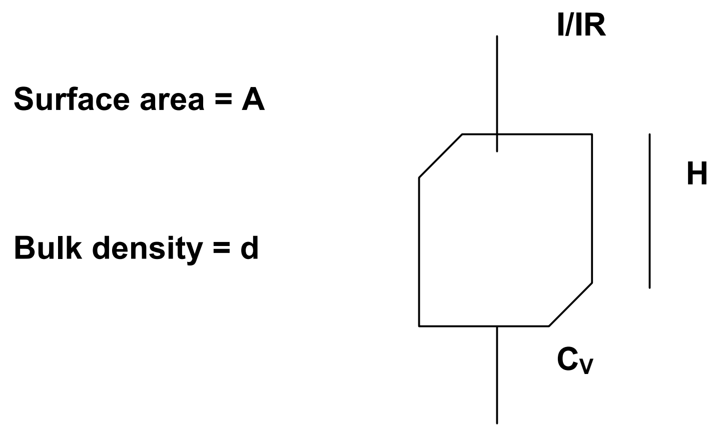



**Figure 5.15 Simplified physical description of a utilisation application containing a granular inorganic material**

This simplified model does not directly take into account the biogeochemical processes in the unsaturated zone below the site and in the aquifer, which would delay and retain a given leachate component during the transport of the leachate from the bottom of the "box" of utilised material to the drinking water extraction point. These attenuation processes therefore constitute an unquantified extra margin of safety.

**The criteria related timeframe, $T_C$**

The leaching of several components, including e.g. salts, from alternative materials will often show high initial concentrations in the leachate with subsequently decreasing leachate concentrations as the leaching progresses and the liquid to solid ratio (L/S) increases. The concentration of other components (e.g. lead) in the leachate will be controlled mainly by other factors such as pH or redox potential. Since the model is based on the consideration of the flux of contaminants rather than contaminant concentrations, it seems reasonable to use an average value of $C_V$ for a given component over a period of time, $T_C$, referred to as the criteria related timeframe. This implies e.g. that it is accepted that $C_V$ for the component in question is exceeded during the initial phase of the leaching, whereas the concentration of the component during a later phase will be lower than $C_V$, ensuring that the average concentration of the component in the leachate over the entire period $T_C$ does not exceed $C_V$.

It will most likely be necessary to assign different values of $T_C$ to different groups of components. Components, which are leached quickly and which are mobile in the unsaturated zone and the aquifer (e.g. several inorganic salts), should be assigned relatively low values of $T_C$ (e.g. 1-3 years). Higher values of $T_C$ (e.g. 10 –25 years) can safely be assigned to less mobile components which are leached relatively slowly (e.g. several trace elements). The leaching of certain components, e.g. arsenic, are often solubility controlled in such a way that constantly increasing concentration levels with increasing L/S may be observed for a very long period of time. For such components $T_C$ must be assigned and the model applied with care. Table 5.8 presents some proposed values of GE and $T_C$ for a number of components.

**Table 5.8 Proposed values of the maximum acceptable elevation of the concentration in the groundwater at the extraction well, GE, and the criteria related timeframe, $T_C$ (Hjelmar et al. 1998)**

| Component | Proposed value of GE mg/l | Proposed value of $T_C$ Years |
|---|---|---|
| Chloride | 250 | 1 to 3 |
| Sulfate | 220 | 1 to 3 |
| Na | 150 | 1 to 3 |
| K | 280 | 1 to 3 |
| As | 0.009 | 10 |
| Cd | 0.005 | 25 |
| Cu | 0.1 | 25 |
| Cr | 0.05 | 10 |
| Hg | 0.001 | 25 |
| Ni | 0.015 | 25 |
| Pb | 0.009 | 25 |
| Se | 0.01 | 10 |
| Zn | 0.04 | 25 |

The proposed values of $T_C$ are based on the principles described above, whereas the proposed values of GE are based on considerations of the existing background concentrations and the acceptable total concentrations in drinking water of the components in question. The determination of GE may depend on the regional groundwater quality and the resulting safety margins are somewhat related to the chosen value of the dilution factor, D. The values of GE shown in Table 5.8 are related to Danish groundwater quality.

**Specific acceptable mass, $M_{SA}$, and accumulated leached mass, $ALM_C$**

If the flux of a given component leached from the box of utilised material is considered, the specific acceptable mass of that component per unit weight of utilised material, $M_{SA}$, (e.g. expressed in mg/kg) which can be leached during the time period $T_C$ may be calculated by substituting the equation defining $C_V$ above into the expression used to calcuate the flux of the component out of the utilised material. This leads to the following equation:

$$M_{SA} = GE \times D \times P \times T_C \times I/(d \times H)$$

The result of a leaching test, which is usually accelerated, may for granular inorganic materials often be expressed as an amount of leached components per unit weight of material as a function of L/S or at a given L/S ratio. Assuming ideal conditions, L/S (e.g. expressed as l/kg = $m^3$/t) can be related to time for the physical scenario under consideration by the following equation:

$T = (L/S) \times d \times H/(I/IR)$

where T is the time corresponding to the value of L/S used. If the same time perspective is applied to the physical scenario describing a utilisation situation for a material and to the interpretation of the result of an accelerated leaching test on the same material, the equation shown above can be used to establish a relationship between the specific acceptable mass, $M_{SA}$, leached from the utilised material within the criteria related timeframe, $T_C$, and the result of the leaching test. The impact on the groundwater quality will not exceed an increased concentration corresponding to GE at the point of drinking water extraction as long as $M_{SA}$ is not exceeded. The criteria related value of L/S corresponding to $T_C$ for a given component can be determined from the following equation:

$(L/S)_C = T_C \times I/(IR \times d \times H)$

Under idealised conditions, where the leached amounts of a given component as a function of L/S based on the results of leaching tests are available and where this description can be assumed to simulate the actual leaching conditions, the following condition must be satisfied to ensure that GE is not exceeded at the point of extraction of drinking water from the aquifer:

$ALM_{Ci} < M_{SAi}$

where $ALM_{Ci}$ is the accumulated leached mass of component i found experimentally at the accumulated L/S value $(L/S)_C$ (see Figure 5.16) and where $M_{SAi}$ is the calculated specific acceptable mass of component i leached from the utilisation scenario.

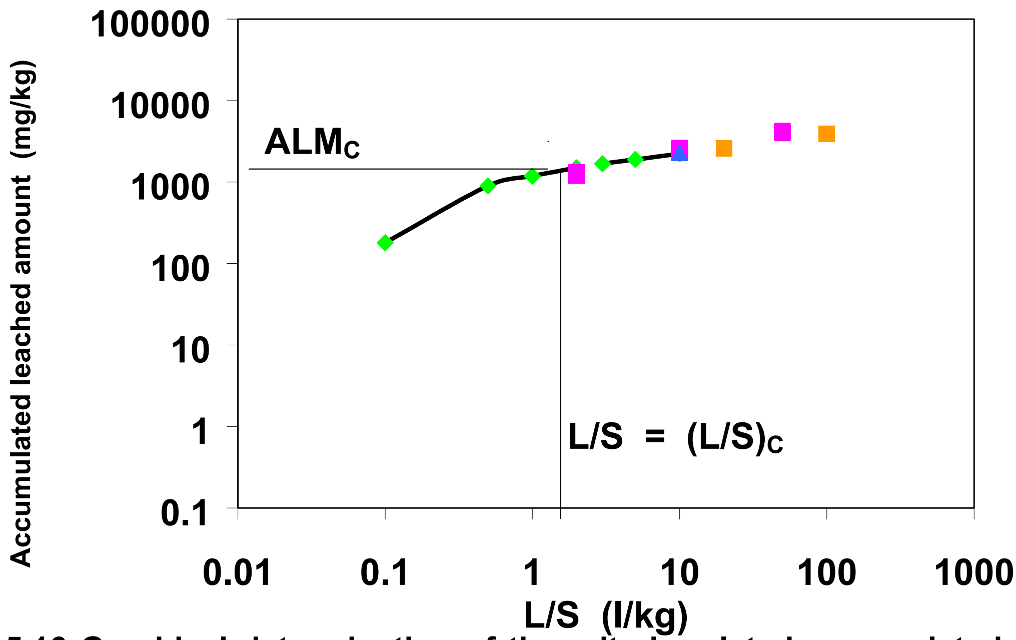



**Figure 5.16 Graphical determination of the criteria related accumulated leached amount, $ALM_C$**

### 5.6.2 Scenario calculations: two examples

To illustrate the use of the concept and the model, they are applied to two different utilsation scenarios: an embankment with soil cover and road utilisation scenario (sub-base under a paved road). In both cases the waste material is MSWI bottom ash from a stockpile. The scenarios, which are very simple, are characterised by the parameters shown in Table 5.9. For both scenarios dilution factors of 10, groundwater priority factors of 1 (high priority), annual precipitation infiltration rates of 300 mm and bottom ash bulk densities of 1.5 t/m$^3$ are assumed. It is further assumed that the embankment has an average height of 5 m and a top cover, which reduces the rate of infiltration by a factor of 2, whereas the road sub-base has a thickness of 0.5 m with a surface pavement which reduces the rate of infiltration by (at least) a factor of 10. The flow regime is assumed to be percolation in both cases.

Two components of the MSWI, sulfate and copper (Cu), are considered. The relatively abundant and mobile sulfate ion is assigned a criteria related timeframe of $T_C$ = 3 years (Table 5.8), whereas Cu, which is not very mobile, is assigned a $T_C$ = 25 years (Table 5.8). The following maximum acceptable elevations of the concentrations in the groundwater at the extraction point, GE, are chosen (Table 5.8): 220 mg/l for sulfate and 0.1 mg/l for Cu. The calculated values of the specific acceptable leached amounts, $M_{SA}$, and the criteria related L/S values, $(L/S)_C$, are shown in Table 5.10.

Figure 5.17 shows the results of the column leaching test on the Danish MSWI bottom ash from the stockpile for sulfate and copper. These results are used to determine the accumulated leached mass, $ALM_C$, corresponding to the values of $(L/S)_C$ shown in Table 5.10.

**Table 5.9 Definition of sample scenarios**

| Parameter | Unit | Embankment scenario | Road subbase scenario |
|---|---|---|---|
| Dilution factor, D | none | 10 | 10 |
| Groundwater priority factor, P | none | 1 | 1 |
| Rate of infiltration of precipitation, I | m/year | 0.3 | 0.3 |
| Dry bulk density of MSWI bottom ash, d | $t/m^3$ | 1.5 | 1.5 |
| Infiltration reduction factor, IR | none | 2 | 10 |
| Height of embankment/subbase, H | m | 5 | 0.5 |

**Table 5.10 Calculation of $M_{SA}$ and $(L/S)_C$**

| Scenario | Parameter | Sulfate | Copper |
|---|---|---|---|
| Embankment | $M_{SA}$ | 264 mg/kg | 1 mg/kg |
| Road subbase | $M_{SA}$ | 2640 mg/kg | 10 mg/kg |
| | | | |
| Embankment | $(L/S)_C$ | 0.06 l/kg | 0.5 l/kg |
| Road subbase | $(L/S)_C$ | 0.12 l/kg | 1.0 l/kg |

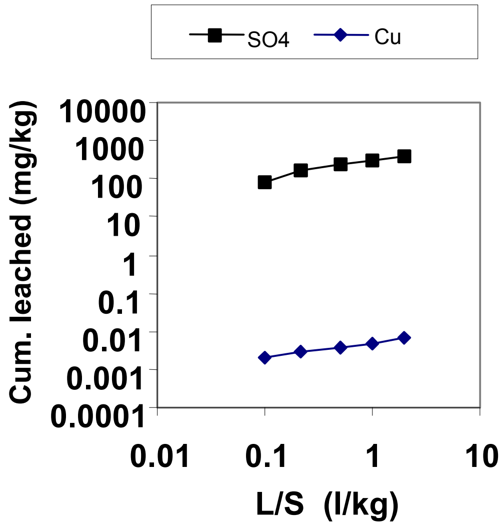



**Figure 5.17 Results of column leaching tests on MSWI bottom ash.**

The results are presented in Table 5.11, which also shows the final comparison of $ALM_C$ and $M_{SA}$ for each scenario and each component. $ALM_C$ for sulfate for the embankment scenario, corresponding to $(L/S)_C$ = 0.06 l/kg is estimated since the lowest L/S value available from the column data is 0.1 l/kg.

**Table 5.11 Calculation of $ALM_C$ and check on fulfilment of criteria ($ALM_C/M_{SA}$ < 1)**

| Scenario | Parameter | Sulfate | Copper |
|---|---|---|---|
| Embankment | $ALM_C$ | 400 mg/kg | 0.0036 mg/kg |
| Road sub-base | $ALM_C$ | 1600 mg/kg | 0.0046 mg/kg |
| Embankment | $ALM_C/M_{SA}$ | 1.5 | 0.0037 |
| Road sub-base | $ALM_C/M_{SA}$ | 0.61 | 0.00046 |

The criteria are fulfilled for both scenarios for copper ($ALM_C/M_{SA}$ < 1) but only for the road sub-base scenario for sulphate. This indicates that leaching of sulfate from MSWI bottom ash used in road embankments without a cover that reduces infiltration of precipitation may be a problem if the road is located in a catchment area for potable groundwater. The results are also indicative of the ability of the model to identify leachable components with potentially detrimental effects on downstream groundwater quality.

Application of the same scenario calculations to crushed concrete results in fulfilment of the criteria.

## 5.7 CONCLUSIONS

European or international standardisation is less advanced within the field of assessment of the environmental properties of alternative residues than within the field of mechanical tests. Standardisation work is, however, in progress, and several standard CEN tests for characterisation of alternative materials may be expected to emerge over the coming years. In the meantime, a number of national standards, pre-standard CEN tests or Nordtest recommended leaching test methods are available to assess the leaching properties of alternative materials under different circumstances. Several of these tests were selected and applied in this project, and it is recommended that a set of leaching methods rather than one single test should be used in order to fully characterise the leaching properties of the alternative materials. Comparison of the results of these tests with lysimeter and climate chamber tests indicates that column tests provide the most detailed simulation of the actual leaching behaviour of the materials under normal circumstances.

If there is any chance that the pH of the material might change significantly in the field, for example by carbonation of oxides/hydroxides or oxidation of sulfides, pH-static tests should be used to estimate the effect of the anticipated pH change. Simulation leaching tests at high liquid to solid (L/S) ratios (e.g. availability tests) are of limited value in road construction applications, unless the road does not have a relatively impermeable surface layer (e.g. gravel roads in rural areas).

Impact assessments and predictions should be based on scenario calculations, i.e. a description of the physical lay-out of the site in question, the flow of water through the site in conjunction with a description of the composition of the leachate formed as a function of L/S or time, the latter derived from laboratory or lysimeter leaching tests.

Among the useful tools for assessment of the environmental properties of alternative materials used in road construction, the following are particularly recommended:

- Draft prENV12920 Characterisation of waste: Methodology guideline for the determination of the leaching behaviour of waste under specified conditions;
- Column leaching test NT ENVIR 002;
- Batch compliance test prEN 12457.
- The pH-dependency of the leaching behaviour should be investigated, e.g. using a pH-static leaching test.

Most of these leaching procedures are currently being developed as European Standards by CEN/TC 292.

The three-level testing hierarchy introduced by CEN/TC 292 is found to be a very useful logistic framework for characterisation of alternative materials for road construction. It divides test methods into three levels: Level 1 - Basic characterisation, Level 2 - Compliance testing and Level 3 - On-site verification. Materials are generally characterised thoroughly once at level 1 to establish fundamental behaviour such as total composition, availability, the influence of pH on leaching behaviour, leaching as a function of L/S at low (lysimeter and column tests), intermediate and high (batch leaching tests) L/S values. Once a material has been characterised at level 1, further quality control and monitoring testing may be carried out at level 2 using much simpler compliance tests utilising the information from the characterisation at level 1. Only if the material or the process from which it originates undergo a significant change will it be necessary to repeat the characterisation at level 1. Level 3 testing, on-site verification, is a rapid check to confirm that the waste is what the accompanying documents state it is, based on level 2 and level 1 testing. In some cases level 3 testing may just be a visual check.

When effects of climate are to be predicted in larger systems, then lysimeters and climate chamber tests can be used. The conditions for lysimeter tests will resemble natural conditions more closely than laboratory leaching tests, since they will be exposed to the natural climatic conditions. In most cases, laboratory leaching tests can be used to give a conservative estimate of environmental effects, since laboratory tests in most cases will overestimate actual leaching. The results from the lysimeter and climate chamber tests suggest that the pH which is developed in the material over time is the most significant factor in the composition of the leachate. It is thus essential to understand the mineralogy of an alternative material and its likely behaviour in a road pavement in order to make sensible predictions about its leaching behaviour. If the pH is likely to change with time, as a result of oxidation, carbonation or hydration reactions, pH-static leaching tests should be carried out at an appropriate range of pH values.

A model has been adopted to predict the impact of leaching from alternative materials in road construction on the quality of groundwater. The model is site specific and is based on the allowable increase in concentration of contaminants in the groundwater. For each contaminant, a critical length of time is estimated based on its relative mobility; highly mobile ions such as potassium are allocated a shorter critical time than less mobile metals such as chromium. The critical length of time can be converted to a critical L/S ratio on the basis of the road geometry, contributing area of the road to the groundwater catchment and the rate of infiltration into the road. The cumulative amount leached at this L/S ratio is derived from leaching test results; if it is less than the allowable cumulative amount leached, the material may be used in the road construction. The model, which is based on flux considerations, is conservative in that it does not account for the attenuation of contaminants during transport from the application through the unsaturated zone and the aquifer to the point of groundwater extraction.

When applied to a road embankment scenario using MSWI bottom ash, the model indicates that the leaching of sulfate may be too high to be acceptable in a groundwater catchment area. The use of MSWI bottom ash under a paved road does not appear to constitute an unacceptable risk to the groundwater in similar surroundings. The use of crushed concrete appears acceptable in both scenarios.

# 6. HYDRODYNAMIC TESTS

## 6.1 HYDRODYNAMIC INVESTIGATIONS OF MSWI BOTTOM ASH

For alternative materials in general, but for MSWI bottom ash more specifically, mechanical performances and pollutant release risks are related to the water content of the material. Therefore, a series of hydrodynamic tests on MSWI bottom ash were carried out as part of the ALT-MAT project.

To improve the understanding of the behaviour of MSWI bottom ash in road applications, the study of moisture changes is essential. These can occur according to the type of application, to the hydrodynamic characteristics of the lower and upper courses, and to the local weather conditions. It is essential first of all, to determine MSWI bottom ash hydrodynamic properties, both saturated and unsaturated with water.

The technical objectives of this work were to measure the hydraulic conductivity (K) of saturated MSWI bottom ashes, and to establish the relation between the material suction (S) and its water content (W or $\theta$).

In order to assess the physio-chemical processes which can occur with ageing of MSWI bottom ash and which have an effect on their hydraulic properties, tests were carried out on two materials (Ivry and Egletons) at two different ages: a few months (young –Y); and a year and a half (older - O).

Suction properties of MSWI bottom ash have been compared with those of natural soils (sand and silt). Measured permeability has been compared to bibliographical references for soils and MSWI bottom ash.

The research of MSWI bottom ash hydrodynamic properties had to deal with the high electric conductivity of the material. Therefore, the usual method based on electromagnetic measurements was inadequate for the water content measurement, and the development of a specific method directly based on water fluxes was necessary. It consists of vibro-compression up to the required density for the samples, checking the homogeneity by means of a gamma-densitometer, sawing the sample in 3 cm thick slices and the use of a pressure chamber. The test methods are described in Appendix E.

Results for the retention curves (hydration - H, and de-hydration - D) are given in Figure 6.1 (according to the weight water content - W) and in Figure 6.2 (according to the volume water content - $\theta$). From these curves, the volume water content at which the material is saturated ($\theta_s$) has been assessed (Table 6.1). The parameter $\theta_{1000}$ gives an indication of the volume water content at which it becomes difficult to extract water from the material.

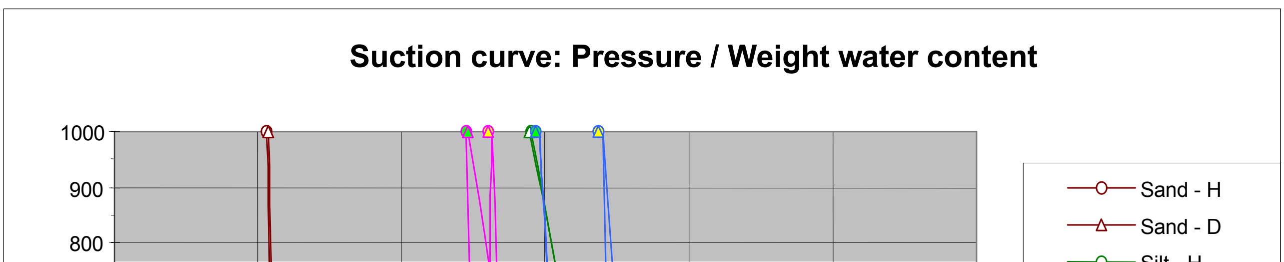


**Figure 6.1 Suction curve: Pressure / Weight water content**

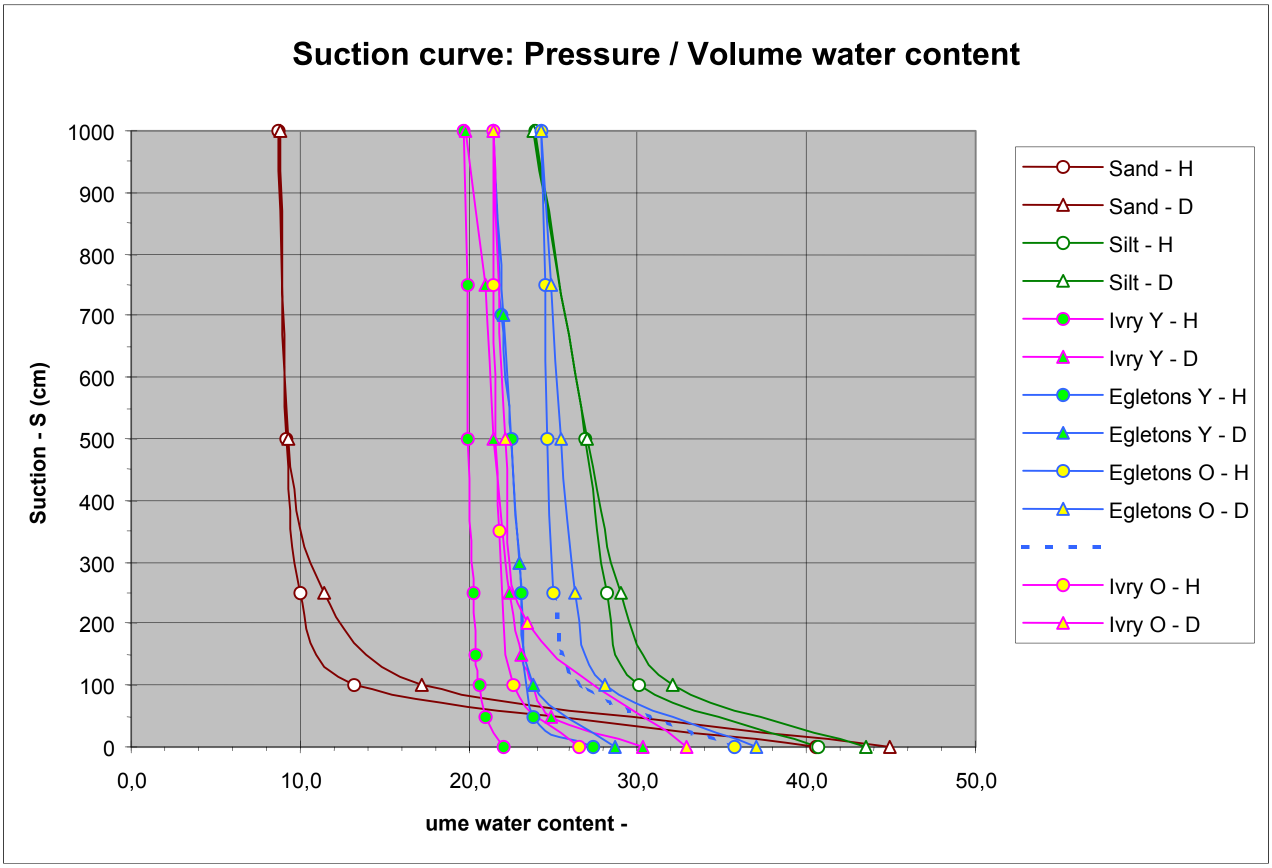



**Table 6.1 Saturated water content ($\theta_S$) and hard to exchange water content ($\theta_{1000}$)**

| Material | $\theta_S$ | $\theta_{1000}$ |
| --- | --- | --- |
| Ivry – Young | 30 % | 20 % |
| Egletons – Young | 29 % | 21 % |
| Ivry – Older | 33 % | 21 % |
| Egletons – Older | 37 % | 24 % |

The saturated hydraulic conductivity was assessed by means of the classical method. The sample was slowly saturated from the bottom to the top. The hydraulic load was applied four times in order to calculate a mean value of the permeability (Table 6.2).

**Table 6.2 Saturated hydraulic conductivity of the samples**

| Material | Ivry - Y | Ivry - O | Egletons - Y | Egletons - O |
| --- | --- | --- | --- | --- |
| Age (month) | 6 | 19 | 9 | 18 |
| Saturated Hydraulic Conductivity (m/s) | $6.1 \times 10^{-5}$ | $3.2. \times 10^{-4}$ | $7.2 \times 10^{-5}$ | $1.9 \times 10^{-5}$ |

On the hydrodynamic point of view, MSWI bottom ash resembles a silty soil. It appears as a material into which water infiltrates easily and with draining properties. Nevertheless, it seems that it tends to retain a relatively high amount of water (more than 20 % volume - $\theta_{1000}$ parameter), especially under the low suction conditions which occur in road layers (less than 1m suction).

The tendency to retain water increases with ageing. The moving of the suction curves toward higher water contents has been noted for both materials, but the general shape of the curves does not change with time. Moreover, this evolution does not seem to have a consistent effect on the permeability of the material. With this permeability, MSWI bottom ash can be qualified as “quite permeable to permeable”.

This evolution has been observed on materials ageing on stockpiles. We cannot conclude on the in-situ evolution of MSWI bottom ash. The evolution of the MSWI bottom ash suction curve is a result of its physio-chemical evolution. The parameters and the kinetics acting on stockpiles or in-situ are not necessarily the same. Further studies on MSWI bottom ash hydrodynamic properties would need to be combined with mineralogical studies.

In order to represent more accurately the actual phenomena which take place in road constructions, further studies would also have to concentrate the measurements in the range of suctions observed in road layers in normal conditions. That means no more than 1 metre suction in temperate countries. For the frost risk assessment, higher suction would be required.

The methodology used to determine the suction curves in this study seems reliable and could be used for further research.

A point which might have practical implications is the Modified Proctor Optimum water content (either in weight or in volume) in relation to $\theta_{1000}$. In actual applications, the optimum water content sometimes appears lower than the water content corresponding to high suctions ($\theta_{1000}$). If implemented in such conditions, the MSWI bottom ash will draw water from the surrounding road layers, in order to balance its suction and its water content.

## 6.2 EVALUATION OF TEST METHODS FOR HYDRODYNAMIC TESTS (HYDROLOGICAL STATE AND PERMEABILITY OF ALTERNATIVE MATERIALS IN ROAD CONSTRUCTION)

### 6.2.1 Introduction

Information on the hydrological state of materials is indispensable to the understanding of the chemical, mechanical and the hydrological behavior of soils [Hillel, 1988], of natural materials, and especially of alternative materials which are variable and which have been the object of studies for only a few years.

Studies of the in situ and laboratory hydrological state of alternative materials can help in understanding the water movements within the alternative materials, and in estimating water inflows and outflows. In a second step, thanks to modelling, this can help in forecasting the behaviour of these materials in actual road applications.

The hydrological state of a material can be determined by measuring either *its water content* (W or $\theta$) or its *water potential* (S). The water potential represents the energy state of the soil water. The *water content* and the *potential* are linked. The suction curve giving the relation between the *water content* and the *water potential* is a major parameter to characterise the hydrological properties of unsaturated materials, which is the state road materials are generally in.

The hydraulic conductivity of the material (or its permeability) is the second essential hydrodynamic parameter as it controls the water flow through materials. The hydraulic conductivity (K) of a material evolves with its hydrological state. Thus, in order to study water movements through non-saturated materials, it is essential to understand this second relation. The relation between the hydrological state and the permeability of the material is explained in Appendix B. In this chapter, only the available methods for the evaluation of hydraulic conductivity will be presented.

### 6.2.2 Objective

The objective of this chapter is to present briefly the more important methods that already exist for *water content* and *water potential* measurement and for the permeability evaluation (principles of the methods, advantages, disadvantages). This includes methods that can be used in situ or in the laboratory. Based on these descriptions, the more relevant aspects for alternative material characterisation will automatically come out and the last point will be recommendations for hydrodynamic tests for alternative materials.

### 6.2.3 Measurement methods

#### 6.2.3.1 Hydrological state

The water content can be expressed as the weight the water represents in the total mass of the material (noted W) or as the volume the water represents in the total volume of the material (noted $\theta$). The water potential expresses the energy state the water is in, resulting mainly from the matrix suction (expressed in terms of water height). Details are given in Appendix B (Water movement).

**Water content measurement**

**A - Gravimetric method :**

The most traditional method is the direct measurement based on the comparison between the wet weight and the dry weight of a sample. It provides the weight water content.

Obtaining the volume water content from the gravimetric method, requires the measurement of its density. Several methods are available for the density measurement, but with the sample weighing and the sample drying, they represent an additional source of error in the volume water content evaluation.

Drying at 105°C may damage some organic matter [Hillel, 1988] but also cause volatilisation of Hg [IAWG, 1997], and lead to an over-estimate of the water content. On the contrary, at this temperature, some clays may still retain large amounts of absorbed water.

This method is the simplest to carry out, but it is also the most laborious and slow.

The sampling methodology of the gravimetric method is destructive.

**B - Capacitive method :**

The principle of the soil water content measurement by the *capacitive method* is based on the fact that if two electrodes are set in the soil, they will act as condenser plates, and the soil will play the role of a dielectric [Livet, 1982]. The condenser capacity varies with dielectric constants of the soil components (air, solid particles, water). For all the frequencies below 5 GHz, the contrast between the different soil components permitivities is very high (respectively 1; 5; 80). Thus, the dielectric constant of a soil depends essentially on its water content. After calibration, the capacity measurement gives the soil water content directly.

In practice, the capacitive methods works in the range 1MHz – 1GHz [Raimbault, 1986].

The precision of the measurement depends on the geometry of the electrodes. The electric resistivity of the material does not influence the water content measurement until it is lower than 33 ohm-meters. For studying more conductive materials, the length of the electrodes must be reduced, and they must eventually be spaced. As a consequence, the precision of the measurement decreases. This method does not work when the material is too conductive.

The capacitive method is a very precise method, able to deliver water content measurements with a precision of 0.1 % [Livet, 1982].

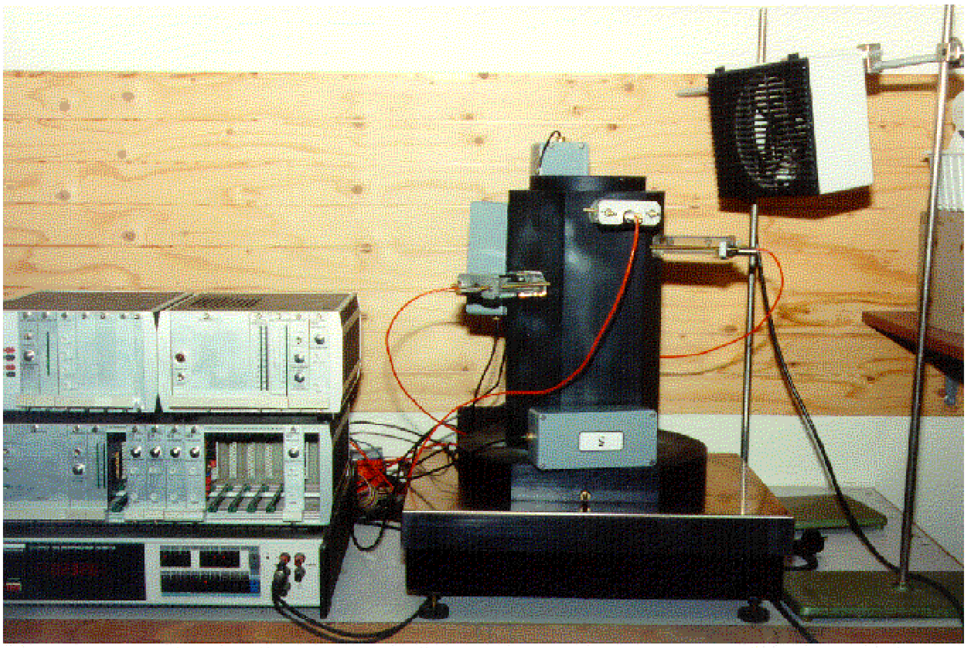


**Figure 6.3 Capacitive cells (in grey) used in a laboratory testing**
(see Section 6.2.3.2)

The capacitive method can also be applied to hydraulic conductivity measurement (see Figure 6.3 and Section 6.2.3.2).

Also using the principle of high differences between dielectric constants of soil components, the *Time Domain Reflectometry* (TDR) measurement technique consists of determining the speed at which electromagnetic waves are propagated in a waveguide (the probe) placed within the soil (Figure 6.4). The speed of propagation depends on the electromagnetic permittivity of the material. As the permittivity of water is very much greater than that of soil minerals, the material permittivity value can be related to its volumetric water content [Raimbault, Hornych, 1999]. Relating an experiment conducted by

Robertson and Birgisson [1998], Raimbault and Hornych conclude that the TDR probes have a considerable potential for precisely monitoring the infiltration of water into pavements and the way it is drained away.

For materials with high electrical conductivity (saline soils, by products) specific wave-guides can be used that are able to measure smaller and less energetic reflected pulses.

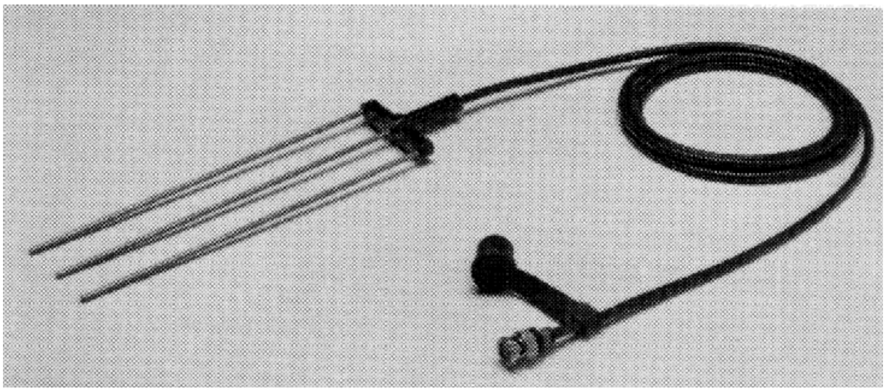


**Figure 6.4 TDR waveguide**

**C - <u>Nuclear methods :</u>**

The neutron *humidimeter* (Figure 6.5) is made of two elements: a probe (acting as a quick neutron source and a slow neutron detector) and a counter (which determines the flow of slow neutrons).

When quick neutrons are emitted in the soil, they collide with various atomic nuclei and gradually lose their kinetic energy. As the mass of the neutrons is similar to that of the hydrogen nucleus, when they collide, the energy loss is maximised. The slowed-down neutrons (thermal neutrons) disperse in the soil and form a sphere around the probe. Some of them come back to the probe and are counted by the slow neutron detector [Hillel, 1988]. As the majority of the hydrogen nuclei present in soils are included in water, the flux of slow neutrons is related to the soil water content via the hydrogen nucleus count.

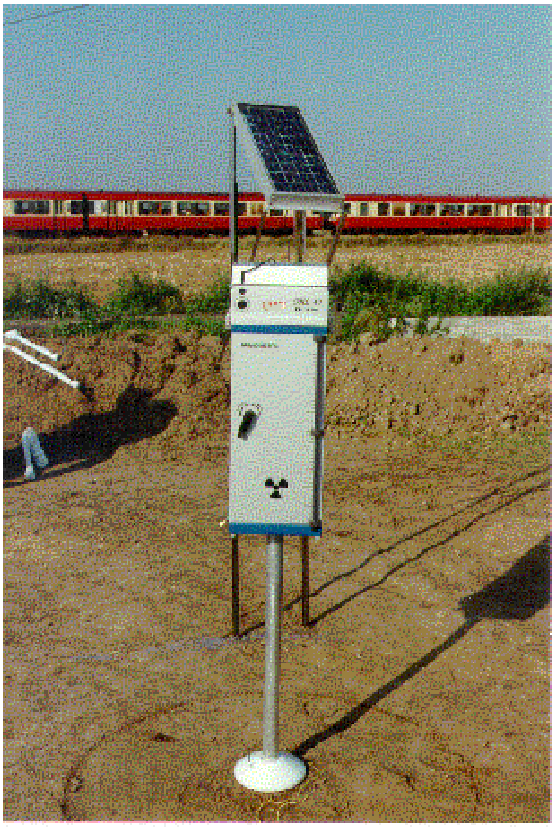


**Figure 6.5 Neutron humidimeter used in the field (Lille – France)**

The volume in which the water content is measured depends on the concentration of hydrogen nuclei, that means on the volume water content. The volume of soil investigated is a sphere about 15 cm in diameter in a humid soil, more than 50 cm in a dry soil.

This is a resolution power too low to allow detection of discontinuities in the soil water contents (wetting front, differences between layers), or measurement close to the soil surface. On the contrary the high volume of measurement is useful for the purpose of water balance calculation.

Polluted soils or alternative materials may contain hydrogen under other forms than water. Some chemical elements have also the ability to absorb thermal neutrons before they reach the detector (particularly boron, chloride, manganese and cadmium). This may disturb the correct water content measurement. For a non-natural soil, specific calibration is indispensable.

The quick neutron source also emits some gamma radiation. Adequate protection for the operator is therefore required.

Assessing the weight water content from the neutron method requires the wet density measurement. The gamma method allows this, as it can also allow a direct water content assessment.
The principle of this method is that for determining a material density (provided its chemical composition is known), measuring its electronic density

is enough [LCPC, 1966]. The proportion of gamma rays able to go across a material without collision depends on the chemical composition of this material. With the gamma *densitometer*, a radioactive source emits gamma rays that are counted by a detector (Geiger Muller tube).

Three geometries are available for measuring the density: scattering (the source and the detector are out of the material); transmission (the source inside, the detector outside); double probe (the source and the detector inside) (Figure 6.6).

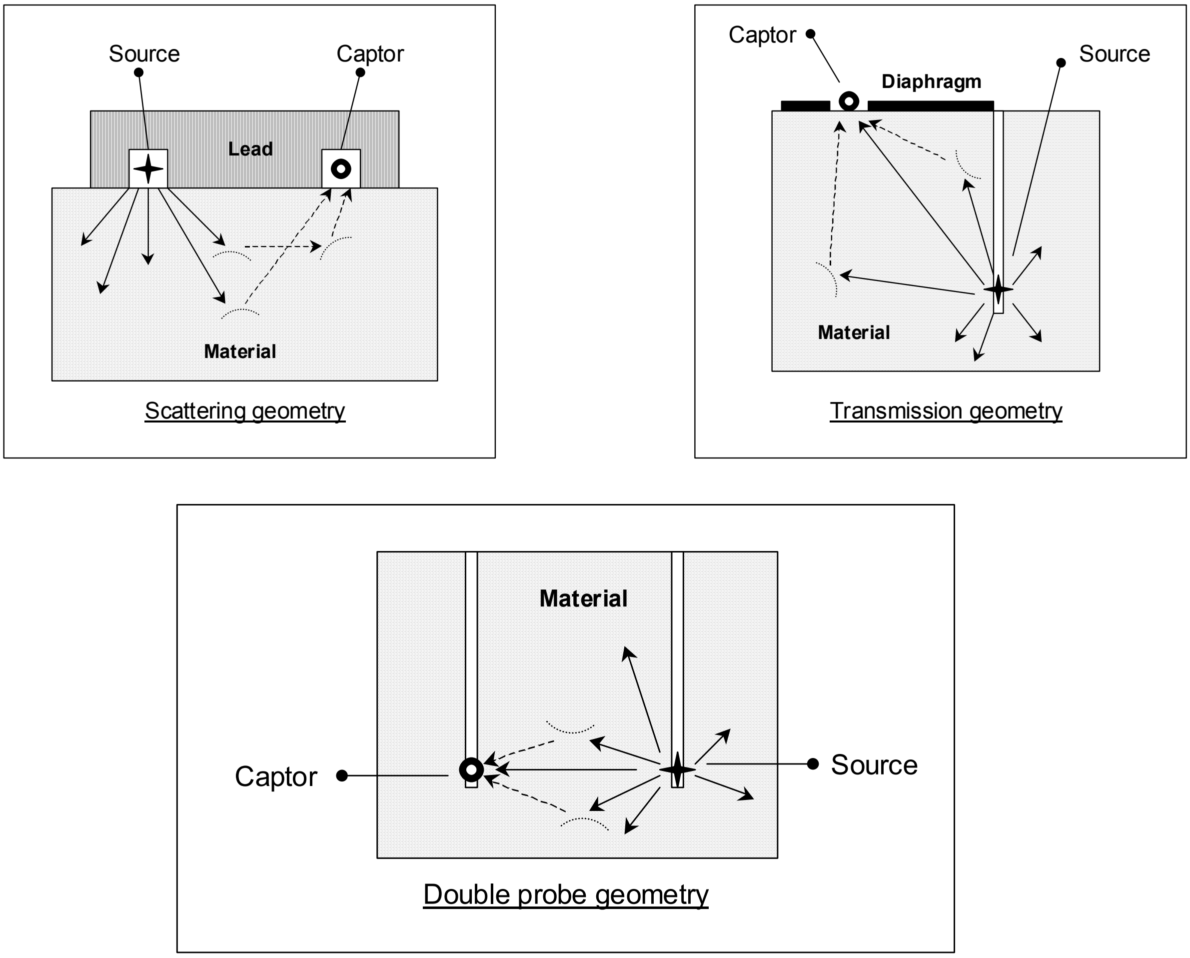



**Figure 6.6 Gamma densitometer geometries (from LCPC, 1966)**

The first geometry, the simplest to handle and non destructive, is the most sensitive to the material chemical composition and the most difficult to interpret (because of various scattering properties of the material compounds, and the depth of investigation). The second, then the third, geometries are relatively more destructive but give more accurate results by limiting the count of scattered gamma rays. The double probe allows measurement at different levels in the soil.

For normal soils and road materials, the relation between the reflected gamma flux and the material density is known thanks to calibration on natural materials at various densities. The gamma ray absorption (mass absorption coefficient) by a material containing heavy elements (heavy metals) will be higher. For unusual materials, a total chemical analysis is necessary to calculate the correct density. For calibration each point of the curve requires 2 to 3 tons of material [LCPC, 1966].

For assessing the dry density, for each material a calibration is necessary at various water contents and densities.

The double probe allows the following of variations of the wet density. As the dry density is considered as constant, if there is no swelling, the density variations with time can be assigned to the water content evolution.

**Water potential measurement**

**A – <u>Tensiometers :</u>**

A tensiometer consists of a porous ceramic filter which is connected to a water reservoir and a pressure transducer (Figure 6.7). When the ceramic filter, which is saturated, is placed in the soil, it loses water until the negative pressure in the tensiometer reaches equilibrium with the pressure in the soil. The pressure transducer measures the negative pressure.

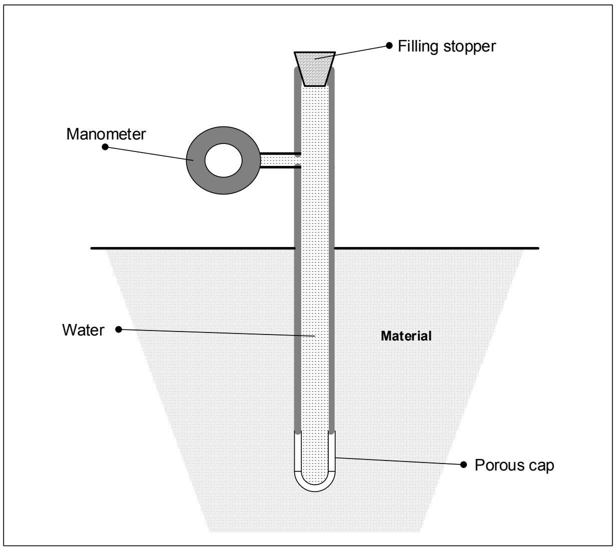



**Figure 6.7 Diagram of the tensiometer (from Hillel [1988])**

The tensiometer technique is limited to suctions below 100 kPa (1 bar), but the scale 0 to 0.8 bar includes a large part of the soil water potential observed in usual conditions.

This measurement range is usually adequate for temperate countries where subgrade suctions remain moderate, but not for arid or semi-arid regions where much greater suctions can occur (of the order of 1000 kPa) [Raimbault, Hornych, 1999], or for cold regions subjected to high frost risks.

Among the difficulties encountered with the tensiometer technique is the air presence. If the air pressure in the soil is lower than the atmospheric pressure, the water potential will be over-estimated. The contrary occurs if the soil air pressure is higher. Thus, the air trapped in the soil will affect the measurement. The air cushions created by rough installation of the tensiometer will do so [Livet and Raimbault, 1987].

Any gas trapped in the soil, like fermentation gas from the soil organic matter, will affect the measurement.

The water exchange principle of the tensiometer method makes it sensitive to frost. To protect the material it is possible to add some alcohol to the water of the tensiometer circuit. A water-ethanol mixture of 10-15% does not affect the order of size of the measured tensions [Livet and Raimbault, 1987].

The tensiometer is the most widely used technique for measuring suction [Ridley, 1998].

**B - <u>Pressure chamber :</u>**

Another method available for the laboratory water potential measurement only, but which gives at the same time information on the water content, is the pressure chamber method. It uses the same principle as the tensiometer but the operator has the possibility to act directly on the pressure.

A sample of soil is placed in a pressure chamber on a ceramic plate, permeable to water, not to air (Figure 6.8). The lower side of the plate is connected to a water tank. A constant pressure is applied to the sample. According to the pressure applied, the material water content, and the suction the material is able to apply, either the water will leave the sample, or it will be sucked from the tank, until a balance will be reached between the pressure and the material water content. The balance is reached when the water exchange between the tank and the sample stops. At this point, the material suction will balance the applied pressure.

This method presents the advantage to allow material studies under various controlled conditions (pressure, density) and it gives directly the relation between the water potential, S, and the water content.

As it provides more information, it requires a relatively long and careful preparation for the samples.

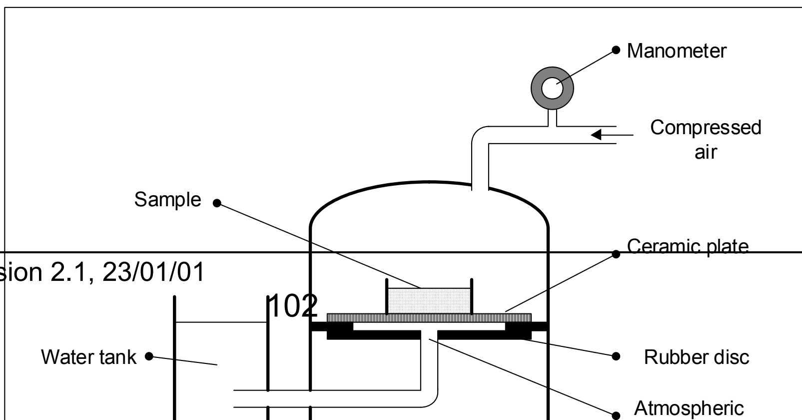


**Figure 6.8 Diagram of the pressure chamber (from Soltner [1981])**

#### 6.2.3.2 Hydraulic conductivity evaluation

The hydraulic conductivity expresses the ratio from the water flux to hydraulic gradient. It controls the velocity at which water will circulate through a material. For the materials or the scenarios of use (drainage layers for example), it is a fundamental parameter to know. In some countries (such as Austria, RVS 8S.05.11) it is a parameter taken into account in the design of road applications, for example to ensure proper drainage in the unbound base course.

**Physical methods**

**A – Permeameter method**

In general two different, quite convenient permeameter methods can be used. One method working with constant hydraulic head, mainly used in laboratory experiments and one working with falling hydraulic head, often used in field tests. The constant head method determines the $K_f$ (saturated permeability) of cylindrical cores of a porous medium, which is first wetted to saturation and then water flows through the sample at a steady rate under constant head. With the falling head method water flows through a saturated sample under a falling head of water. The range of $K_f$ that practically can be measured is about $10^{-3}$ to $10^{-10}$ m/s [Carter, 1993]. Permeameter methods applied in the field are known as infiltrometer tests. Infiltrometer tests are performed with a variety of different devices. Permeameter methods describe the saturated hydraulic conductivity.

Samples tested in the laboratory with permeameter methods are normally circulated from the bottom to the top. This avoids the disturbance of the flow by air bubbles which often occurs when the flow is from the top down (e.g. infiltrometer tests).

**B – Grain size distribution method**

The hydraulic conductivity of non-compacted unbound materials can be calculated on the basis of the grain size distribution [Hazen, 1893]. If the uniformity coefficient (ratio of grain size at 60 %/grain size at 10% of distribution) is < 5 a mathematical calculation can be used, if it is > 5 a graphical deduction after Nahrgang [1983] can be used. This method gives rather inaccurate results and does not take any compaction into account.

**C - <u>Capacitive method</u>**

A soil cylindrical sample is firstly saturated with water. A permeability test under a constant hydraulic load is then carried out, which gives the hydraulic conductivity in saturated conditions.

Then the sample is slowly dried from its upper part, whereas the bottom remains watertight (Figure 6.9). During the drying, the water stock held between the bottom of the sample and a reference plane located close to the surface where the evaporation occurs is measured. The water stock (or sample total water content at a given moment) is known thanks to several water content measurements at different heights with capacitive probes. In parallel, the hydraulic gradient is assessed thanks to the water potential measured at the reference plane level with tensiometers. The soil hydraulic conductivity at different water content is deduced from the rate of decrease of the water stock and from the hydraulic potential [Raimbault, 1986].

Other test methods like pumping tests, packer tests or geophysical methods like tracing with radioactive tracer and oscillation method are designed especially for measurements under the ground water table. This is not the case in road construction and therefore these methods are not described here.

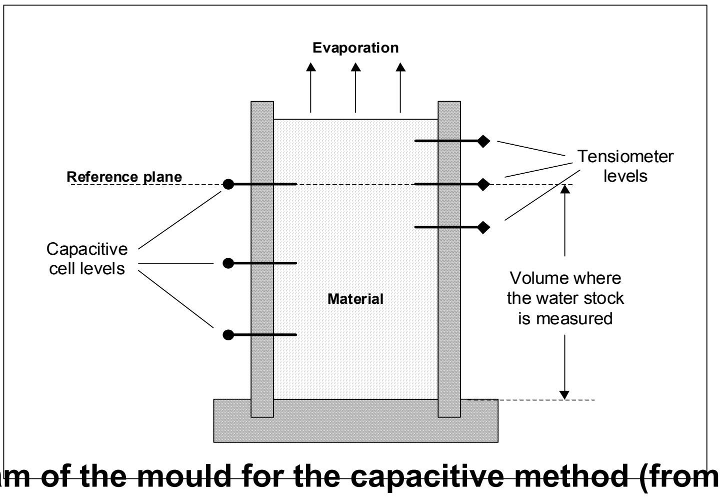



**Figure 6.9 Diagram of the mould for the capacitive method (from Raimbault [1986])**

Figure 6.9 provides a diagram of the mould, the capacitive cells and the tensiometers.

**D – <u>Methods for measuring unsaturated hydraulic conductivity</u>**

Convenient laboratory methods are the determination of $K\phi$ (which is unsaturated permeability, that varies with water content, $\phi$ ) by Buchner funnel and estimation from suction curves [Carter, 1993]. A more recent method is the open flow centrifugation. This method covers determination of hydraulic conductivity using an unsaturated flow apparatus (UFA) [ASTM, 1999]. The term UFA is now used in the literature for any apparatus using open-flow centrifugation, i.e., an apparatus providing an adjustable fluid flux during centrifugation and at adjustable accelerations. Using a UFA is effective because it allows the operator to set the variables in Darcy's Law. Darcy's Law states that the fluid flux equals the hydraulic conductivity times the fluid driving force. The driving force is fixed by imposing an acceleration on the sample through an adjustable rotation speed. The flux is fixed by setting the flow rate into the sample with an appropriate constant-flow pump and dispersing the flow front evenly over the sample. Thus, the sample reaches the steady-state hydraulic conductivity which is dictated by that combined flux and driving force. The operator can impose whatever hydraulic conductivity is desired within the operational range of rotation speeds and flow rates, usually between $10^{-4}$ m/s (10 darcy; $10^{-7}$ $cm^2$) and $10^{-13}$ m/s ($10^{-8}$ darcy; $10^{-16}$ $cm^2$). It is most convenient to saturate the sample using a traditional falling head or constant head method followed by step-wise desaturation in the UFA by increasing the speed and decreasing the flow rate, allowing steady-state to be reached at each step. Because a relatively large driving force is used, the UFA achieves hydraulic steady state in a few hours for most geologic materials, even at very low water contents.

Tension infiltrometer methods are used for determining unsaturated hydraulic conductivity in the field.

**Chemical methods**

With chemical methods, hydraulic conductivity can be determined indirectly by measuring the time a defined amount of water needs to flow through the ”sample”. Either saturated an unsaturated conditions could be simulated. Especially with field experiments running over a long period of time like lysimeters, chemical methods can be used. Tracing the infiltrating water with “conservative” (non sorptive) tracers or using the natural stable (16O, 18O, 2H) and unstable (3H) water isotopes, the breakthrough can be determined and water movement in general could be investigated.

### 6.2.4 In situ methods - Laboratory methods

#### 6.2.4.1 Hydrological state

The gravimetric water content measurement method is a pure laboratory method. For measuring in situ water content, this method requires sampling and transporting the samples to the laboratory. As it is a destructive method it can be used for characterizing a soil or a road layer once, but it is incompatible with any follow up.

The capacitive method is non destructive and can be used in the field as in the laboratory. It is a precise method but this advantage may decrease for materials that are too conductive. It can be used for follow up and monitoring.

The TDR alternative method, also available in situ and in the laboratory, may be more adapted to conductive materials than the classical method. The TDR technology can be monitored and allows follow up. Portable probes allow control measurements.

The neutron method (humidimeter) has been designed for field control. It gives global information on the water content and has consequently a relatively lower resolution power than the capacitive method. It can be used as a laboratory method, for relatively large samples (because of the volume of the measured sphere). Because neutron probes are calibrated for natural materials, using them for alternative materials requires a total chemical analysis of the material and a specific calibration. To provide the weight water content, this method has to be associated with the gamma method (densitometer) which also requires a chemical analysis for unusual materials. Nuclear methods require particular attention to operator protection. The gamma method can be used in the laboratory and in situ.

For the water potential measurement, the very flexible tensiometer method is available both for the laboratory and the field, where it allows follow up and monitoring. It works in the range of pressure usually encountered in road layers of temperate regions. For more extreme climatic conditions (high suctions, frost risk) it cannot be used. The pressure chamber method is then an alternative solution, only available for the laboratory, which allows study under high pressure and which presents the advantage of providing the relation between the suction and the water content.

#### 6.2.4.2 Hydraulic conductivity evaluation

It is well established that field or in situ measurements of saturated hydraulic conductivity are essential for accurate determination of water movement in the field. When $k_f$ is measured in the unsaturated zone (above the water table) it is often referred to as the ”field saturated” hydraulic conductivity. This is in recognition of the fact that air bubbles are usually entrapped in porous media when it is saturated by downward-infiltrating water, particularly when the infiltration occurs under ponded conditions. The water content of a porous medium at “field saturation” is consequently lower than at complete or true saturation. Nevertheless the most convenient in situ experiments are infiltrometer methods using single or double ring infiltrometers.

### 6.2.5 Conclusion and recommendations for alternative material studies

The conclusion that comes out after the scanning of the methods available today for the hydrological state assessment, is that for alternative materials, none of the methods can be definitively excluded. The use of each method depends on the purpose of the study and on the material nature, particularly its electrical conductivity or more generally its chemical composition.

For *in situ control* purposes only, both the gravimetric and the neutron methods can be used, with the advantages and disadvantages described above (a heavy and destructive method in one case; a low resolution power, requiring specific abilities of the operator, but simple and fast method in the other case).

For *in situ follow up* purposes, both the dielectric (capacitive or TDR) and the tensiometer methods are available. For the first method, compatibility of the material electrical conductivity with the method must be checked. The tensiometer method is not applicable in all climatic conditions, and if necessary, must be complemented by pressure chamber tests in the laboratory.

Standard calibration of nuclear methods does not suit a range of soils and alternative materials containing hydrogen in forms other than water, and/or containing neutron or gamma ray captors. The correct interpretation of the measurements by these methods requires the chemical analysis of the products and eventually the determination of a calibration curve. That calibration curve would be useful only for chemically homogeneous materials. For heterogeneous materials, the neutron method would only allow the follow up of the water content independently from one point to another. The comparison between points (to draw hydraulic gradients for example) would only be possible after extraction of the material and its total chemical analysis (and water content gravimetric measurement). That would be the same with the gamma double probe.

Such requirements for nuclear methods would be more easily managed *in the laboratory*. For materials with not too high electric conductivity, the capacitive method is fully available for the laboratory. For laboratory study purposes under normal pressure conditions, the tensiometer method is also fully available.

The homogeneity of the tested materials is also a crucial factor influencing hydraulic conductivity. The best results will be obtained with a combination of different methods and multiple tests. In Austria a recent study recommended performing at least 3 infiltrometer tests per 4000 $m^2$ (Bundesministerium für wirtschaftliche Angelegenheiten, 1999). The recommended threshold value (for Austrian road applications) is $1x10^{-5}$ m/s.

The time factor also influences permeability. Certain materials could have hydraulic or pozzolanic properties. Even after years, newly formed minerals could block pores and so decrease $K_f$ values. With the assessment of the results of chemical and mineralogical analysis, the behaviour of materials in the future is predictable.

One can conclude that in order to choose the way to study the hydrological state and behaviour of an alternative material, any study should start by a total chemical analysis of the material, an assessment of its homogeneity, and by its electrical conductivity measurement.

Table 6.3 summarises these conclusions.

**Table 6.3 Comparison between the methods**

| METHOD | Gravimetric Method | Capacitive Method | TDR | Neutron - Humidi-meter | Gamma - Densito-meter | Tensio-meter | Pressure chamber |
|---|---|---|---|---|---|---|---|
| **Measures…** | Mass | Dielectric constant | Dielectric constant | Thermal neutrons | Gamma rays | Pressure | Mass and pressure |
| **Provides…** | **W** | **W** or θ depending on calibration | **W** or θ Depending on calibration | θ requires ρ to obtain W | ρ or **W** with the double probe | **S** | **S** and **W** |
| **In situ control** | Yes | Need to know the density | Need to know the density | Yes | Yes for ρ<br>No for W | Possible | No |
| **In situ follow up** | No | Yes | Yes | Yes | Yes for W | Yes | No |
| **Laboratory** | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Electrical compatibility assessment** | No | Yes | Yes | No | No | No | No |
| **Chemical compatibility assessment** | No | Useful | Useful | Yes | Yes | No | No |

# 7. CASE STUDIES

## 7.1 INSPECTION OF EXISTING ROADS

### 7.1.1 Denmark (1): Crushed concrete as unbound base

**Location**

For the ALT-MAT project a local road in Skibet Vejle, Jutland in western Denmark has been chosen, since some historical data on crushed concrete from the construction of the road and after are available. The mean summer temperature at the site is 16 degree Celsius; mean winter temperature is 0 degree Celsius, with several changes between freeze and thaw during the winter season. The subgrade is sand.

**Type of road**

It is a local road with very light traffic. The road was opened to traffic in October 1990. The road is constructed as follows:

| | |
|---|---|
| Asphalt concrete | 70 mm |
| Crushed concrete | 200 mm |
| Unbound sand | 300 mm |
| Sand | Subgrade |

In the reference section unbound natural gravel replace crushed concrete.

**Mechanical test results**

<u>Non-destructive field tests</u>
During the examination of the existing road in 1998 the following non-destructive tests were carried out: Main inspection (general functional behaviour) and bearing capacity measurements (roads structural condition).

It was found that the general functional behaviour of the road is good with a Danish Pavement Condition Index of 0.70 (0 – 1.99 is generally considered good standard).

The roads structural condition is good measured with the Falling Weight Deflectometer (FWD).

| Materials | 1991 June [1)] | 1998 May [2)] |
|---|---|---|
| Crushed concrete | 320 | 540 |
| Gravel | 200 | 215 |

Table: E-moduli Unbound Material in MPa.
[1)] Estimated values, FWD [2)] Calculated values (average of three)

The E-modulus for the crushed concrete has developed from approx. 300 MPa during construction to 500 MPa today. It seems that the crushed concrete has been hydraulically bound to some extend. The timescale for this binder effect is unknown. The E-moduli for crushed concrete are significantly higher than for the reference sections with traditional base course gravel. The E-moduli for the reference basecourse is lower than normal (normally 300 MPa).

Intrusive field investigations and mechanical laboratory tests
In the test section with crushed concrete and in the reference section with natural gravel as base, trial pits and sampling were made both for mechanical and environmental testing. Samples were taken from each layer: asphalt wearing course, unbound gravel as base course, sub-base and subgrade to a depth of 1 metre below the road surface. Each set of samples consisted of specimens from each 0.10 metre layer.

Four sets of density measurements in 10, 15 and 20 cm depth were carried out on the two different base materials with a nuclear gauge. The reference density is measured with Vibrating Table. The results show very high compaction degrees for the crushed concrete all through the layer; whereas the granular base material shows a trend to increase down through the layer.

Several mechanical classification tests were made on the base material of crushed concrete and natural gravel. Some historical data from construction of the road are available, and these data and present results were compared. There is no significant change of the classification data in the period after the construction of the road.

**Figure 7.1 Measurement of field density at the site (nuclear gauge method)**

**Environmental test results**

A composite sample of crushed concrete from the 20 cm unbound base layer has been subjected to chemical characterisation, including total chemical analysis for selected major and trace elements. The results show that the total content of most trace elements in the crushed concrete is moderate and somewhat higher than the trace element concentration in the natural aggregate. The pH of the crushed concrete is, as could be expected, high. The total organic compound (TOC) content of the crushed concrete is low.

A representative subsample of the crushed concrete which had been size-reduced to < 4 mm was subjected to a 2-stage compliance batch leaching test with demineralised water at L/S = 2 l/kg and L/S = 8 l/kg (prEN 12457). The leaching of salts from the crushed concrete appears to be quite low, except for Ca. The eluate is strongly alkaline, and it is therefore not surprising that Cr (in the form of chromate) and the amphoteric Pb are leached in higher quantities from the crushed concrete than from the bottom ash (which is fully carbonated and therefore produces an almost neutral pH, see Section 7.1.2) and the reference sand.

**Conclusions**

The inspection and testing of the eight-year-old road in Vejle with crushed concrete as base layer has shown good functional behaviour. The roads structural condition is even better in the crushed concrete section than in the reference section with natural aggregates. The E-modulus for the crushed concrete has developed from approx. 300 MPa during construction to 500 MPa today. It seems that the crushed concrete has been hydraulically bound to some extend.

The results from measurement of field density show very high compaction degrees for the crushed concrete all through the layer; whereas the granular base material shows a trend to increase down through the layer.

The environmental tests show that the total content of most trace elements in the crushed concrete is moderate and somewhat higher than the trace element concentrations in natural aggregates. Due to the lime content of concrete, the pH is high. The total organic content (TOC) is low. Due to the high pH in the eluate, the leaching of Cr and Pb is higher from the crushed concrete than from bottom ash and reference sand. The leaching of salts from the crushed concrete is low.

### 7.1.2 Denmark (2): MSWI bottom ash as unbound sub-base

**Location**

For the ALT-MAT project a local road in Skælskør, Zealand in eastern Denmark has been chosen, since historical data of MSWI bottom ash from the construction of the road and after are available. The mean summer temperature at the site is 16 degree Celsius, mean winter temperature is 0 degree Celsius with several changes between freeze and thaw during the winter season. The subgrade is boulder clay.

**Type of road**

It is a heavily trafficked local road, with approximately $5x10^4$ equivalent 10-ton axles per year. The road was opened to traffic in September 1993. The road is constructed as follows:

| | |
|---|---|
| Asphalt wearing course | 30 mm |
| Asphalt concrete | 90 mm |
| Unbound gravel | 200 mm |
| MSWI bottom ash | 300 mm |
| Boulder clay | Subgrade |

In the reference section unbound natural sand replace MSWI bottom ash.

**Mechanical test results**

<u>Non-destructive field tests</u>
During the examination of the existing road in 1998 the following non-destructive tests have been carried out: Main inspection (general functional behaviour), measurement of evenness and rutting and bearing capacity measurements (structural condition).

It was found that the general functional behaviour of the road is good with a Danish Pavement Condition Index of 0.50 (0 – 1.99 is generally considered good standard). Furthermore, the results of the measurement of evenness and rutting show low values, which can be expressed as a good standard.

The roads structural condition is relatively good measured with the Falling Weight Deflectometer (FWD). The results can be compared to the historical data and data from measurements made in 1996. The results shown in the table indicate that the E-moduli for the MSWI bottom ash are lower than the E-moduli of the natural materials.

| Materials | 1993 August | 1994 August | 1995 April | 1995 June | 1996 June | 1998 June |
|---|---|---|---|---|---|---|
| Gravel + Bottom Ash | 112 | 119 | (239) | 191 | 168 | 241 |
| Gravel + Sand | 167 | 209 | (350) | 308 | 282 | 344 |

Table: E-moduli Unbound Material in MPa (Average of six measurements)
( - - ) Values uncertain

Intrusive field investigations and mechanical laboratory tests

In the test sections with MSWI bottom ash and in the reference section with natural sand as sub-base, trial pits and sampling were made both for mechanical and environmental testing. Three sets of samples were taken down to a depth of 1 metre below the road surface in the wheels tracks and in between. Each set consisted of specimens from each 0.10 meter layer.


**Figure 7.2 Measurement of field density at the site (Sand replacement method)**

During the laboratory tests historical and present results have been compared. There is no significant change of the classification data in the period after construction of the road and up to this date.

**Environmental test results**

Samples of bottom ash and natural sand from the test sites as well as samples of the same materials collected before they were placed in the road have been characterised chemically and subjected to laboratory leaching tests.

The leaching tests performed on MSWI bottom ash and the subgrade material collected at various depths indicate that some salts have leached from the sub-base and migrated into the underlying subgrade material. Similar tests on materials from the reference site showed very small leachability and little or no migration. With the exception of Cu, Mo and Zn, the leachable amounts of trace elements in the bottom ash are low. Only a very limited amount of salts can be leached from the natural sand excavated from the reference site.

In addition, the same samples were subjected to partial digestion with half concentrated HNO3 in a teflon bomb at 1 atmosphere for 2 hours. The results indicate that all the materials tested comply with the Danish regulations for utilisation.

| Parameter | Unit | Material from test site | | Stockpile 1998 | Existing criteria for utilisation |
|---|---|---|---|---|---|
| | | Natural sand | MSWI BA | MSWI BA | |
| Cd | mg/kg | < 0.01 | 3.0 | 3.8 | < 10 |
| Hg | mg/kg | < 0.02 | 0.11 | 0.06 | < 0.5 |
| Pb | mg/kg | 3 | 1500 | 1700 | < 3000 |
| pH (1% slurry) | - | 9.8 | 9.2 | 9.6 | > 9.0 |
| Alkalinity | eqv/kg | 1.8 | 2.2 | 2.6 | > 1.5 |

New Danish regulations, which are also based on the leaching properties and the risk of migration of leached contaminants into the groundwater, are currently being prepared by the Danish EPA. The leaching results indicate that the bottom ash recovered from the test road will meet the expected new limit values for materials placed below a pavement of low permeability (with surface runoff) whereas it is not likely to meet the limit values for materials placed without cover (e.g. under the shoulders of the road).

**Conclusions**

The inspection and testing of the five-year-old road in Skælskør with MSWI bottom ash as unbound sub-base has shown good functional behaviour. Furthermore, the results of the measurement of evenness and rutting are low values, i.e. good standard. The structural condition of the road is relatively good in spite of the fact that the road is heavily trafficked. The bearing capacity as measured with the Falling Weight Deflectometer (FWD) is not as good for MSWI bottom ash as for similar natural aggregates.

During the laboratory tests historical and present results have been compared. There is no significant change of the classification data in the period after construction and up to this date. There has been no significant crushing of the MSWI bottom ash due to five years of traffic load.

The leaching tests performed on MSWI bottom ash and the subgrade material collected at various depths indicate that some salts have leached from the sub-base and migrated into the underlying subgrade. Only a very limited amount of salts can be leached from the natural sand excavated from the reference site.

All the bottom ash samples investigated comply with the current Danish quality criteria for utilisation. The future guidelines are likely to meet for bottom ash placed below the pavement but not for bottom ash under the shoulders of the road.

### 7.1.3 France (1) – The “La Teste” site

#### The location

The city of La Teste is located in the south-west of France, 50 km south-west from Bordeaux, on the bank of the Arcachon basin. The climatic context of this area is oceanic. On the geological point of view the area belongs to the Aquitaine basin. On the inspection site, the soil is made of sand and can be subject to rapid fluctuations of the water table. The area is flat.

**Figure 7.3 La Teste incineration plant and the inspected road**

#### The road

The road investigated is the access lane to the incineration plant of the urban district. It has been designed as a loop 320 m long and 7 m wide. It is used by 30 to 40 heavy lorries a day. It was constructed in 1976.

#### Construction details

The MSWI bottom ash produced by the incineration plant has been used in the sub-base layer as an unbound graded aggregate. Local technicians remember the MSWI bottom ash implementation was not easy. The thickness of this layer was supposed to be 400 mm. The base course was a limestone unbound graded aggregate 100 mm thick. During the construction, no geotextile was laid between the MSWI bottom ash layer and the underlying natural soil. The road has been covered with a bituminous concrete surfacing only in 1995.

Two trenches have been dug in this road. Both were exploited for the study.

#### Results of mechanical tests

Physical characteristics of the MSWI bottom ash have been assessed in situ (deflection, density, water content) and in the laboratory (particle size distribution, physical composition, modified Proctor test, immediate CBR test).

Despite some peaks at 140/100 mm, the average deflection was around 60-66/100 mm and 67-90/100 mm depending on the lane.

The in situ density was 1.74 - 1.99 t/m$^3$ in the first trench, depending on the depth. It was 1.62 - 1.65 t/m$^3$ in the second trench. The in situ water content was around 9 - 10%.

Although the material did not undergo any particular preparation 22 years before, the particle size distribution corresponds to the French NF P 98-129 standard for unbound graded aggregates (0/31.5 mm).

The MSWI bottom ash glass content was very high in the 4/14 mm fraction (30 - 40%).

The first trench sample gave a Modified Proctor optimum dry density of 1.95 t/m$^3$ for a water content of 11.5%, and an Immediate CBR index of 125. The second trench sample obtained respectively 1.85 t/m$^3$, 13.3% and 70. The Proctor test showed that the MSWI bottom ash compaction rate was low (below 90%), due to the initial bad compaction. The CBR test showed that the bearing capacity can be higher with 1% less water content. It showed also the high sensitivity of the MSWI bottom ash bearing capacity to water content variations.

**Results of environmental tests**

Chemical characteristics of the MSWI bottom ash have been assessed through total analysis and leaching tests. Thus the solubility of each component has been deduced. The underlying soil has been sampled at different depths and analysed to assess any pollution due to MSWI bottom ash. To have a reference state, the surrounding soil has also been sampled and analysed.

Today the chemical composition of the old MSWI bottom ash is comparable to the materials produced today, but the ageing (particularly because of the pH decrease around 9) results in a lower global solubility of the old material components.

Some of the parameters measured on the leachates (loss on ignition, soluble fraction, sulphates, Cd, Cr and Pb) have been compared to the limit values set by the present French regulation of MSWI bottom ash use in road construction. They are all below the limits.

The table below summarises the other results.

| Depth (cm) | Nature | PH | Conduc -tivity (:S/cm) | $SO_4^{2-}$ (mg/kg) | Cd (mg/kg) | Cr (mg/kg) | Pb (mg/kg) | Zn (mg/kg) |
|---|---|---|---|---|---|---|---|---|
| **Reference:** | | | | | | | | |
| (20-95) | Sand | 7.1-7.7 | 28-151 | 4-40 | 0.01-0.06 | 2.5-8.2 | 4.4-6.8 | 2.7-7.8 |
| **Trench 1:** | | | | | | | | |
| (12-32) | MSWI ba | 9.1 | 528 | 713 | 2 | 170 | 1010 | 2260 |
| (32-37) | Sand | 8.6 | 256 | 94 | 0.1 | 6.1 | 55 | 122 |
| (37-42) | Sand | 7.1 | 337 | 256 | 0.1 | 4.4 | 8.7 | 8.8 |
| (42-52) | Sand | 7.2 | 190 | 23 | 0.04 | 5.7 | 7.4 | 5.5 |
| **Trench 2:** | | | | | | | | |
| (35-85) | MSWI ba | 9 | 286 | 259 | 4.3 | 215 | 1341 | 4120 |
| (85-90) | Sand | 8.9 | 83 | 16 | 0.05 | 3.1 | 13 | 21 |
| (90-95) | Sand | 8.9 | 69 | 15 | 0.02 | 2.7 | 6.7 | 9.7 |
| (95-105) | Sand | 9 | 103 | 35 | 0.1 | 3.9 | 29 | 48 |

The pH of the underlying natural soil increases at the contact with the MSWI bottom ash layer. For the first trench there is also a conductivity and sulphates concentration increase in the underlying soil.

The concentrations measured in the underlying soil layers for heavy metals have been compared to the intervention limit values calculated with the Dutch environment ministry (VROM) method for the assessment of soil pollution. For Pb and Zn, these concentrations are higher than those measured in the surrounding soil, but they are far below the limit values. Effects of Cd and Cr on the natural soil are nil or negligible.

**Conclusion**

The La Teste inspection allowed the assessment of the mechanical and environmental durability of MSWI bottom ash road layers under actual use conditions during more than 20 years.

The road and the alternative material have obtained rather positive results to the several tests (standards, requirements) they have undergone (good deflection for a flexible structure, no pollution of the underlying soil, very low leaching, very good bearing capacity, good particle size distribution). These results are even more interesting when it is considered that the material did not undergo any particular preparation before implementation. Neither the structure design, nor the technical implementation, were particularly fitted to this non-standard material. Moreover, before 1991, MSWI fly ash, which is far more polluting than bottom ash, was not separated from it.

The influence of MSWI bottom ash on the underlying soil is perceptible mainly as regards the pH, the conductivity, sulphates, lead and zinc. Through the mechanical properties, this inspection has shown the heterogeneity of the material and its water content sensitivity. The solubility of the La Teste MSWI bottom ash compounds is reduced today. It may have been higher when the MSWI bottom ash pH was higher in former times, and pollutants could have been dispersed through the La Teste draining soil. Other inspections must be carried out to compare the results under different scenarios of use.

**Figure 7.4 Underlying soil sampling**

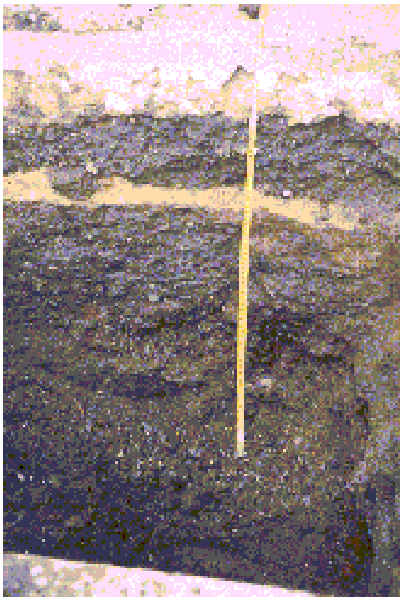


**Figure 7.5 Vertical profile with MSWI bottom ash**

### 7.1.4 France (2) – The "Le Mans" site

#### The location

The city of Le Mans is located in the west of France, 150 km south-west from Paris. The climatic context of this area is oceanic. On the geological point of view the area is located on the margin between the Parisian basin and the old Armoricain massif. On the inspection site, the soil is made of more or less sandy green plastic clay. The inspection site area has a significant relief, so that the underground water is drained away.

**Figure 7.6 Le Mans inspected road**

#### The road

This is an urban road, located on the outskirts of the city. It is managed by the metropolitan district. The section made with alternative material is 430 m long and 10 m wide. It supports a traffic of 12000 vehicles a day, plus a bus route. Heavy lorry traffic is not allowed in this residential area. It was constructed in 1978.

#### Construction details

The MSWI bottom ash produced by the Le Mans incineration plant has been implemented in the sub-base layer and as an unbound graded aggregate. Local technicians remember the MSWI bottom ash implementation was not easy. The thickness of this layer was supposed to be 300 mm. The base course was a natural crushed material as unbound graded aggregate 100 mm thick. During the construction, no geotextile was laid between the MSWI bottom ash layer and the underlying natural soil. The road was covered with a bituminous mixture 150 mm thick.

Two trenches have been dug in this road. Only one was exploitable for the study. In the first trench the MSWI bottom ash was mixed with traditional road materials.

**Results of mechanical tests**

Physical characteristics of the MSWI bottom ash have been assessed in situ (deflection, density, water content) and in the laboratory (particle size distribution, physical composition, modified Proctor test, immediate CBR test).

Deflection did not show peaks higher than 100/100 mm. The average deflection was around 29 - 48/100 mm and 44 - 47/100 mm depending on the side of the road.

The in situ density was 1.73 – 1.78 t/m$^3$, depending on the depth. The in situ water content was around 14 – 15.5%.

Althogh the material did not undergo any particular preparation 20 years before, the particle size distribution corresponds to the French NF P 98 - 129 standard for unbound graded aggregates (0/20 mm).

The MSWI bottom ash glass content was very high in the 4/10 mm fraction (60%).

The Modified Proctor optimum dry density of this MSWI bottom ash was 1.80 t/m$^3$ for a water content of 14.7%, and an Immediate CBR index of 110. The Proctor test showed that the MSWI bottom ash compaction rate was correct (96-99%), thanks to the initial good compaction. The CBR test showed that the bearing capacity cannot be higher. With a small excess or lack of water (+/- 2%), the bearing capacity can decrease significantly.

**Results of environmental tests**

Chemical characteristics of the MSWI bottom ash have been assessed through the total analysis and leaching tests. Thus the solubility of each component has been deduced. The underlying soil has been sampled at different depths and analysed to assess any pollution. To make a reference, the surrounding soil has also been sampled and analysed.

Today, the chemical composition of the old MSWI bottom ash is comparable to the materials produced today, but the ageing (particularly because of the pH decrease around 8) results in a global lower solubility of the old material components.

Some of the parameters measured on the leachates (loss on ignition, soluble fraction, sulphates, Cd, Cr and Pb) have been compared to the limit values set by the present French regulation of MSWI bottom ash use in road construction. They are all below the limits.

The table below summarises the other results.

| Depth (cm) | Nature | pH | Conduc-tivity (:S/cm) | $SO_4^{2-}$ (mg/kg) | Cd (mg/kg) | Cr (mg/kg) | Pb (mg/kg) | Zn (mg/kg) |
|---|---|---|---|---|---|---|---|---|
| **Reference:** | | | | | | | | |
| (40-120) | Sandy clay | 6.5-7.1 | 44-60 | 11-26 | 0.1 | 30-85 | 16-31 | 29-45 |
| **Trench:** | | | | | | | | |
| (35-60) | MSWI ba | 8.3 | 1620 | 3710 | 13 | 403 | 880 | 2880 |
| (60-70) | Sandy clay | 7.9 | 227 | 265 | 0.3 | 43 | 32 | 76 |
| (70-80) | Sandy clay | 7.5 | 219 | 53 | 0.1 | 38 | 26 | 29 |
| (80-100) | Clay | 6.4 | 103 | 429 | < 0.1 | 95 | 26 | 55 |

The underlying natural soil pH increases at the contact with the MSWI bottom ash layer, as do the conductivity and the sulphate concentration.

The concentrations measured in the underlying soil layers for heavy metals have been compared to the intervention limit values calculated with the Dutch environment ministry (VROM) method for the assessment of soil pollution. These concentrations are all far below the limit values, and they are similar to the concentrations measured in the surrounding soil.

**Conclusion**

The Le Mans inspection allows the assessment of the mechanical and environmental durability of MSWI bottom ash road layers under actual use conditions during 20 years (1978-1998).

The road and the alternative material have given rather positive results to the several tests (standards, requirements) they have undergone (very good deflection for a flexible structure, no pollution of the underlying soil, low leaching, very good bearing capacity, good particle size distribution). These results are even more interesting when one considers that the material did not undergo any particular preparation before implementation. Neither the structure design, nor the technical implementation, were particularly fitted to this non-standard material. Moreover, before 1991, MSWI fly ash, which is far more polluting than bottom ash, was not separated from it.

The influence of MSWI bottom ash on the underlying soil is perceptible mainly as regards the pH, the conductivity and sulphate. Through the mechanical properties, this inspection has shown the MSWI bottom ash has high sensitivity to water content variations. The solubility of the Le Mans MSWI bottom ash compounds is reduced today. One can imagine that the solubility may have been higher in the former times. The underlying clay was supposed to fix the elements released from the MSWI bottom ash layer. Now, the concentrations measured are far below the pollution limits. This study provides a good complement to the information delivered by the La Teste inspection conclusions, but some other inspections must be carried out to assess such results and study other use conditions.

**Figure 7.7 In situ density Measurement with the Gamma-densitometer**

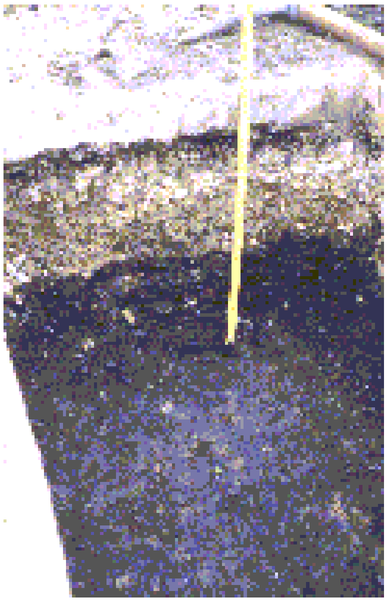


**Figure 7.8 Vertical profile with MSWI bottom ash**

### 7.1.5 Sweden

#### Background

In the past a lot of small iron mines were scattered over the Swedish country. Pig-iron was produced in small blast furnaces and the slag was used as fill and in road pavements close to these metallurgical industries. Nowadays Blast Furnace Slag (BFS) derives from two major steel manufacturing plants.

Air-cooled Blast Furnace Slag (ACBFS) from these plants has been used locally but in quite large quantities in road constructions. In 1986 ACBFS was used in the sub-base in a section of road E4, designed as a Motorway. In 1995 the road was reconstructed as a Highway partly reusing the ACBFS of the Motorway but also constructing two new lanes with ACBFS in the sub-base.

#### Physical conditions

The major road E4 runs along the eastern part of Sweden from the border to Finland in the north to the bridge at Öresund over to Denmark in the south. The inspected site of the road is situated close to the town of Nyköping approximately 150 km south of Stockholm.

This part of Sweden is characterised by fine sediments, silt and clay, deposited in flat plains crossed by eskers with sand and gravel, hillocks with various types of till and hills with Precambrian bedrock like granite and gneiss. At the inspection site sand covers silty sediments.

The hydrogeology at the site is characterised by a rather high ground water level. It fluctuates a little due to the geological and the climatic conditions but generally it is 1.5 – 2 m below ground surface. The outer border of a protected ground water reservoir is situated very close to the Highway and the inspection site. In the area several groundwater tubes were installed in the mid 1980s before the road was constructed.

In this coastal area there is mainly a Maritime Climate affected by the Baltic Sea. The annual precipitation is 500 – 600 mm and the annual mean temperature is approximately + 6° C. The winters are generally mild with temperatures at or just below zero.

#### Road design and traffic

The motorway opened for traffic in 1986 was designed as a carriageway with 7.50 width and two shoulders 2.75 m each. The design was based upon an average annual daily traffic (AADT) of totally 10000 vehicles with approximately 17 % Heavy Vehicles. After the reconstruction to a Highway standard with two lanes in each direction the Swedish National Road Administration (SNRA) has measured the traffic flow four times during 1998.

Based on these measurements the AADT was determined to be 15000 vehicles and approximately 14 % were Heavy Vehicles.

**Pavement strata**

From the inspection and site investigations carried out in August 1998 the following pavement strata and materials were observed and measured in the northbound (reconstructed; Figure 7.9) and the southbound (new constructed; Figure 7.10) carriageways.

**Material properties**

Several laboratory analyses and in-situ tests have been carried out on the ACBFS. These investigations relate both to the old construction as well as the present Highway. The particle size distribution of the ACBFS used as sub-base falls within the requirements of the Technical Specification (ROAD 94) set up by the SNRA.

In order to test the abrasive action on the ACBFS from lorries, dumpers etc during the road construction the material has been tested in the Nordic Ball Mill (EN 1097.9). The obtained Mean value of the $A_N$ from several tests is 23 related to $A_N$ <30 required in ROAD 94 for sub-base material. A “normal” Swedish rock type e.g. a granite usually has an $A_N$ <18.

Even though the Los Angeles Fragmentation Test and the CBR Test are not specified for Swedish road construction requirements the ACBFS has been tested using these methods in order to compare the results with what has been obtained in other countries and on various alternative materials. A mean value of LA for the ACBFS is 35 to be compared with 20-25 for a “normal” CR (reference material). A mean value of CBR for the ACBFS is 145; no CBR test has been performed on CR.

To show that the ACBFS does perform acceptably and even better than a natural aggregate in the road construction, dynamic Triaxial Tests (TT) and measurements with a FWD have been performed. The results from the TT show that the stiffness of ACBFS increases after only 4 weeks of “ageing” and also in comparison to the “fresh” ACBFS as well as the CR. Principal stresses above 1200 kPa created a significant drop of the resilient modulus $M_r$ which slightly could be observed even for the ”fresh” ACBFS. This was probably caused by deterioration of particles. However dynamic vertical stresses above 800 kPa from traffic load on a base course or a sub-base will never occur.

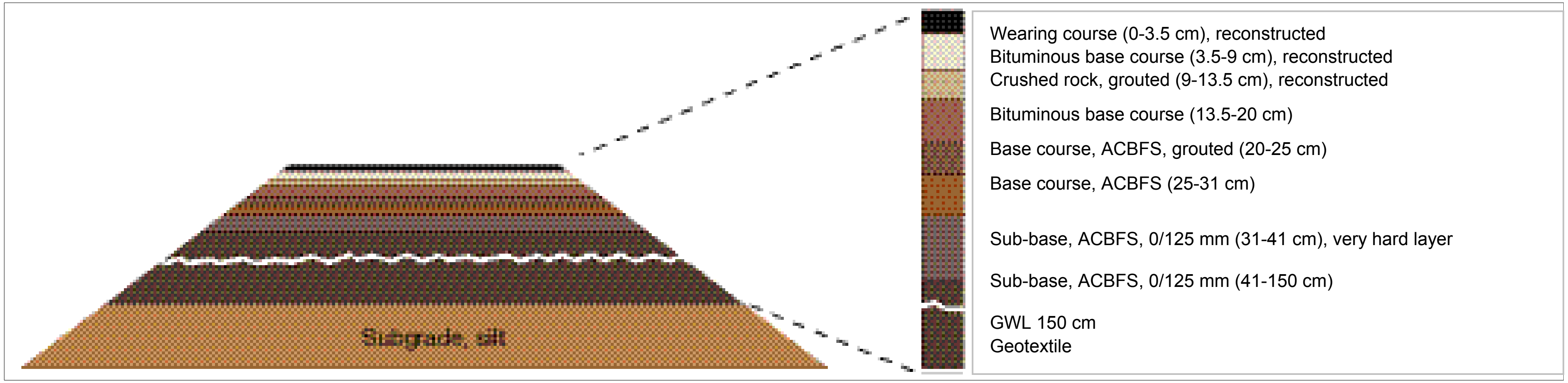



**Figure 7.9 Pavement strata and observations in test pit, northbound lane**

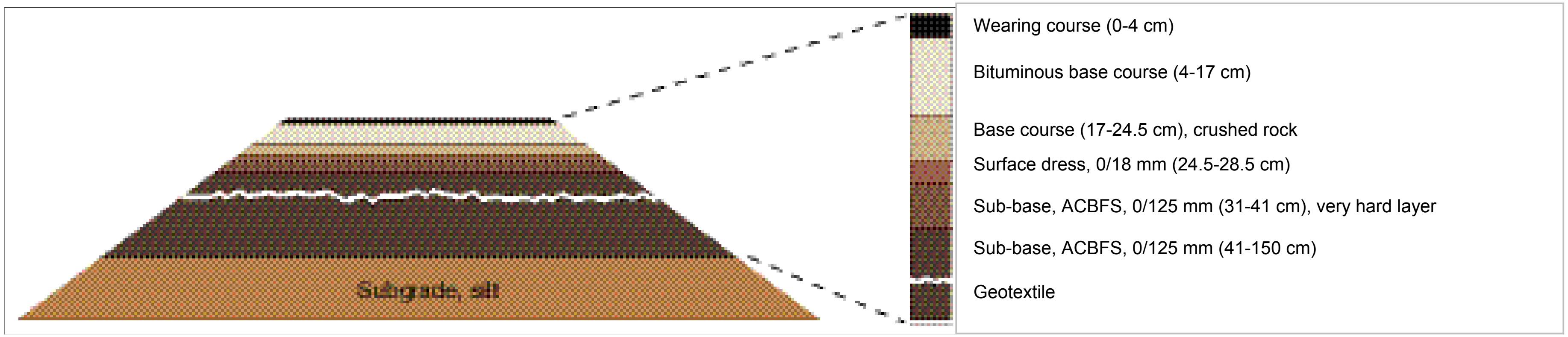



**Figure 7.10 Pavement strata and observations in test pit, southbound lane**

The results obtained from the TT at given principal stresses of 800 kPa give the following resilient moduli:

"Fresh" ACBFS $M_r$= 400 kPa,
"Aged" ACBFS $M_r$= 550 kPa,
CR (granite;ref) $M_r$= 340 kPa.

The permanent deformation is also improved by ageing of the ACBFS. This fact coincides fairly well with the results obtained in the FWD-measurements on the road. From the analysis and back calculations of the resilient modulus for each pavement layer in the Motorway the mean layer modulus of the sub-base with the ACBFS was 600 MPa while it was 300 MPa for the sub-base with CR. The ACBFS in the present Highway shows even higher values.

**Environmental properties**

The total composition of the ACBFS has been analysed and leaching tests have been performed within the ALT-MAT study and were done on ACBFS taken from the road constructed in 1986 (see National report for leaching tests for Sweden, Appendix F). The results showed that Ca, Si, Mg, Al and S are the main components of the slag. Considering the trace elements the amounts are low; only the amount of V is significant. In the leaching tests, only V, of the trace elements, leached in significant amounts. The availability tests performed showed that oxidation of the slag increased the leaching of several trace elements such as Pb, Cd and Cr.

Groundwater sampling in existing tubes was performed four times during 1998-1999. The pH-values are around 7-8. Vanadium and sulphur were analysed. The amounts of V were low, which indicates that the leaching of trace elements is low in the area. The amounts of sulphur are below drinking water standards but in one of the groundwater tubes concentrations of sulphate exceeds background levels.

**Conclusions**

From the laboratory analysis and the field tests carried out on ACBFS in comparison with CR as reference material, a lot of experience has been gained and several conclusions can be drawn. The following facts might be used when this alternative material is proposed to be utilised as road construction material in the future.

1. ACBFS meets the requirements of the Swedish Road Technical Specifications (ROAD 94) when used in sub-base.
2. The thermal insulation properties of ACBFS and its higher stiffness imply thinner thicknesses of the road pavements which save natural aggregates and offer economic advantages.
3. However in countries like Sweden with cold winter climate it has been observed that ACBFS used high up in the pavement may cause potential icing on the road surface especially in early winter.

4. Performance related tests like Dynamic Triaxial Test and FWD-measurements verify a marked increase of stiffness of the ACBFS with age (see below and Sections 7.2.1 and 7.2.2).
5. Cementitious properties of the ACBFS create self-binding, which from both engineering and environmental point of view is very important.
6. Disregarding the thermal properties, the ACBFS can be used in base course. In other words ACBFS can be used high up in the road pavement in countries or regions with milder winter climate than in Sweden.
7. From the sampling performed no environmental impact from the ACBFS can be seen.

The Motorway/Highway E4 with its ACBFS in the sub-base has verified that the road application properties are as good as or even better than those of the reference sections with natural aggregates. The requirements in ROAD 94 were also met on the particle size distribution and the $A_N$. In addition, the stiffness of the ACBFS improved considerably with ageing in the laboratory as well as in the road within a relatively short period. The increase of stiffness in alternative materials is very useful in road applications, and therefore this important property promotes usage in infrastructure constructions with high traffic volumes and/or heavy traffic.

The results obtained from the inspection of the Highway and the investigations of ACBFS clearly show that it is now time to abandon empirical tests in favour of performance related tests. It is also necessary to develop or modify the present technical guidelines or specifications which are appropriate to a large extent for virgin materials or natural aggregate but not for alternative materials in road construction.

### 7.1.6 UK

**Site identification**

The site selected for investigation was in Bracknell, located about 5km to the north east of the TRL Crowthorne site. It is in Southern England, in the Thames Valley to the west of London. The average annual rainfall is 660mm, evenly distributed throughout the year. The average daily minimum temperature in January is +0.5$^0$C, and the average daily maximum is +6.6$^0$C. The corresponding values for July are +10.8$^0$C and 21.5$^0$C. The site is underlain by London Clay, a heavily overconsolidated clay of Eocene age.

A number of roads have been built, as part of new housing estates, in North Bracknell since 1991. Alternative materials were used for capping and sub-base layers in several of these new roads. The roads were designed and constructed by a consortium of private developers but were to be adopted by the Local Authority, and so had to meet government guidelines.

The road chosen for investigation at this site had adjacent lengths of natural (limestone) aggregate sub-base and demolition rubble sub-base. Investigations were conducted at locations over both sub-base areas.

**Road type**

The roads in this housing area are approximately 5-10 years old. The road designs were based on the Local Authority Standards, and the construction used was that for major access roads and intermediate access roads, which are designed to carry less than 250 commercial vehicles per day.

**Construction details**

The road construction for the site contains an unbound sub-base aggregate layer, beneath the (bituminous) pavement surface layer. The thickness of the sub-base varied depending on the CBR of the natural clay subgrade present in the area.

The natural aggregate section contained a purely limestone sub-base. For the alternative aggregate section of road, the Local Authority Standards permit the use of alternative aggregate which just falls outside the sub-base grading limits (‘Type 1’ material), if a layer of Type 1 is placed above it. Hence the sub-base section contained a 100mm layer of natural sub-base over a thicker layer of demolition rubble sub-base.

**Mechanical tests**

Tests were performed both in-situ and on excavated samples of sub-base aggregate.

A falling weight deflectometer (FWD) survey was conducted over sections of road, providing sub-base and subgrade stiffness values. The FWD indicated localised variability in the amount of support given by the sub-base to the road pavement, though not serious enough to have a significant effect on the integrity of the road pavement. The FWD survey indicated that the thicker sub-base layer in the demolition rubble section provided greater support, with a mean value of almost 1000MPa, whilst the limestone sub-base mean value was slightly over 200MPa.

A detailed visual condition survey of the site was also carried out, and showed that there was no discernible difference in the condition of the surface between the two sections of road.

Trial pits were excavated in each section of road, and plate bearing tests were conducted on the sub-base materials. These tests showed that the support given by the sub-base materials in both sections of road was in the 'acceptable-good' range. The limestone sub-base was approximately 150mm thick, and the demolition rubble sub-base was approximately 500mm thick. The rubble consisted mainly of brick with some concrete and masonry. The thickness of the bituminous layer was 250mm to 300mm.

**Figure 7.11 Plate bearing test (using German Dynamic Plate Bearing Test apparatus) conducted in trial pit, at Bracknell demolition rubble sub-base site**

Mechanical tests were performed on samples of the limestone and demolition rubble to classify material as acceptable for use as sub-base and capping, as specified in the UK Department of Transport Specification for Highway Works

(SHW). The demolition rubble fell just outside the grading limits for sub-base. However, it was allowed for use, under the conditions stated above.

The CBR, ten percent fines value and soundness value of the demolition rubble were within the specified limits. The moisture content and frost heave for the demolition rubble were outside the limits specified by the SHW. Test results showed that the rubble had a higher water absorption (and moisture content) than the limestone aggregate.

Using the Building Research Establishment (BRE, 1998) classification system for recycled aggregates (RCA), which gives a general description of composition and properties, the demolition rubble from the Bracknell site can be termed as *Class RCA(III)* material, a mixture of concrete and brick suitable for a range of applications in construction, including roads.

**Environmental tests**

Solid samples were analysed to determine the amounts of selected constituents present in the aggregate. None of the contaminants listed in the ICRCL guidelines (often used in the UK as the standard to assess the significance of risk from various contaminants which may be present in soils) were above the threshold values, for the demolition rubble and the limestone.

The release of soluble constituents upon contact with water is a major concern when using alternative materials, as a potential risk to the environment may result. A two stage batch leaching test (draft European Standard prEN 12457-3) was performed to characterise and assess the constituents which could be leached from the material.

Using CIRIA Report 167, it was possible to classify the demolition rubble and limestone in terms of their potential to affect water quality when used as unbound material, using the results of the leaching tests. The demolition rubble (and limestone) fell into the Group 1 category, ("materials for which there are no restrictions on use based on potential to affect water quality (similar to limestone)").

Analysis of solid samples of the clay subgrade from each of the road sections showed that certain constituents (particularly metals) were in higher concentrations in the clay beneath the demolition rubble, than beneath the limestone. The constituents found in the subgrade beneath the demolition rubble are not in concentrations high enough to cause concern, but analysis of the sub-base materials had shown that these constituents were present in higher concentrations in the demolition rubble than in the limestone. This indicates that leaching of sub-base material has affected the amount of these constituents contained in the clay subgrade.

**Conclusions**

Overall, the investigations showed that the use of demolition rubble provided as good a sub-base for the road as the area of natural limestone aggregate.

Test results showed that the rubble had a higher moisture content and water absorption than the limestone aggregate. This is probably due to the brick and occasional organic content of the rubble aggregate. Apart from the moisture content (which may have altered since material placement), water absorption and frost heave values, the mechanical properties of the demolition rubble comply with the SHW requirements.

The frost heave test specified uses an extreme temperature (-17$^0$C) during the procedure, which may be inappropriate for this specific case, as the actual minimum temperatures of the sub-base material would be significantly higher than this value.

The mechanical test values for limestone are considerably higher than those required by the specification. It may therefore be more efficient to use the demolition rubble for sub-base and the limestone for an application with more demanding requirements.

Chemical analysis of solid and leachate samples of the sub-base materials was conducted to determine the amount of potentially harmful constituents present. The results were compared to national guidelines. None of the parameters exceeded the limiting values listed in the guidelines. Using a system developed by CIRIA (Baldwin et al., 1997), the demolition rubble was classified as a Group I material, i.e. no restrictions based on potential to affect water quality.

The investigations conducted indicated that the demolition rubble is performing satisfactorily as an unbound sub-base material at this site and does not present a threat to the environment.

## 7.2 MONITORING OF TRIAL ROADS

### 7.2.1 Sweden (S)

#### Background

Crushed concrete (CC) is, by nature a very variable material. Its properties depend strongly on the source of the concrete and on the blended additives e.g. brick, reinforcing steel bars, light extraneous material like wood, plastic etc.

Each year, approximately 50 million tonnes of rock and natural gravel are used as road construction material in Sweden. At the same time, building demolition operations generate about 1 million tonne of waste generally in a rubble form consisting mainly of concrete and brick. 75% of this is placed in landfills; 20% of the building demolition debris is reclaimed and 5% is too hazardous to be deposited.

Experiences from the Netherlands; Belgium and Denmark show that it is possible to use CC as road construction material. In Sweden, the use of CC for this purpose is relatively unexplored. Overall there has been little research and characterisation of building demolition material for utilisation in road construction.

The possibilities of using the CC in road construction are currently enhanced in Sweden. It must be demonstrated however that the material and its properties do not differ significantly from those of unbound granular material. The General Technical Specifications for Roads (ROAD 94) need to be adapted for CC as well as other alternative materials and the final performance of the product should be equal to that for virgin materials.

In the ALT-MAT project two test roads, Rd 109 (south Sweden) and Rd 597 (north Sweden) with CC and Crushed Rock (CR) as reference sections have been investigated and monitored. Rd 597 is described in the following chapter (7.2.2).

#### Physical conditions

Rd 109 is situated approximately 7 km east of the city of Helsingborg in the county of Skåne. The area is mainly flat but in some places undulating. The soils are deep and the underlying bedrock is dominated by Mesozoic sedimentary rocks. Clay till or silty clayey till covers the main part of the area.

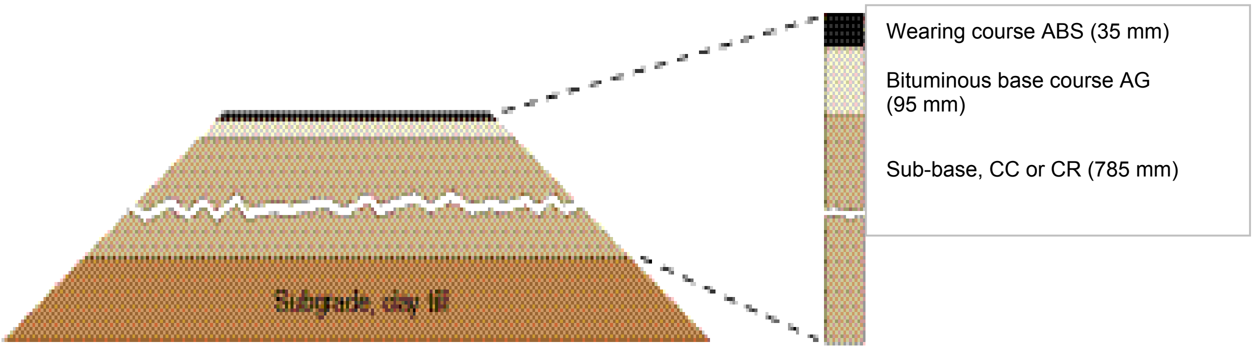
Large quantities of ground water exist in the deep sedimentary rocks. In the till the ground water level is situated deeper than 3 m from the ground surface.

The climate in Skåne is Maritime with warm summers and mild winters. The frost depth is seldom more than 200 mm in the road constructions. The mean annual precipitation is 650 – 750 mm.

**Road design, pavement strata and traffic**

The road including the test and the reference section was designed as a Gravel Bitumen Pavement (ROAD 94). The test section has CC in the sub-base while the reference section has CR in that layer. The length of the sections is approximately 80 m and 100 m respectively The road was constructed with a total width of 9 m, the carriageway being 7.5 m wide and each shoulder 0.75 m wide.

During the construction of the road in the summer of 1997 the formation level was adjusted on the test and reference sections. Although the weather was warm and dry, the formation had a high moisture content and after drying for 1 month the required stiffness (ROAD 94) of the formation had still not been reached. To achieve the requirement for stiffness the thickness of the sub-base layer of both sections was increased from 565 mm to 765 mm (Figure 7.12).




*Note. ABS = Stone Mastic Asphalt; AG = Hot-mix base course*

**Figure 7.12 Pavement strata of test section and reference section, Rd 109**

The road was opened for traffic in autumn 1997 and the predicted traffic volume was ESA < $5.0 \times 10^6$, Traffic Class 4 (ROAD 94).

**Material properties**

For the construction of the test section approximately 2000 tonnes CC was used from a stockpile containing waste concrete from different buildings. After some processing including removing of reinforcing bars and extraneous material like wallpaper, wood etc. 1500 tonnes of concrete with high purity was crushed and utilised in the test section.

More than thirty samples of the CC have been sieved. All samples were approved according to ROAD 94. In Figure 7.13 an average grading curve for all samples is depicted and the curve falls extremely well into the required grading envelope for sub-base material.

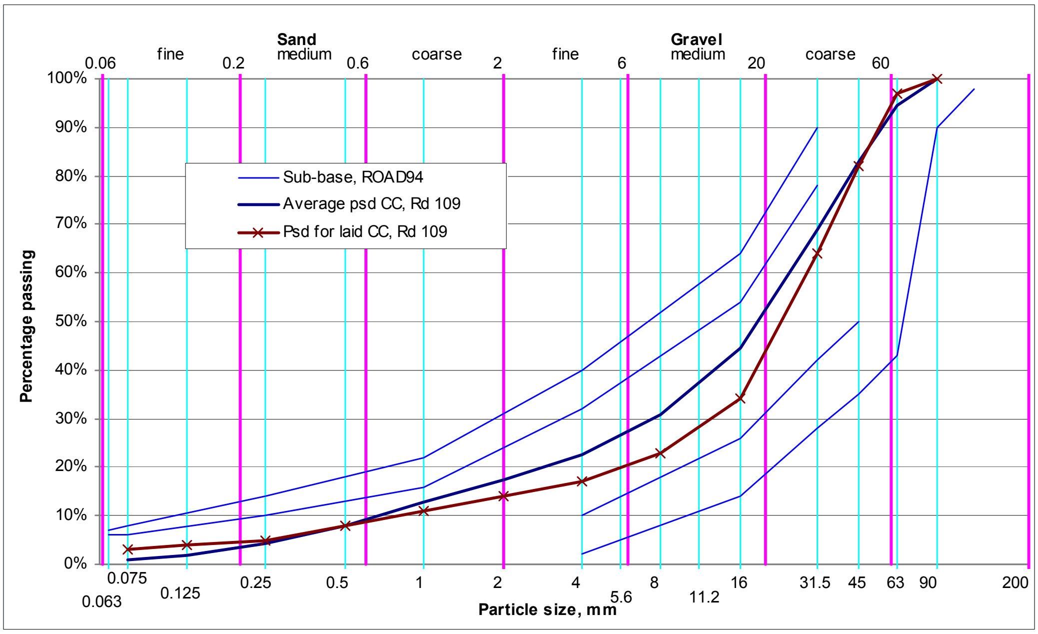



**Figure 7.13 Average grading curve for 32 samples of CC and the grading curve for the CC after construction**

To check a possible deterioration of the CC during transport etc in the construction phase the particle size distribution (psd) was analysed on samples taken three weeks after laying. The psd is shown in the figure above. A very small increase of fines was identified.

When tested in the Nordic Ball Mill the obtained abrasion value $A_N$ was 28 which is approved for sub-base material according to ROAD 94 (cf Section 7.1.5). Even though the CR in the reference section was not tested the $A_N$ for such material in general is <18.

Two samples of the CC from the sub-base were analysed in the Los Angeles Fragmentation apparatus and the CBR equipment. The LA obtained was 33 (both samples) and the CBR was 230 and 264. The LA for a normal Swedish CR similar to that material used in the reference section is generally 20 – 25.

The frost susceptibilty of the CC in this road as well as the one used in Rd 597 (see Section 7.2.2) is low.

The tests of the CC in the Triaxial equipment to evaluate the performance of the material and to compare the Resilient Modulus $M_r$ obtained with the layer modulus of the material using the Falling Weight Deflectometer (FWD) show an increase of stiffness in both cases (Figures 7.14 and 7.15).

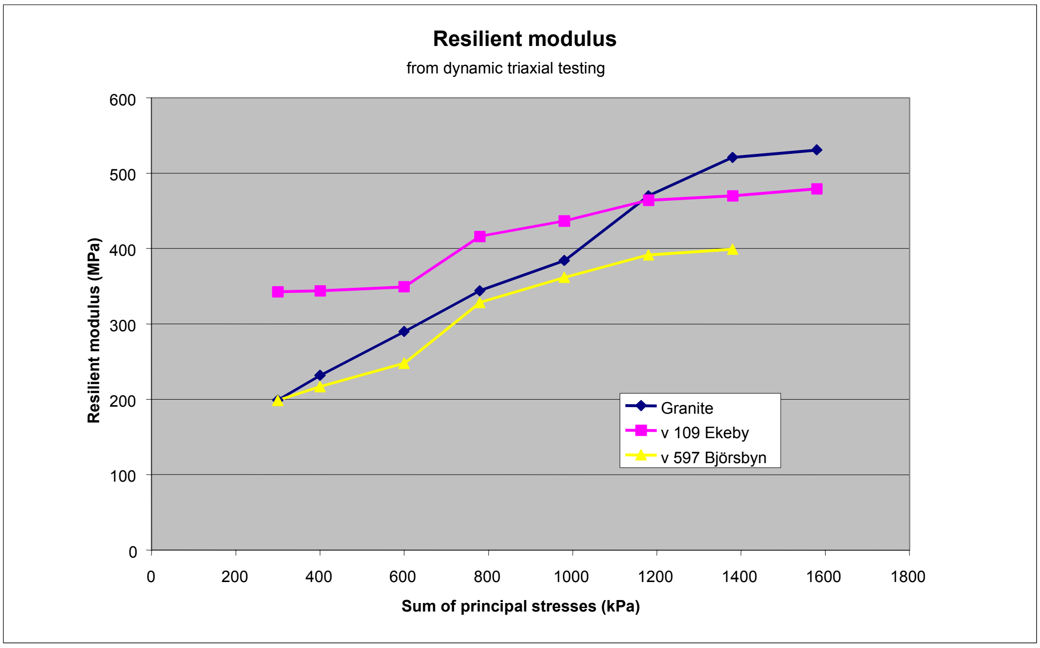



**Figure 7.14 $M_r$ for CC in Rd 109 and Rd 597 compared with a CR (granite) as a reference material**

As can be seen in Figure 7.14 the $M_r$ of the CC in Rd 109 is higher (up to a total stress level of 1200 kPa) than the $M_r$ for the CR, a granite commonly used in many Swedish road constructions. This particular CR is also used as a reference material in various laboratory analyses and performance related tests carried out at VTI. By comparing the stress level at approximately 800 kPa which corresponds to the highest traffic load of a Swedish road construction it is obvious that the stiffness of this particular CC is higher than that of a natural aggregate.

In order to determine if there were any changes in the stiffness of the sub-base in Rd 109 over time measurements with the FWD were performed on the carriageway after the road was completed. The measurements were repeated on three further occasions – three and nine months and nearly two years after completion of the road (Figure 7.15). After 3 months, the layer modulus of the CC had increased from 200 to 600 MPa; in other words 300 %. This increase might be compared with the CR in the reference section where the increase was only about 25% for the same period.

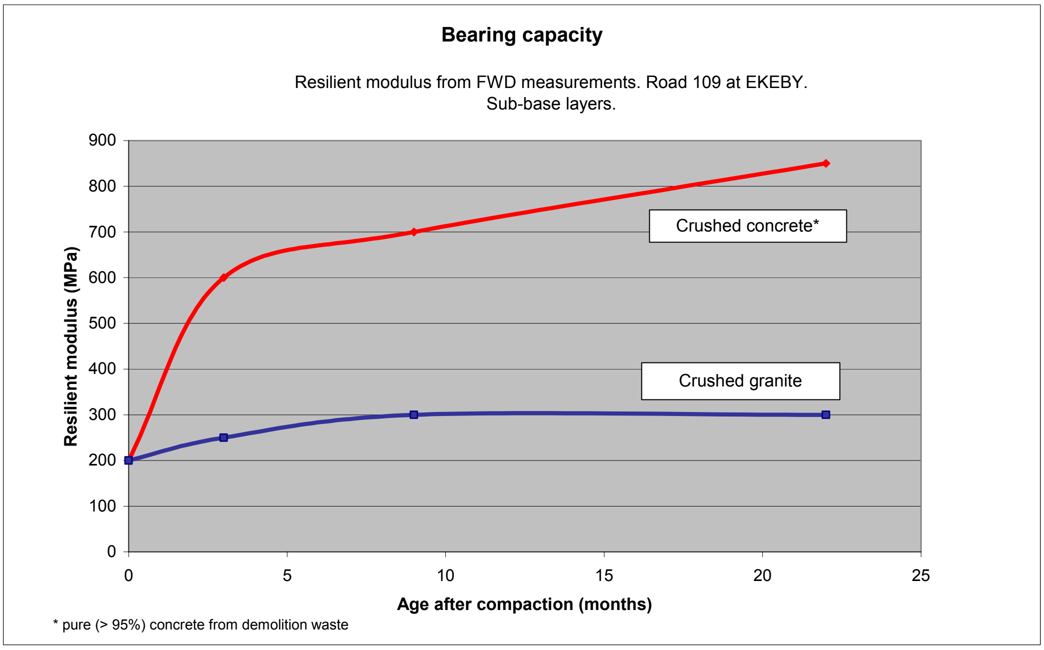



**Figure 7.15 Layer modulus for the CC in the sub-base of Rd 109**

The increase of stiffness in the CC, also identified in Rd 597 (see Section 7.2.2), is caused by two processes. Carbonation binds the free lime in the CC and hydration causes unhydrated cement to react with water. These processes probably took place quite quickly after construction. It has to be noted that the stiffness of the CC increased without extra watering during laying! The self-cementing properties of the CC have also been verified by a visual inspection (see Section 7.2.2).

Continuous Compaction Control (CCC) was performed and the stiffness $E_{v2}$ was determined for those two points where the lowest stiffness had been obtained using the Static Plate Load. The test section with the CC in the sub-base met the requirements regardless of whether Static Plate Load Test was performed on the sub-base or on the base course. The reference section generally met the requirements.

### Environmental properties

The total composition has been analysed and leaching tests have been performed within the ALT-MAT study on the CC. The results showed that the CC mainly consists of compounds of Si, Al and Ca. Of the heavy metals Ni and Cr occur in the largest amounts. Cr is the trace element that is leached in largest amounts in the leaching tests.

The total content of the CC seems to be in the same range as natural materials, the leachability of the CC seems however to be higher for some elements as for example Cr, Pb than the leachability of natural materials.

Samples of leaching water from the road section with CC have been taken. Also samples were taken from a section with conventional materials. The concentrations of trace elements Cr, Cu, Ni and Pb were higher in the leachate from the CC than in the leachates from the conventional material.

**Conclusions**

1. Performance related tests like Dynamic Triaxial Test and FWD-measurements verify marked increases of stiffness of the CC with time.
2. Cementitious properties of the CC create self-binding which from both engineering and environmental points of view are very attractive.
3. The increase of stiffness and the local output of quite small quantities in general are prompting utilisation of CC in parking lots, sidewalks or loading bays.
4. CC from the building demolition waste meets the ROAD 94 requirements set up for conventional road construction material when used in sub-base.
5. The frost susceptibility of CC is low.
6. The functional performance of CC (see below) may enable this material to be used even in base course.
7. It is recommended to be cautious and to prevent excessive crushing of a road building material like CC during and after laying.
8. There might be raised amounts of some elements e.g. Cr in leaching water from CC compared to conventional materials.

### 7.2.2 Sweden (N)

**Physical conditions**

Two test sections with CC (Figure 7.17) and two reference sections with CR were constructed on Rd 597 approximately 3 km Northwest of the town of Luleå in the county of Norrbotten, northern Sweden. The surroundings of the road are characterised by hillocks with forests scattered in an area with cultivated flat plains.

The hillocks mainly contain Precambrian bedrock generally covered with silty till. In the plains the silt dominates and this soil is very frost susceptible.

The climate in Norrbotten is Continental with mild summers and very cold and often snow-rich winters. The cold climate causes considerable frost depth in snow free roads (see below) creating frost heaving and scattered damages on the road surfaces during thawing in springtime. The lowest frost depth (mid March 1998 and 1999) in the sections was approximately 1.70 m below road surface.

The ground water level is situated lower than 1 m from the road surface.

**Figure 7.16 Recycling strategy:"The Leaning House of Boden" used as sub-base in test sections**

**Road Design, pavement strata and traffic**

The construction of Rd 597 is a strengthening project and the requirements of ROAD 94 are therefore not applicable in this case. Nevertheless a comparison has been made between the results from the laboratory analysis and the field investigations and these requirements.

As depicted in Figure 7.17 one test section with CC and one reference section with CR in the base course have been constructed. Another test section and a reference section have CC and CR respectively in the sub-base (Figure 7.18). The length of the first two sections was 50 m and 100 m for the third and the fourth ones. The cross section of the road is 6.5 m with two shoulders of 0.25 m each.

In connection to these sections two other trial sections have been constructed. Those sections constructed with ACBFS and Ferro Sand are not investigated in the present ALT-MAT project.

All sections were covered with 35 mm Cold Mix Asphalt (CMA) but the surfacing appeared to be too weak and a resurfacing of 20 mm Soft Asphalt had to be applied.

The traffic volume of the road is assumed to ESA $< 0.5 \times 10^6$, Traffic Class 1 (ROAD 94).

**Material properties**

The particle size distribution was examined for 5 samples of the CC for the sub-base (Figure 7.19) and 5 samples for the base course.

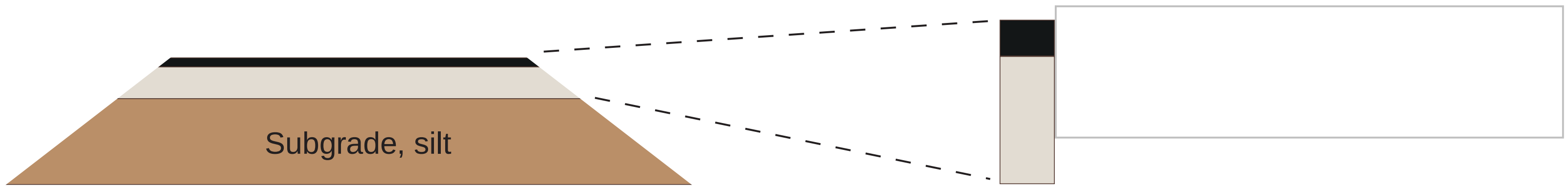



**Figure 7.17 Strengthening of Rd 597: Pavement strata of a test section and a reference section**

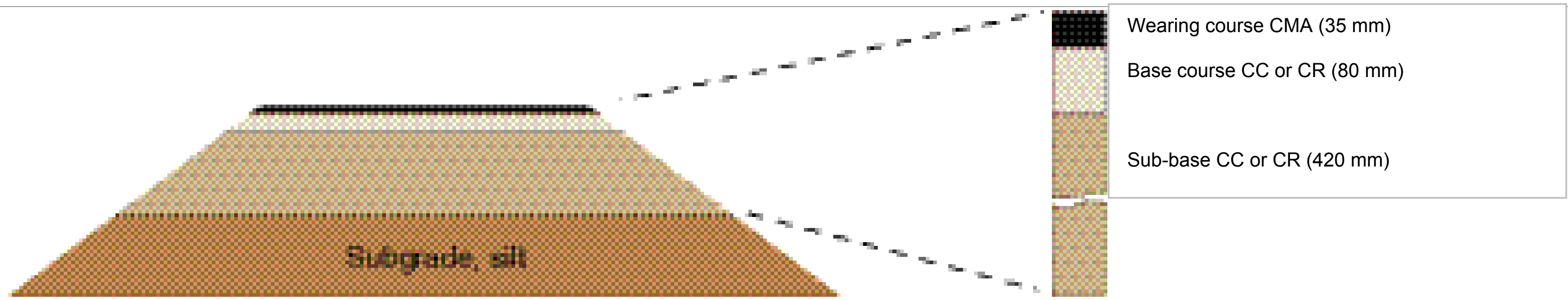



**Figure 7.18 Soil replacement of Rd 597: Pavement strata of a test section and a reference section**

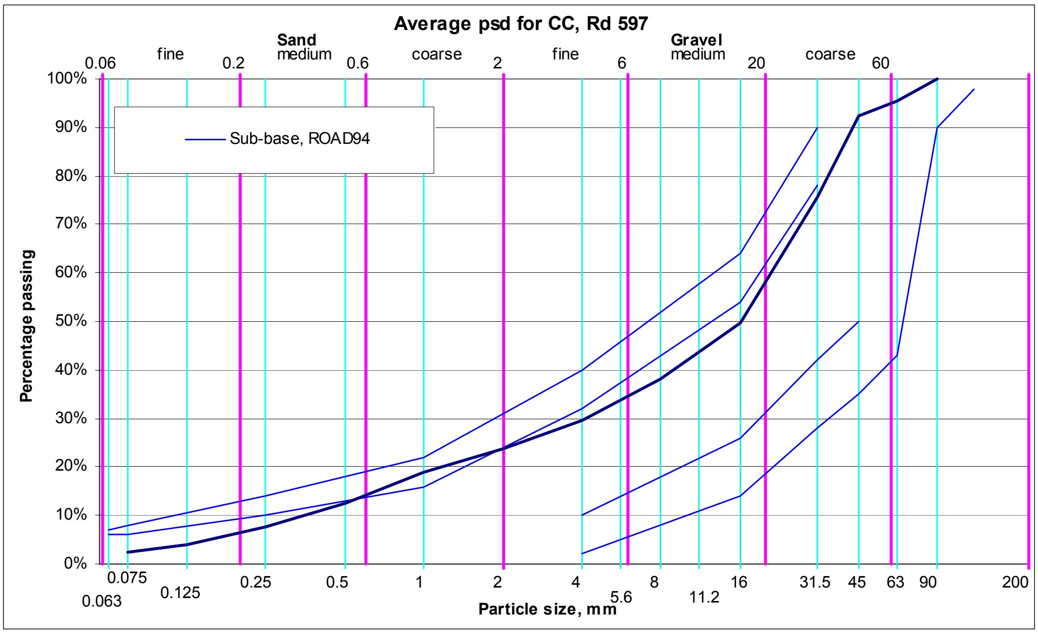



**Figure 7.19 Average grading curve for the CC in the sub-base**

All samples of CC for the base course were rejected according to ROAD 94. The content of particles 0.25 – 8 mm was too high to fulfil the present requirement. A Crushed Gravel CG with an approved grading curve was therefore used as a reference section. The results from the sieving analysis show fairly well the precaution to be taken when sieving a CC demonstrating tendencies to crushing (cf Section 7.2.1). A material like CC containing soft and fine mortar will always create too many fines when sieving.

Approximately 1000 tonnes of concrete was used for the construction of the test sections on Rd 597. The content of extraneous material in the CC was determined in one sample. The CC contained 2.7% by mass of light weight concrete and a very low quantity of wood, paper, plastic, etc. Even at low levels the light weight material may influence the behaviour as well as the function of a road construction.

The CC in Rd 597 has not been analysed in the LA Test. The mean value $A_N$ obtained in the Nordic Ball Mill test was 22 (28 in Rd 109). This CC is thus approved for use in sub-base (ROAD 94). No test was carried out on the CR (cf Section 7.2.1).

The stiffness of the CC was tested on samples with a psd of 0-32 mm. The CC was compared with the standard CR (granite) described in the previous Section (see Figure 7.14). Within the range of "normal to a high traffic load" (600-800 kPa), the $M_r$ is somewhat lower for the CC in Rd 597 than for the crushed granite. However as mentioned above the CC in Rd 597 contains some quantity of light-weight material and this may cause a lower $M_r$. In addition to this fact the content of mortar was also much higher in this CC (38 % by weight) than in the CC (21 %) of Rd 109.

The stiffness of the CC in the sub-base on Rd 597 has increased with time and the result shown in figure 5 is almost the same as for the CC in Rd 109 (Figure 7.15). The process causing the increase is described in that Section 7.2.1.

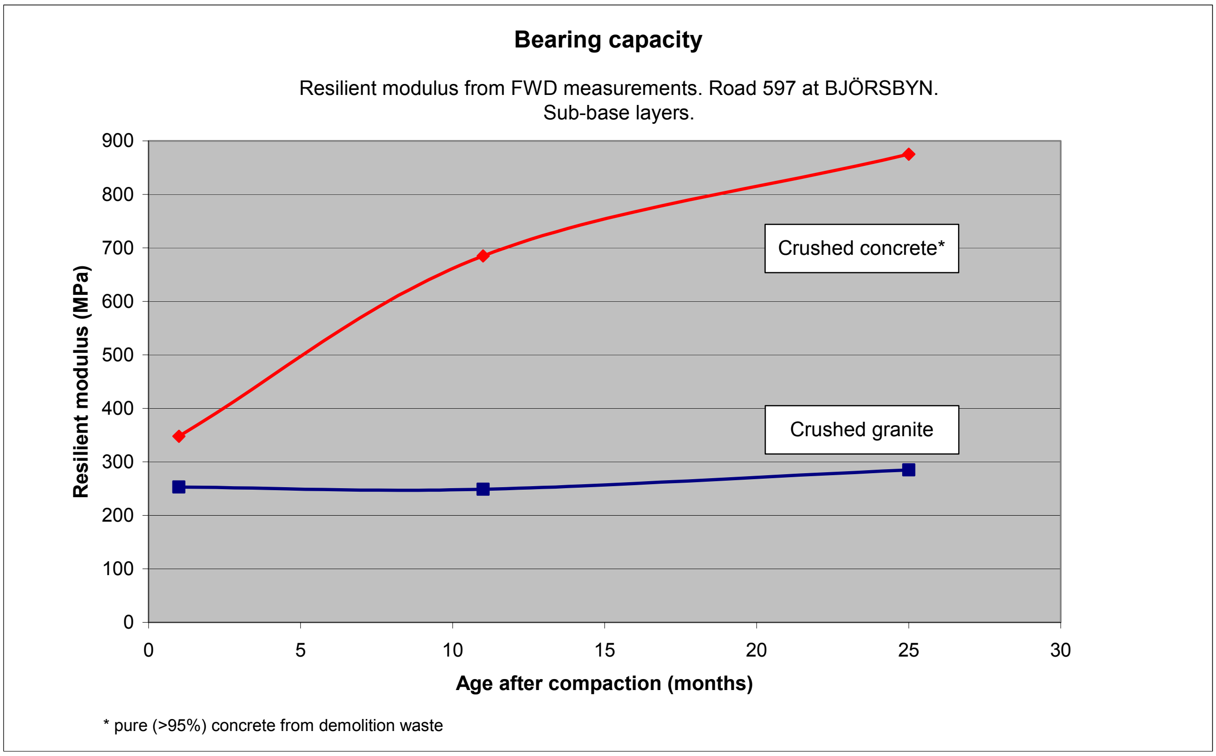



**Figure 7.20 Layer modulus for the CC and the CR in the sub-base of Rd 597**

It is impossible to detect, verify and thereby calculate the layer modulus of the CC and the CR in the sections where these materials were used as strengthening base courses (see above). The layers are too thin.

### Environmental properties

The CC for Rd 597 has been analysed with respect to total composition. The results showed that the CC mainly consists of compounds with Si, Al and Ca and are quite similar in total composition to the CC for Rd 109 (Section 7.2.1). No leaching tests have been performed on CC for Rd 597.

Samples of leaching water from the road section with CC and from a section with conventional material were taken once. The concentrations of trace elements Cr, Cu and Pb were higher in the leachate from the CC than in the leachate from the conventional material.

### Conclusions

The findings and the results from the investigations of CC in Rd 597 are almost the same as specified for the CC in Rd 109 (Section 7.2.1). However it has to be noted again that too thin unbound layers e.g. the CC and the CR which are used as base in the strengthening sections of Rd 597 cannot be separated from other layers and materials when using the FWD.

## 7.3 SUMMARY

The results of the inspections of existing roads are summarised in Table 7.1, and the national reports with all the test results are included in Appendix D. Overall, the investigations showed that the alternative materials provide as good support to the road pavement as natural aggregates in control sections. Tests on CC and BFS have shown that these materials increase in stiffness with time as a result of self-cementing reactions. Performance tests, such as FWD and cyclic load triaxial tests, give better indications of the suitability of alternative materials than empirical laboratory tests. Analysis of the subgrade beneath the alternative materials indicated that leaching of the alternative materials had increased the amount of certain constituents in the subgrade. However, the leaching tests performed have indicated that the use of alternative materials has little potential to affect water quality and that the effects are below national pollution limits. The inspections thus give confidence in the use of alternative materials in road construction.


**Figure 7.21 Excavation for investigation of existing road, Denmark**

## Table 7.1 Results of inspections of existing roads

| | Alternative Material | Acceptability | |
|---|---|---|---|
| | | Mechanically | Environmentally |
| UK | Building demolition material (brick and concrete) sub-base | Acceptable-good<br>GDPBT: 48 MPa<br>Spec.'s: CBR, soundness and ten percent fines within national spec (SHW). Frost heave above spec. for sub-base<br>E-moduli: >900MPa | Certain constituents in the clay subgrade effected by leaching of sub-base. Classified as unrestricted for unbound road layers (CIRIA report 167: Group 1). |
| | Reference, Limestone aggregate sub-base | Acceptable good GDPBT: 35-47 MPa<br>Spec.'s: All within national spec.'s (SHW)<br>E-moduli: >200MPa | Classified as unrestricted for unbound road layers (CIRIA report 167: Group 1). |
| France | MSWI bottom ash sub-base | Good behaviour (deflection). Water sensitive during construction (CBR) | Far below national pollution limits |
| | MSWI bottom ash sub-base | Good behaviour (deflection). Water sensitive during construction (CBR) | Far below national pollution limits (first cm's of the subgrade) |
| Denmark | Crushed concrete base | Very good PCI: 0.70<br>E-moduli: 300-500 MPa and increasing | High pH and calcium in leachate, chromium and lead higher than sand/gravel reference material |
| | Reference, natural base | Good PCI: 0.70<br>E-moduli: 200 MPa | |
| | MSWI bottom ash sub-base | Good PCI: 0.50<br>E-moduli: 240 MPa<br>on top of sand/gravel base | Some migration of salts into subgrade. All samples comply with current Danish quality criteria |
| | Reference, natural sand sub-base | Good PCI: 0.5<br>E-moduli: 340 MPa<br>on top of sand/gravel base | Very low leachability and little or no migration into subgrade |
| Sweden | AcBFS sub-base | Acceptable good<br>CBR 130-180<br>E-moduli >600 MPa<br>Distance from surface at least 250mm in cold climate | Only vanadium potential risk. However, leaching reduced by selfbinding of the slag |
| | Reference, crushed rock Base and sub-base | Good behaviour<br>Base CBR 200-250<br>Sub-base E-moduli approx. 300 MPa | |
| | Crushed concrete sub-base | E-moduli >600 MPa and increasing | Concentration of Cr, Cu, Ni and Pb in leachate from concrete higher than crushed rock |
| | Reference, crushed rock | E-moduli: 300 MPa | |

GDPBT: German dynamic plate bearing test
PCI: Danish Pavement Condition Index
AcBFS: Air-cooled blast furnace slag

# 8. MITIGATION MEASURES

## 8.1 INTRODUCTION

Depending on the risk assessed regarding the utilisation of alternative materials, a range of mitigation measures is applicable. Alternative materials intended for use in road structures may be either treated to alter the potential contaminant release mechanism, or protected during storage and handling in such a way that any release of dust and soluble components into the environment is limited. If necessary, protection should be such that humans and animals do not come into direct contact with the materials during their normal daily actions. For materials used in road construction, sufficient protection may be provided through layers stabilised with bitumen binder, a gravel covering layer or by topsoil on slopes.

## 8.2 RISK ASSESSMENT AND QUALIFICATION

Common environmental regulations are based on normative legislation leading to certain concentration limits on the discharge of harmful substances. These depend on natural and human activities resulting in discharges of such substances and on the general sensitivity of the environment.

The alternative to a normative principle is a relative principle, meaning that concentration levels could be raised as a percentage of the natural or existing background level. Due to the risk involved in such an approach it is common that the permission to discharge harmful substances is also regulated according to the sensitivity, and the total amount, of all the discharges of the area.

The use of alternative materials always requires some kind of risk assessment. This assessment should contain the environmental impact of the alternative material with regard to the above principles, the construction itself and the sensitivity of the site. According to assessments, pollution risk can be divided into three different qualification categories. The categories and corresponding measures are as follows:

1. low risk -> no additional measures
2. medium risk -> no measures, but monitoring
3. high risk -> measures to be taken.

## 8.3 QUANTIFICATION OF INFILTRATION WATER IN RISK ASSESSMENT

### 8.3.1 Factors affecting infiltration

The quantification of infiltration water through road construction is needed for risk assessment. It is a difficult process and always based on several assumptions to determine the annual water quantity infiltrating into a road structure (including the bituminous pavement and slopes) in order to predict the amount of possible leachate/ contaminant released during the service life of the structure (flux). The following input data are needed for such calculations:

- permeability values of the materials (e.g. asphalt pavement, slope materials) in both saturated and unsaturated conditions,
- the duration of wet and dry periods,
- rain intensity as a function of time and period of the year
- expected fluctuations during the year (as a simplification, a water pressure gradient may be applied).

In areas with cold climates these structures are frozen for part of the year, and therefore practically impermeable. Areas kept clear of snow, which therefore have a black/dark surface, will absorb radiation and melt earlier.

In addition to those already mentioned there are a range of other parameters which should also be taken into account.

In the case of asphalt pavements, the width, length and location of cracks have to be observed. Even small cracks can increase the infiltration rate by several orders of magnitude. Rutting in pavements and deformations may leave areas covered for longer periods by water, and thus act as pathways for infiltration. Surface water guided from pavements towards the slopes will increase the potential for infiltration from the slope areas, as this increases the amount of water (i.e., water present from the usual rainfall quantity) in this area. The properties of natural material used for slope protection, such as sandy clay etc., will change over time. Natural materials are subject to drying-wetting cycles, freeze-thaw cycles or mechanical disturbance. This is also true for by-products placed into a road structure. The quantity of water which may come into contact with these materials may vary, depending on the materials location in respect to protective layers, the geometry and the drainage properties of the structure.

### 8.3.2 A simple method to quantify infiltration in road construction

Baldwin et al. (1996) have considered a simple model for leaching in road constructions. They have assumed, that the predominant methods of water entry into road construction (Figure 8.1) are as follows:

1. by the seepage of water into subgrade through the haunches of the road especially in cuttings
2. by a rise or fall in the level of water table
3. by the percolation of water through the surface of the road; although this is generally a vertical movement of moisture, severe cracking may lead to the penetration of water into sub-base resulting in horizontal movements of moisture then taking place
4. rainfall on the unfinished road may lead to changes in subgrade moisture content as a result of horizontal movement of moisture through the sub-base.

The construction time of a road is the time whilst the embankment is not covered. Baldwin et al. suggest that at least 20% of the mean intensity of one years rainfall should be assumed to flow through the material layer. After the construction of a covering soil layer, the rate of infiltration can assumed to be 10% of the mean annual rainfall. This is because more water will be shed by this covering layer into the drainage system. When the practically impermeable pavement is constructed, the main route of infiltration water into the structure is through the shoulders and slopes. Then the above figures can be used, but the amount of infiltration water should be reduced by the ratio of the area of infiltration to the total area of material layer.

For modelling purposes it is assumed that the changes in the ground water table are controlled by a functioning drainage system. Thus, this water ingress method can be ignored. An efficient drainage system is also assumed to control the seepage water from higher ground adjacent to the road. For cuttings in soil, Baldwin et al. assumed that 1% of rain falling on cuttings will arrive at the subgrade below the sub-base. Capillary action may allow wetting of the sub-base from the subgrade lying below. Again, it is assumed that 25% of the moisture reaching subgrade is available to wet the sub-base. Usually this capillary rise can be ignored.

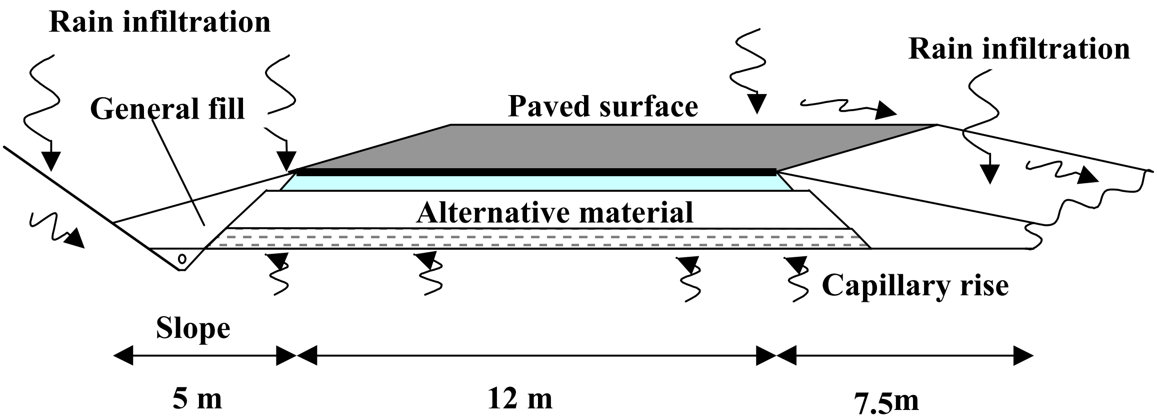



**Figure 8.1 Water entry into a road construction.**

One difficult problem is the seepage through the surface of the road. The infiltration through the road pavement is related to the permeability of road components. The permeability of "impermeable" asphalt (also referred to as “dense asphalt”) should be < $10^{-9}$ m/s. If permeability is approximately $5*10^{-9}$ m/s, 10 % of annual rainfall can be estimated to infiltrate through the asphalt layer. The permeability of a road pavement can also be reduced by the placement of additional materials e.g. geomembranes.

The presence of non-waterproof joints and the existence of cracks are related matters. One simple way to model the asphalt layer is to estimate that 10% of annual rainfall infiltrates through it. This assumption is based on the permeability of asphalt being approximately $5*10^{-9}$ m/s.

## 8.4 MITIGATION DETAILS

Mitigation measures can be source or pathway based. Source based measures are measures which happen during production, sorting and storing. These methods can include ageing or cooling methods etc. Pathway based measures are mitigation methods based on minimising the infiltration to the construction, or construction of barriers to reduce water movement.

The environmental and economic efficiency of different measures has to be evaluated. However it must be noted that experience of many mitigation measures is very limited, and this lack of experience can cause problems in evaluating their environmental and economic efficiency. Table 8.1 contains mitigation methods, their advantages, disadvantages and application situations.

**Table 8.1 Mitigation measures for permanent construction**

| Measure | Advantages | Disadvantages | Application situations |
|---|---|---|---|
| Basic covering | Cheap, some maintenance with asphalt layer | Covering must remain efficient | Basic alternative to the materials with low leaching risks |
| Dense asphalt and impermeable layer in slopes | Relatively economic | Measure must remain efficient | To demanding circumstances |
| Effective drainage system | Must be combined with other methods, economic | Some extra maintenance is needed | Must be combined with other methods |
| Treatment: Stabilisation, ageing, cooling etc. | Depends on treatment, can be very effective | Material-specific, can be expensive, not much experience | Can be combined with other methods |
| Impermeable bottom layer | Quite safe measure | The most expensive, separate drainage and water treatment systems needed, maintenance of drainage systems | To very demanding circumstances, important ground water areas etc. |

Source based mitigation measures can include treatment of material at source or on site. Some materials may be stored in heaps, where they are kept for some time. This process is called ageing. In the UK the use of steel slag is only permitted if it has been aged. This allows unslaked lime to hydrate and prevents subsequent expansion of the material. It also reduces the pH from highly alkaline values to near neutral, thus improving the leaching characteristics. It is not appropriate for all materials because the mechanical properties of some materials can deteriorate during ageing. Methods of cooling during slag production can affect the leaching properties of the material produced. So far, there has only been limited experience of source based mitigation measures so their environmental or economic efficiencies are difficult to estimate.

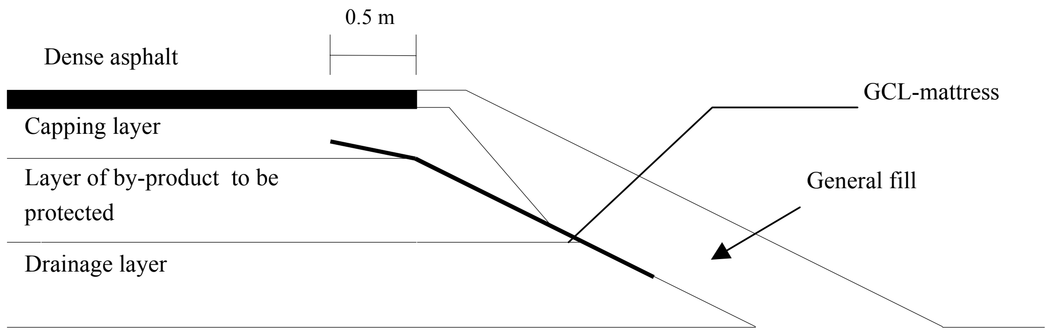
Most mitigation measures used are pathway based. The purpose of the protective measures is usually to reduce the amount of infiltrating water and thus to minimise the flux of possible contaminants further into the environment. The demands on mitigation measures are assessed by the leaching properties of the alternative material and the location in respect to the environment.

The basic requirement for using alternative materials in road construction is that of a covering. The covering should be such that no human or animal can, in their normal daily action, come into contact with the alternative material. Also, dust arising from the spreading of alternative materials should be prevented. Asphalt pavements can be designed to reduce the quantity of infiltration of water by 90 %. To meet this reduction requirement, the asphalt cannot be open graded, the road base must be even and dense and the asphalt must be well compacted. The uniformity of the road structure must remain throughout its whole lifetime. Thus, the base of the whole construction must be even and frost action must not be allowed to impact upon it. Also, the asphalt layer needs maintenance: if cracks form, they must be repaired rapidly. Such simple and inexpensive actions can efficiently limit leaching.

Basic measures to take also include ensuring that slope material is dense and of low permeability.

The drainage system must work well during the whole lifetime of the construction and no water must be allowed to stand in side ditches. The groundwater level must be below the bottom of the alternative material, so that the alternative material is not subject to long term wetting. An effective drainage system also includes adequate gradients so that water is quickly drawn away from the road construction. Also, in order to operate effectively, drainage systems will always need some maintenance. A working drainage system is another simple and cheap measure which can efficiently limit leaching.

Another method is to stabilise the material with bitumen or cement binder. In some special cases alternative material can be used in bound asphalt layers (for instance ferrochrome slag and MSWI bottom ash).



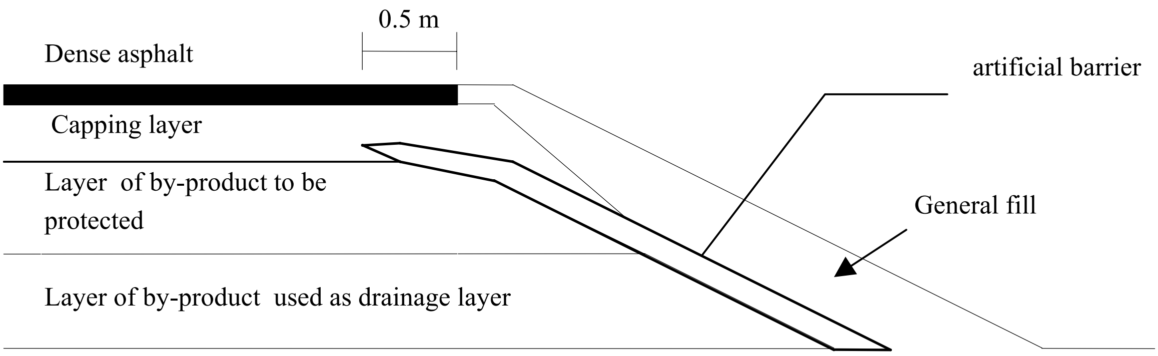



**Figure 8.2 Examples of mitigation by impermeable layers.**

When more demanding mitigation measures are needed, a rough estimation of the possible amount of infiltration through the pavement may be based on figures related to the maximum permeability of asphalt layers and slope protection layers. This means that an asphalt pavement should have a low permeability (dense asphalt).

At the edges of the pavement some additional mitigation measures are necessary, such as artificial barriers. These should be constructed using a GCL (geosynthetic clay liner) mattress or other suitable liner material, which prohibit surface water affecting layers which have been constructed with by-products. As a guideline, the infiltration rate may be restricted to a value of $5^* \ 10^{-9}$ $m^3/m^2/s$, which corresponds to a water quantity of 43 mm/year assuming that there are 100 rainy days (43 litres /$m^2$).

Figure 8.2 shows some examples of impermeable layers. A GCL mattress will normally fulfil the requirements needed of an infiltration barrier and can easily be combined with a dense asphalt layer. Mineral soils treated for reduced permeability (addition of bentonite or similar) may be equally suitable for the purpose, if they can be placed in homogeneous layers of specified thickness.

The impermeable layers described are schemes which are not yet common practice, but more experience will be gained with use. Similar constructions have been completed in some ground water protection areas, and these constructions have as a whole worked well. They are relatively easy to construct, they can effectively limit infiltration through the alternative material and no maintenance is needed. However, they are more expensive than just a basic covering.

The methods mentioned above have been based on preventing water contacting the alternative material. One method to prevent leachate percolating into groundwater is to construct an impermeable bottom layer under the alternative material. This impermeable layer is usually combined with a surface water drainage system. The water from the drainage system should be collected and treated by an appropriate method. In some cases another drainage system is also needed beneath it, and both drainage systems need continuous maintenance. This method can be very effective, but it is also the most expensive of the methods described. Its application may be required for very demanding circumstances, for example on important ground water areas.

The major way to mitigate leaching during production, sorting and construction is to limit the volume of water in contact with alternative material. Such mitigation methods could include:

- covering alternative material as soon as possible
- shortening construction time (uncovered time)
- an effective drainage system with good gradients, so that water does not remain on the alternative material.

# 9. SUITABILITY OF MATERIALS TESTED

## 9.1 INTRODUCTION

During the course of the ALT-MAT project a variety of materials were tested, to assess both their mechanical properties and their leaching behaviour. In this way it was possible, not only to identify which test methods were most appropriate when assessing the performance of an alternative material, but also to assess the performance and suitability of the alternative material itself for use in road construction, and to compare this performance to that of a reference material.

This Chapter provides a summary of the findings of the various mechanical and chemical tests performed by the ALT-MAT partners, and assesses the suitability and performance of the alternative materials tested in the various European countries involved in this project. It should be noted that the results refer to the particular samples tested, and should not be regarded as indicating that all samples of the material will behave in the same way.

The results and findings of the mechanical and chemical tests on selected materials are reported in detail as National Reports on test methods, in Appendix F. Details of investigations conducted to assess the properties of alternative materials at existing road sites are given in Chapter 7.

## 9.2 AUSTRIA

### 9.2.1 Materials

The Austrian alternative materials selected for investigation were:

- MSWI bottom ash (Vienna, Spittelau plant)
- MSWI bottom ash (Vienna, Floetzersteig plant)

And the reference material used was:

- dolomite

### 9.2.2 Suitability

***Mechanical tests:***

Currently MSWI bottom ashes are not used for road construction purposes in Austria. Several tests were performed according to the Austrian standard for base and sub-base materials (RVS 8S.05.11 (FVS, 1997)) on the MSWI bottom ashes; the results and the suitability are given in the table below.

| | ***MSWI bottom ash*** |
|---|---|

| | Requirement base | Requirement sub-base |
|---|---|---|
| **Grain size distribution** | Failed | X |
| **Grain fragmentation (ΔG)** | Passed | Passed |
| **Grain shape** | Failed | X |
| **Freeze-thaw resistance (w-% < 1,6 mm)** | Failed | X |
| **Frost susceptibility** | Passed[1] | Passed[1] |
| **Permeability ($K_f$ m/s)** | Failed | Failed |
| **Resistance (Los Angeles-value, %)** | Failed | X |
| **Summary** | Failed | Failed |

Requirements for (sub)base material according to RVS 8S.05.11

[1] requirement fulfilled but significant decrease in the bearing capacity (expressed as CBR-values) after the frost heave test

In a pure form, the MSWI bottom ashes investigated do not fulfil the Austrian requirements for base and sub-base material. In particular, the low permeability and the high proportion of grains smaller than 0.063mm (~15-20 mass-%) prevent the application as a road construction material. Although the ashes passed the frost susceptibility test, accompanying CBR-tests before and after the frost heave test showed a decrease in the bearing capacity far beyond a “normal” decrease of about 20%.

In the modified proctor test the optimum water content for the bottom ashes was much higher than the one for comparable natural materials, but the achievable densities of the bottom ashes are less sensitive to deviations in the water content.

Summing up, an improvement of the mechanical properties of the Austrian MSWI bottom ashes would be necessary to fulfill the present national requirements for (sub)base material. This could be done e.g. by lowering the amount of the fraction <0.063mm to adjust the grain size distribution, to enhance the permeability and to reduce the frost susceptibilty.

***Chemical analyses:***

At present, the use of MSWI bottom ash in Austria as a road construction material is not permitted by the legislator and no standards for the utilisation are available. MSWI bottom ashes have to be deposited according to the “Deponieverordnung” (BGBl 164/1996). The classification of the MSWI bottom ashes is based both upon the total concentration within the material and upon the concentration of certain elements within the leachate.

Two kinds of batch tests and climate chamber tests combined with percolation tests were performed on the MSWI bottom ashes.

The homogenised bottom ashes used for investigation are similar to each other with respect to the composition of major elements. In contrast to that, large variations were found for some minor and trace elements (e.g. Pb, Zn, Cu) in different charges of bottom ash sampled over a period of about two months.

At the end of the climate chamber tests:

- the buffer system of the box material was still dominated by hydroxides, carbonation did not take place to a major extent (pH-values within the leachate > 10).
- the conductivity, used as a measure for the total concentration of the leachate, had decreased by about 1 to 2 orders of magnitude. This was mainly due to the highly soluble elements (Na, K, Cl and $SO_4$), which were released to a major extent in the first stages of the experiment.
- availability was high only for Cl, $SO_4$ and Na (~10-50%) and moderate for Al, K and Ca (~1-3%). For the minor and trace elements the availability usually was not more than a few tenths of a percent with the exception of molybdenum (~10-15%).

According to the present Austrian legislation, the necessary pretreatments on MSWI bottom ashes could rest upon a guideline for contaminated soils (BRV "Richtlinie für die Aufbereitung kontaminierter Böden und Bauteile", 1995).

To fulfill the threshold values for unrestricted use, possible measures would be a separation of the non-iron metals, or a longer period of storing and washing of the ashes. This would lower the pH-value and the conductivity and minimise the leaching of Al, Pb, Cu and Zn.

***Climate chamber:***

The climate chamber tests were performed mainly to assess the impact of freezing-thawing cycles (FTC) on the leaching properties of the bottom ash material. The FTC were combined with wetting operations to collect and analyse the leachate of the box material. Various combinations of bottom ash and inert material were tested in different boxes, with two boxes of the natural reference material (dolomite). Although not all boxes containing bottom ash behaved in the same manner during the FTC, two different cases of impact on the leachate concentrations and the loads can be distinguished:

- a "jump" in the cumulative loads during FTC (e.g. Fe, Zn, Mn, Pb), which is possibly due to an increased contact time between leachant and bottom ash during the FTC
- higher rates of dissolving after the FTC (e.g. Ca, Al, Cr, Sb). For a proper explanation of these observations further research would be necessary. Possibly the formation of new penetration paths or changes in grain size due to the FTC are the cause for these observations.

In addition to the standard frost heave test, measurements on frost heave were performed on the box materials during the FTC as well. It turned out that the bottom ash boxes did not behave significantly differently from the dolomite references, which can be regarded as non frost susceptible.

For a more detailed discussion both of the leaching behaviour and of the climate chamber tests, see section 5.3.2. and the Austrian national report (Appendix F1).

## 9.3 DENMARK

### 9.3.1 Materials

The Danish alternative materials selected for investigation were:

- Crushed concrete (CC)
- MSWI bottom ash

And the reference materials used were:

- natural base material (sand/gravel)
- natural sub-base material (sand)

### 9.3.2 Suitability

***Mechanical tests:***

At present, no specific requirements for crushed concrete exist in Denmark, but the material falls within the limits set for grain size distribution for natural base material.

The table below shows which of the tests conducted are required by Danish National Standards, and the suitability of the MSWI bottom ash tested, for sub-base material.

| | MSWI bottom ash | | Natural Sub-base Material | |
|---|---|---|---|---|
| Test | National requirement | Fulfilled | National requirement | Fulfilled |
| Water content in situ | Yes | Yes | | |
| Particle size distribution | Yes | Yes | Yes | Yes |
| Vibrating table compaction | | | | |
| CBR v. proctor compaction | (Yes) | Yes | | |
| Los Angeles abrasion value | | | | |
| Petrographic description | | | | |
| Reduced loss on ignition | | | | |
| Frost heave test | | | | |

Both the CC and the MSWI bottom ash had as good relative bearing capacity (CBR - values) as the natural reference materials in spite of the fact that the particle strength (LA - values) of the alternative materials was much lower than for natural reference materials. At water contents higher than the optimum, both alternative materials still gave fairly high CBR values which is normally not the case for natural base materials.

For CC, the vibrating table and the frost heave test showed similar results to those conducted on the reference material. For the MSWI bottom ash, the vibrating table results were similar, and the frost heave results were better (ie, lower) than the natural reference material.

Once built in - if correctly done - the alternative materials have good bearing capacity. These general conclusions, from testing of materials in the laboratory, are in good agreement with in-situ observations from the inspection of the existing roads containing crushed concrete and MSWI bottom ash.

***Existing road excavation - Crushed concrete as unbound base:***

The inspection and testing of an eight-year-old road in Vejle containing crushed concrete as base layer has shown good functional behaviour. The roads structural condition is even better in the crushed concrete section than in the reference section with natural aggregates. The strength of the crushed concrete has increased since construction. It seems that the crushed concrete has been hydraulically bound to some extent.

The leaching tests conducted on the materials showed that the total content of most trace elements in the crushed concrete is moderate and somewhat higher than the trace element concentrations in natural aggregates. Due to the lime content of concrete, the pH is high. The total organic content (TOC) is low. Due to the high pH in the eluate, the leaching of Cr and Pb is higher from the crushed concrete than from bottom ash and reference sand. The leaching of salts from the crushed concrete is low.

***Existing road excavation - MSWI bottom ash as unbound sub-base:***

The inspection and testing of a five-year-old road, in Skælskør, with MSWI bottom ash as unbound sub-base has shown good functional behaviour. Furthermore, the results of the measurement of evenness and rutting are low values (i.e. good standard). The structural condition of the road is relatively good in spite of the fact that the road is heavily trafficked. The bearing capacity as measured with the falling weight deflectometer (FWD) is not as good for MSWI bottom ash as for similar natural aggregates.

During the laboratory testing historical and present results were compared. There is no significant change in the data in the period after construction and up to this date. Five years of traffic load on the road has not caused any significant crushing of the MSWI bottom ash.

The leaching tests performed on MSWI bottom ash and the subgrade material collected at various depths indicate that some salts have leached from the sub-base and migrated into the underlying subgrade. Only a very limited amount of salts were leached from the natural sand excavated from the reference site.

All the bottom ash samples investigated comply with the current Danish quality criteria for utilisation. The future guidelines are likely to be met for bottom ash placed below the pavement but not for bottom ash under the shoulders of the road.

## 9.4 FINLAND

### 9.4.1 Materials

The Finnish alternative materials selected for investigation were metallurgical slags:

- ferrochrome slag, FCS (from stainless steel production)
- blast furnace slag, BFS

And the reference material used was:

- granite

The selected materials were two metallurgical slags: ferrochrome slag and blast furnace slag. These slags were chosen because their general use as sub-base in a highway is always subject to special permission from the Finnish Environmental Institute. Mechanical properties of both air and water cooled (granulated) ferrochrome slag (FCS) and blast furnace slag (BFS) have been investigated. Granite was chosen as an inert reference material, because it is a typical kind of stone located all over Finland.

### 9.4.2 Suitability

Several studies have been made to investigate the mechanical and chemical properties of the selected materials. The Finnish Road Administration has not introduced any technical requirements for by-products and secondary materials. Tammirinne et al. (1998) reported the technical requirements applicable to alternative materials. The proposed procedures may be applied, but no general agreement on acceptance criteria other than for natural materials has yet been reached.

***Mechanical tests:***

For both of the slags it can be noted that even as new unbound material they have good strength and bearing capacities. The strength and deformation properties of air cooled slag are probably even better than those of granulated (water cooled) slag. The thermal insulation capacities are excellent. Saturation decreases the stiffness of blast furnace slag by at least 10 - 20%. However it can be assumed that periodic saturation does not decrease the long-term bearing capacity, because permeability is high and the slag is frost resistant.

The mechanical stress properties of blast furnace slag are comparable to those of granite, and only abrasion values differ noticably. Also the mechanical stress properties of FCS are good, although Los Angeles and Swedish impact values are lower than others. The mechanical stress properties are so good, that both BFS and FCS are well suited to most parts of road constructions and also to bound layers or pavements. High abrasion values of BFS indicate that it does not fit quite so well to those pavements where high abrasion resistance is demanded. According to long-term mechanical properties both slags can be used in most parts of the road construction, but not in the road base of high standard roads. However, the drainage system of road pavements should be sufficiently good that alternative materials are not subject to long term wetting.

The mechanical stress properties of the chosen reference material, Teisko granite, are excellent. Granite's other mechanical properties depend on particle size distribution. In general it can be said that granite products can be used in every part of road construction, where the particle size distribution is applicable.

***Chemical analyses:***

Many different leaching tests were conducted on BFS and FCS. In the leaching tests on the FCS the main interest was focused on the leaching properties of chromium, aluminium and iron. Only a few leaching tests were conducted on the granite. A widespread assumption is that the leached amounts of harmful elements of granite are insignificant.

The solubility of harmful elements of FCS slag is so small that the use of the slag is acceptable in every part of road construction, while the slag is covered or bound. The total amount of chromium is 6.5 %, but it is in insoluble form. The magnitude of dissolved chromium in column tests is a few ppm (parts per millions). Toxicological tests performed showed that the leachates of FCS have no acute toxic effects to Daphnia Magna water fleas.

The cooling method during slag production influences the leaching properties of blast furnace slag, especially the leaching of sulphate. It is probable that high pressure water jets leach sulphate in the water cooling method. The leached amounts of sulphate of air cooled slag are much greater than the water cooled slag. With regard to other components this kind of behaviour was not observed. The leached amounts of vanadium and other harmful elements were clearly under the acceptable limits. So there are no chemical obstacles to use blast furnace slag in any part of road construction, while the slag is covered or bound.

No leaching was detected from the natural reference materials.

***Climate chamber:***

The purpose of climate chamber tests is to simulate the field conditions of road structures without a pavement. This will give the opportunity to relate data from experiments performed in the laboratory and full scale trial embankments, on different scales. The systems mainly study the release of contaminants due to accelerated climatic cycles and liquids used for winter maintenance in Finland. The objective was to determine rates of release of contaminants from the two selected slags, when treated with salt solution and subjected to freeze-thaw cycles.

In the climate chamber tests (CCT) the leached amounts of many metals were low - usually below the limit of detection. Drying-wetting and freezing-thawing cycles did not accelerate the leaching process of these elements. Even the use of the salt solution seemed to have no effect on the leaching of these elements. The use of salt solution as a leachant did increase the amount of sodium, potassium, calcium, magnesium and sulphate in the CCT, but this increase was difficult to distinguish from the initial constituents of the salt solution, which included some of these elements.

## 9.5 FRANCE

### 9.5.1 Materials

The French alternative materials selected for investigation were:

- MSWI bottom ash (from urban area, Ivry plant)
- MSWI bottom ash (from rural area, Egletons plant)

And the reference material used was:

- diorite

Two existing road sites where MSWI bottom ash had been used in construction were also investigated.

### 9.5.2 Suitability

***Mechanical tests:***

From the Micro-Deval tests conducted on the French MSWI bottom ash samples, first studied in May 1998, we have seen in one case (Egleton sample) an improvement of the attrition mechanical properties with ageing, and in the other case (Ivry sample) the constancy of the mechanical properties. That would mean an eventual hardening of the softer Egleton material with time, and the stability of the harder Ivry material. For the fragmentation mechanical properties (Los Angeles) the conclusions are not so clear.

The softer MSWI bottom ash (Egletons) showed a high sensitivity to abrasion under the single effect of sieving. The harder Ivry MSWI bottom ash did not shown such a sensitivity.

The apparently high sensitivity of one MSWI bottom ash to some parameters (e.g. time, handling), and the apparent insensitivity of the other MSWI bottom ash to the same parameters, firstly demands an explanation of such variations and secondly would demand a typology of these materials to facilitate their handling in road construction.

The Micro-Deval test shows an almost linear behaviour for natural aggregates. Both MSWI bottom ashes have poor results for this test compared to the reference material, but above all, what must be considered is the non linear behaviour of the MSWI bottom ash samples and the importance of the first part of the test. During the first revolutions of the test, the slope of the curve for the MSWI bottom ashes is steep and different from the reference material. After this, the Ivry material results become more constant, but the Egletons values continue to rise.

The Los Angeles test shows a perfectly linear response for the natural reference aggregate. The test also clearly showed the non linearity for the MSWI bottom ashes.

With ageing, the Egletons MSWI bottom ash seems to show the same evolution it had for the Micro-Deval test. One year after the characterisation in May 1998, its Los Angeles coefficient had decreased from 58.7 to 48 (but one must consider the high standard deviation, 14.1 of this last measurement before making conclusions). For the other French MSWI bottom ash (Ivry), the same constancy as for the Micro-Deval test can be noted: 40.4 in May 1998 ; 40 in June 1999.

Alternative materials, which are used as a way of saving natural resources, without taking into account the maximisation of material performance, can show noticeably worse Los Angeles and Micro-Deval coefficients than some natural aggregates. This is the case for MSWI bottom ash in particular, for which the coefficients can commonly reach the values of 50 and 45 respectively (SETRA, 1997). The tests carried out on one of the materials selected for the programme show that the results can even be worse. However, this does not prevent the use of this material in road construction for the purpose it is being used, because properties of the material other than the single particle mechanical strength can have a major effect on the road structure properties.

***Chemical analyses:***

From the results of the total analysis, the composition of the two MSWI bottom ashes appears very similar.

From the NF X 31-210 standard, which is the current French compliance test, it appears that with ageing, both the electrical conductivity and the pH of the MSWI bottom ash leachate decreases. The global solubility of the material diminishes with time, and the pH moves toward neutral. The most soluble elements are the chlorides, the sulphates, Ca, Al, K and Na. The least soluble element is Cd. Ageing has no effect on the solubility of some elements, but does affect the solubility of others. The Pb and Zn solubility decreases with time.

The two-stage batch leaching test results resemble those of the NF X 31-210 test results, but also show high levels of Mg.

The various tests show many coherent results. Compositions of the two MSWI bottom ashes are very similar despite their different origin. When considering the scenarios for material use, one must remember that the two materials also showed different behaviour for their mechanical and hydrodynamic properties (see Appendix F4). Despite their chemical homogeneity, there could be a mineralogical heterogeneity which may explain such functional differences.

***Existing road excavation - La Teste site:***

The La Teste inspection allowed the assessment of the mechanical and environmental durability of MSWI bottom ash road layers under actual use conditions during more than 20 years.

The road, and the alternative material, have produced rather positive results to the tests (covering French standards and requirements) conducted. The tests undertaken showed good deflection for a flexible structure, no pollution of the underlying soil, very low leaching, very good bearing capacity and good particle size distribution. These results are even more interesting when it is considered that the material did not undergo any particular preparation before use in the construction of the road. Neither the structure design, nor the technical implementation, were particularly fitted to this non-standard material. Moreover, before 1991 MSWI fly ash, which is far more polluting than bottom ash, was not separated from MSWI material used in construction.

The influence of MSWI bottom ash on the underlying soil is perceptible principally as regards the pH, the conductivity and the sulphates. The investigation of mechanical properties has shown the heterogeneity of the material and its water content sensitivity. The solubility of the La Teste MSWI bottom ash compounds is reduced today. It may have been greater when the MSWI bottom ash pH was higher, several years ago, and pollutants could have been dispersed through the La Teste draining soil. Other inspections must be carried out to before being able to compare the results from this site to different scenarios of use.

***Existing road excavation - Le Mans site:***

The Le Mans inspection allowed the assessment of the mechanical and environmental durability of MSWI bottom ash road layers under actual use conditions during 20 years (1978-1998).

The road and the alternative material gave good results to the mechanical tests conducted, as for the MSWI ash at the La Teste site. This material also did not undergo any particular preparation before use.

As for the La Teste site, the influence of the MSWI bottom ash on the underlying soil is perceptible principally as regards the pH, the conductivity and the sulphates. Also, the inspection again showed that the MSWI bottom ash has high sensitivity to water content variations, and that the solubility of Le Mans MSWI bottom ash compounds is reduced today. The underlying clay was intended to fix the elements released from the MSWI bottom ash layer. Today, the concentrations measured are far below the pollution limits. This study provides good complementary data to the La Teste inspection conclusions.

## 9.6 SWEDEN

### 9.6.1 Materials

The Swedish alternative materials selected for investigation were:

- Air cooled blast furnace slag (ACBFS)
- Crushed concrete (CC)

And the reference materials used were:

- Crushed rock (CR) sub-base and base course material

### 9.6.2 Suitability

Mechanical tests:

In laboratory analysis determining the mechanical properties of ACBFS and CC, a few properties proved to be poorer than for natural reference material. In some cases it was difficult to meet the requirements established. The requirement on the abrasion value $A_N$, was difficult to meet. However analysing ACBFS or especially CC by using the Nordic Ball Mill or the Los Angeles Drum do not really justify the relevant road application or the performance of these materials. This fact corresponds with an important statement presented in the OECD Report 1997: ”The current survey results clearly show the tendency to abandon empirical tests in favour of performance-related tests”. Therefore ACBFS and CC as well as other alternative materials should be analysed using tests like repeated Load Triaxial Test in the laboratory and FWD-measurements in the field.

On the other hand, in this ALT-MAT project the Motorway/Highway with ACBFS and the test sections with CC in the sub-base have verified that the road application properties are as good as or even better than those on the reference sections with natural aggregates. The requirements in the Swedish Road Technical Specifications, ROAD 94, were met on bearing capacity, degree of compaction and particle size distribution of both materials used as sub-base. In addition, the stiffness of ACBFS and CC improved considerably in the laboratory as well as in the roads within a relatively short period and the CC did not show any deterioration in bearing capacity when thawing during springtime.

The increase of stiffness in alternative materials is very useful in road applications, and therefore this important property promotes usage in infrastructure constructions with high and heavy traffic

**Chemical analyses:**

In Sweden no national requirements exist that determines the use of alternative materials. The decisions whether a material is allowed to be used or not are made on a case by case basis by the local environmental authorities. However, it must be shown that the material is not harmful to the environment.

The total composition of the ACBFS and the CC do not differ much from the composition of till and crushed rock. Exceptions are the amounts V in the ACBFS and Cr in the CC, which are higher than the amounts in the natural materials.

Considering all conducted leaching tests, the leaching of V seems to be higher from the ACBFS compared to the leaching from the natural materials investigated. From the CC leached amounts of Cr are higher than from natural materials. For some leaching tests the leaching of Pb and Co from the CC are higher than from the reference materials. The leached amounts of the other elements that have been examined are in the same range as the leached amounts from the reference materials.

The lysimeter tests, that simulate field conditions, show higher leached amounts from the ACBFS than from the natural materials for almost all elements compared. The pH-value was however for the lysimeter test initially lower than in the leachates from the laboratory tests, which reflects the importance of the actual pH-value for the leaching.

***Material analysis:***

From the laboratory analysis and the field tests carried out on ACBFS and CC in comparison with CR as reference material, much information has been gained and several conclusions can be drawn. The following facts might be used when these alternative materials are proposed to be utilised as road construction material in the future.

***Air cooled blast furnace slag:***

1. ACBFS meets the requirements of the Swedish Road Technical Specifications (ROAD 94) when used in sub-base.
2. The thermal insulation properties of ACBFS and its higher stiffness imply thinner thicknesses of the road pavements which save natural aggregates and offer economic advantages.
3. However in countries like Sweden with cold winter climate it has been observed that ACBFS used high up in the pavement may cause potential icing on the road surface especially in early winter.
4. Performance related tests like Dynamic Triaxial Test and FWD-measurements verify a marked increase of stiffness of the ACBFS with age (see also for CC).
5. Cementitious properties of the ACBFS create self-binding, which from both engineering and environmental points of view is very important.
6. Disregarding the thermal properties, the ACBFS can be used in the base course. In other words ACBFS can be used high up in the road pavement in countries or regions with a milder winter climate than in Sweden.
7. From the groundwater sampling performed at Road E4 no evident environmental impact from the ACBFS can be seen neither regarding the pH of the leachate nor any of the examined elements. The leaching tests indicated that the leaching of V could be high.

***Crushed concrete:***

1. Performance related tests like Dynamic Triaxial Test and FWD-measurements verify a marked increase of stiffness of the CC.
2. Cementitious properties of the CC create self-binding which from both engineering and environmental point of view are very attractive.
3. CC from the building demolition waste meets the ROAD 94 requirements set up for conventional road construction material when used in sub-base.
4. The frost susceptibility of CC is low.

5. The overall performance of CC may enable this material to be used even in base course.
6. In leaching tests performed on the CC, the element Cr has the highest leached amounts compared to conventional materials.

## 9.7 SWITZERLAND

### 9.7.1 Materials

The Swiss alternative materials selected for investigation were:

- Recycling glass (crushed glass bottles)

And two slags from a new thermal waste incineration process

- VRG – slag (glass-like, not crushed)
- VRS – slag (mineral-like, crushed)

And the reference materials used were:

- Natural aggregate (crushed to different aggregate size from an alluvial deposit )
- Limestone filler

### 9.7.2 Suitability

***Material characterisation:***

Swiss Standards define the requirements for natural aggregates used in bituminous pavements. Alternative materials have to meet the same quality demands and therefore the same test methods are applied. (See Appendix F6 for details).

No requirements for the density of aggregates exist in the Swiss standards.

Los-Angeles test requirements for bituminous bound pavements :

**Evaluation of application in different pavement layers for the material tested**

| Layer | Wearing course | | Wearing course | | Base course | |
|---|---|---|---|---|---|---|
| Type | H, S | | N, L | | H, S, N, L | |
| Sample Fraction | #6/11 | 11/16 | #6/11 | 11/16 | #6/11 | #11/16 |
| Maximum Los Angeles coefficient allowed | 20 | 18 | 23 | 21 | 25 | 23 |
| Natural aggregate | **passed** | | **passed** | | **passed** | |
| Recycling glass | **passed** | | **passed** | | **passed** | |
| VRG-slag | **passed** | | **passed** | | **passed** | |
| VRS-slag | **passed** | | **passed** | | **passed** | |

There are petrographic examination and hardness requirements for bituminous bound and concrete pavements, but for alternative materials no petrographic description is possible. Recycling glass and VRG-slag are not crystalline and therefore no minerals can be assigned. The hardness has to be measured by a special mechanical test method. The VRS-slag is micro-crystalline because it had time to generate small crystals as a consequence of the longer cooling process. But characterisation is not possible with the standard method by visual inspection and special techniques have to be applied.

***Aggregate shape requirements:***

In the Swiss standard the percentage of non-cubic particles is counted. Requirement for all bituminous pavements is the same: 20-50% non-cubic particles are required. If less than 20% are non-cubic, the bituminous mixture has to be tested for sensitivity to rutting.

Percentage of non-cubic particles of the materials tested

| | fraction | result | pass/fail |
|---|---|---|---|
| Natural aggregate | 0/3 | 43% | **passed** |
| Natural aggregate | 3/6 | 42% | **passed** |
| Natural aggregate | 6/11 | 25% | **passed** |
| Recycling glass | 2/4 | 45% | **passed** |
| VRG-slag | 2/4 | 15% | **failed** |
| VRS-slag | 6/11 | 51% | **failed** |

Percentage of crushed aggregates - requirements of Swiss standards for bituminous bound and concrete pavements :

For alternative materials, this test is not applicable, as they do not originate from round stones. However, this method is actually used to measure the percentage of smooth surfaces, which is for natural gravel at the outside. The smoothness of the surface plays an important role in the adhesion of bituminous binder to the aggregate surface. But recycling glass or VRG-slag also have very smooth surfaces. Therefore an adaptation of the current standard is required to make it applicable for alternative materials too.

Most of the results of the mechanical tests carried out on the three alternative materials lie within the requirements of the Swiss standards for aggregates used in bituminous pavements. There were only problems with two test methods, which are the percentage of non-cubic particles and the petrographic examination. The petrographic examination, which counts the amount of hard minerals, was not applicable to the alternative materials, because these are not crystalline materials.

Regarding the percentage of non-cubic particles, the VRS-slag had slightly too much and the VRG-slag had too little non-cubic particles. But the requirement for a minimum amount of non-cubic particles in the Swiss standard is problematic, as the pending European standard only defines maximum amounts of non-cubic particles. Hence, the VRG-slag will be in the highest quality class according to the European standard, but is not allowed when following the Swiss standard.

Therefore it is better to clarify these contradictions by other mechanical test methods on bituminous mixtures, (covered in detail in Appendix F6) the findings of which are summarised below.

***Mechanical tests:***

Recycling glass -

Mixtures containing 30% of broken recycling glass showed some problems with adhesion between binder and the smooth glass surface. Nonetheless, test results for stability, water sensitivity and rutting lie within the limits for an asphalt concrete AB 11S. But the performance of the mix with recycling glass was generally clearly worse than the reference mixture. In contrast to the expectations before the project, the recycling glass proved to be very sound and was not prone to crushing.

If the adhesion property could be improved, for example by roughening of the surface, recycling glass could be an even better alternative material for bituminous mixtures. Although the recycling glass was not cleaned before use, attention should be paid to impurities.

VRG-slag -

The glass-like VRG-slag behaved very similarly to the recycling glass except in moisture sensitivity test, where the tensile strength ratio of the VRG-slag was clearly higher. Performance of the mixes were equally inferior compared to the reference mixture, but all the criteria for the asphalt concrete AB 11S were fulfilled. As for the recycling glass, some adhesion problems are expected, as the surface is also very smooth. But because of the dark colour of the slag, this was not observed by the test methods applied.

Some problems were observed in the gyratory compaction test on the unbound material, where a high percentage of the material was damaged. This might come from the numerous sharp edges which break under high load. On the other hand the Los Angeles coefficients were good, which shows that the type of abrasion test is very important for this material.

Unfortunately no particles larger than 3 mm can be produced from this material, because the size is determined by the sudden cooling of the liquid melt with water. As a sand fraction the VRG-slag is not so valuable for the application in bituminous pavements.

VRS-slag -

This is a very interesting material with a performance which comes close to natural materials of high quality. It is actually the same material as the VRG-slag with the only difference that the melt was allowed to cool slowly enough to generate micro crystals and surface pores. When crushed, it looks very much like a natural basalt. Mixes containing VRS-slag showed very good rutting behaviour and high stability, essentially equal to the reference mixture. However, the moisture sensitivity is not very good, especially after frost cycles. This is probably because of the slightly porous surface, which is also reflected in a slightly higher binder consumption of the trial mixtures.

As the cooling process is not yet optimised, the material characteristics still can be improved. But already the VRS-slag is a very good alternative material for bituminous mixtures, especially because it can also be crushed into any desired particle size.

***Overall mechanical test conclusions:***

From the mechanical point of view, the alternative materials tested by EMPA in the ALT-MAT project are good materials for bituminous mixtures. This is especially true when they are mixed with natural materials and good bituminous mixtures are produced, which even fulfil the key requirements of wearing courses in Switzerland. However, it was not possible to investigate all mechanical properties in the ALT-MAT project, e.g. test methods for low temperature cracking and fatigue properties were not evaluated.

Mixtures consisting solely of alternative materials were not investigated in this project. But there are indications, that some negative effects accumulate and could lead to severe problems (adhesion, water sensitivity).

***Chemical analyses:***

The results of the leaching tests showed that the two slags behaved in a similar way to the recycling glass. As discussed in Part 1 of the Swiss national report (see Appendix F6) all materials fulfilled the limit values of the TVA-test. From the results of the leaching tests, there is no reason against the use of the two slags for the construction of road pavements, especially because recycling glass, which gave similar leaching results, is officially permitted in Switzerland.

However, if the chemical composition is taken in consideration, the two slags contain higher amounts of heavy metals, especially zinc, copper and chromium, than recycling glass. Therefore the application in wearing courses is not recommended, as the surface degrades through trafficking, over time. But for all bituminous pavement layers below the wearing course, the use of the three alternative materials has be proven to be applicable, both from the ecological and the mechanical point of view.

## 9.8 UNITED KINGDOM

### 9.8.1 Materials

The UK alternative materials selected for investigation were:

- Demolition rubble
- Steel slag

And the reference material used was:

- Limestone

### 9.8.2 Suitability

***Mechanical tests:***

Overall, the in situ and laboratory investigations conducted showed that the use of demolition rubble provided as good a sub-base for roads as limestone aggregate.

Data from the falling weight deflectometer (FWD) and German dynamic plate bearing tests (GDPBT) on the limestone (reference) and demolition rubble sub-base materials, at the existing road site investigated, indicated that they provided acceptable to good support for the pavement at both sites.

Generally the mechanical properties of the demolition rubble from the existing road site are comparable to those of the limestone (all of which complied with the UK limits for acceptance as a ‘Type 1’ sub-base material). The demolition rubble particle size distribution fell just outside the sub-base grading limits, but local authority specifications permitted its use by placement of a thin limestone layer above the alternative material. Also, the frost heave value exceeded the limit, but the specified test may not be completely appropriate for use, as the temperatures used are much lower than those usually encountered in this part of the UK. The demolition rubble CBR is lower than the limestone (66% compared to 156%), but is still greater than the limit of 30% specified by the SHW, as acceptable for sub-base aggregate.

The steel slag also met all the UK national specifications for use as a sub-base, apart from the Type 1 grading curve, which it fell just outside.

The mechanical requirements specified by the UK Specification for Highway Works (SHW) which were not met for certain applications, would not prove difficult to overcome. Most were related to the particle size distribution, or moisture content of the material. These properties can be altered and controlled before the material is used in road construction. As stated above, the other main failure of demolition rubble in meeting SHW requirements was in the frost-heave test, which may not be a truly appropriate assessment of relevant properties of materials for road construction, in the UK.

The limestone mechanical test values are considerably higher than those required by the specification. It may therefore be more efficient to use alternative materials for sub-base and the limestone for an application with more demanding requirements.

***Chemical analyses:***

The various concentrations and amounts of constituents leached from the three materials during the various leaching tests have been detailed, compared and contrasted in Appendix F7. It is possible, however to offer a further analysis of the materials using CIRIA Report 167 (Baldwin et al, 1997) which included details of 2-stage batch tests on various materials.

An approach often taken, when analysing leaching test results, is to set an acceptance level, and to relate test values to recognised and accepted water quality standards (WQS) or environmental quality standards (EQS). Thus, it is possible to distinguish between leachate constituents which can be tolerated at relatively high levels, and those which would be unacceptable even at fairly low concentrations.

In this manner, it was decided to relate the 2-stage batch test data conducted for the UK ALT-MAT leaching tests to the EQS/WQS limits listed in CIRIA Report 167. It is, however, worth noting that not all of the determinands listed in the CIRIA reports' EQS/WQS list were tested for in the chemical analysis of the leachates (e.g. tin, phenol, fluoride), and other species not present in the list were tested for (e.g. silicon, selenium, TOC).

Using the criteria and standards of the CIRIA report (details given in Appendix F7) to classify the limestone, demolition rubble and steel slag in terms of their potential to affect water quality, the limestone and demolition rubble fell into the Group 1 category (no restrictions based on potential to effect water quality). The steel slag however fell into the Group 2 category (may need some restrictions based on potential to affect water quality). The constituents in the steel slag all fell within the Group 1 limits except Mo, which fell outside the Group 1 limit, but within the Group 2 limit. All other species for all the leachates were well below specified limits for Group 1 materials.

# 10. TRIAL ROAD STRUCTURE FOR SPECIFYING ENVIRONMENTAL AND MECHANICAL FUNCTIONING

## 10.1 INTRODUCTION

The environmental as well as the technical performance of alternative materials used in road constructions are to a large extent a function of the water regime in and around the road structure. Threshold values for alternative materials are established based on chemical characterisation, generally leaching properties of the different materials in comparison with tolerable concentrations or drinking water standards. But not much is known about the crucial factors controlling leaching and hereby the potential environmental pollution as well as the factors controlling the mechanical durability of the structure - the water movement in road constructions (Joint meeting ALT-MAT, POLMIT and COURAGE, Nantes, March 1999).

Most measurements concerning the behaviour of water in road structures are routine measurements on a laboratory scale (e.g. permeability tests on different construction materials). Laboratory as well as simulated field tests are always performed under controlled conditions and can be compared to nature only to some extent. The knowledge of the mechanisms of water transport and its influence on the environmental and the mechanical performance of a road structure is an important pre requisite for the establishment of threshold values for pollutants, geotechnical parameters and recommendations or standards for road design. A scientific basis for requirements on the chemical and mechanical quality of alternative materials has to be established. Prior to the definition of threshold values, it should be clarified to what extent the material comes into contact with water. The experience and knowledge from trial roads will supply this scientific basis and will increase the certainty and accuracy of the decision makers and legislators regarding where and in which form to use alternative materials.

## 10.2 PROPOSAL FOR SPECIFICATION

### 10.2.1 Basic situations

Three different basic situations regarding the morphology have to be considered for the construction of the trial embankment:

- Embankment: infiltrating water through pavement, shoulders and slopes caused by precipitation; capillary rise from the base
- Hillslope: in addition to precipitation there could be a substantial water flow from the slopes to the base of the road resulting in a potentially high capillary rise

- Cutting: additional potential water flow from both hillsides

### 10.2.2 Design of the trial road structure

This specific trial road structure should help to clarify the following points:

- The water regime in roads constructed with natural (as a reference) and alternative materials
- The leaching behaviour of potentially harmful elements out of the road taking into account the different pathways of the water flow in the road construction
- The mechanical properties and frost susceptibility can be monitored under natural conditions

To fulfil all these requirements it is proposed to divide the trial road structure into 4 different sections.

The first section is constructed with natural material and without a HDPE membrane. This section enables the monitoring of the "normal" water regime in the road embankment including capillary rise from the basement (Figure 10.1).

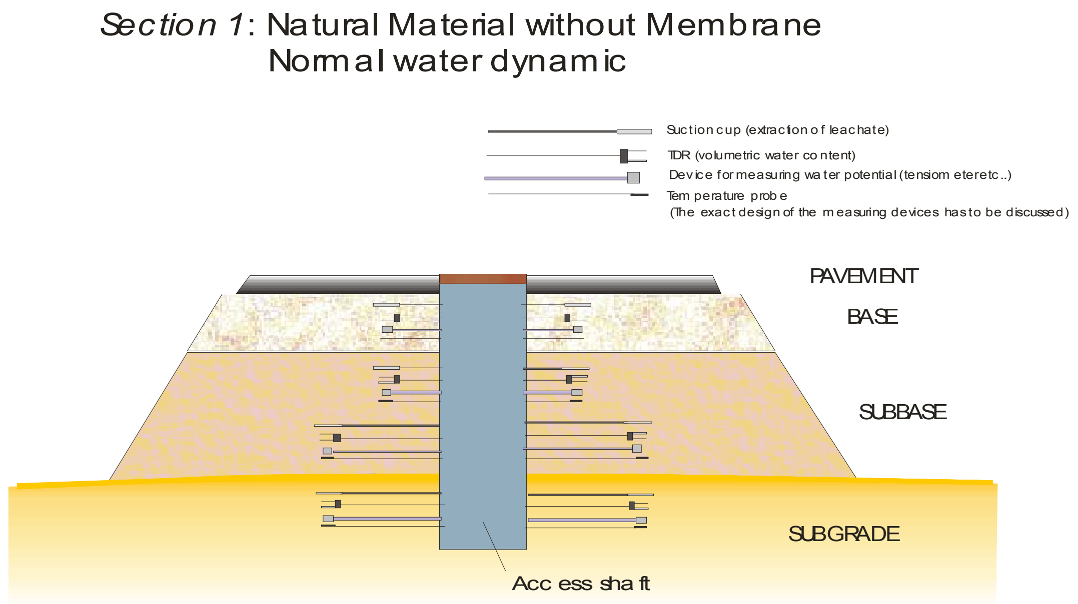



**Figure 10.1: Section 1 of the trial embankment (figure is not to scale)**

Section 2 is constructed with natural material but is sealed with a HDPE membrane (Figure 10.2). This enables the quantification of infiltrating water through the pavement and shoulders (preventing capillary rise). Section 2 is also a reference for the leachate quality.

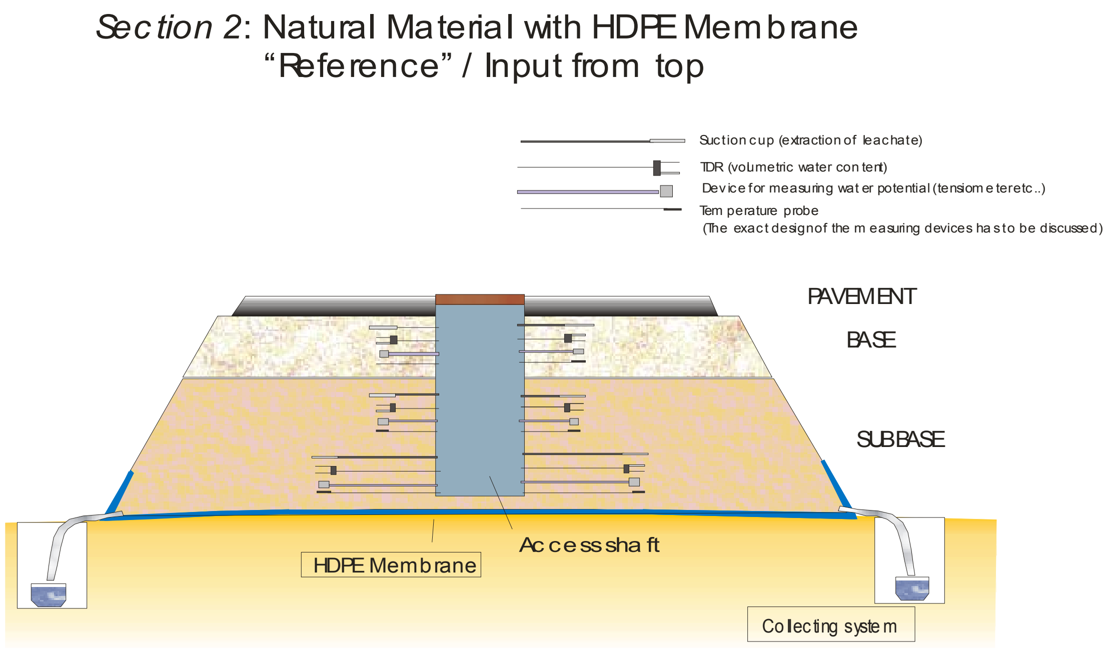



**Figure 10.2: Section 2 of the trial embankment (figure is not to scale)**

In section 3 and 4 of the trial embankment (Figures 10.3 and 10.4) alternative materials are used for road construction. The usage of HDPE membranes enables the collection of the leachate. Additionally an artificial barrier in section 4 at the edges of the pavement enables a separate collection of the water infiltrating through the pavement and through shoulders and slopes.

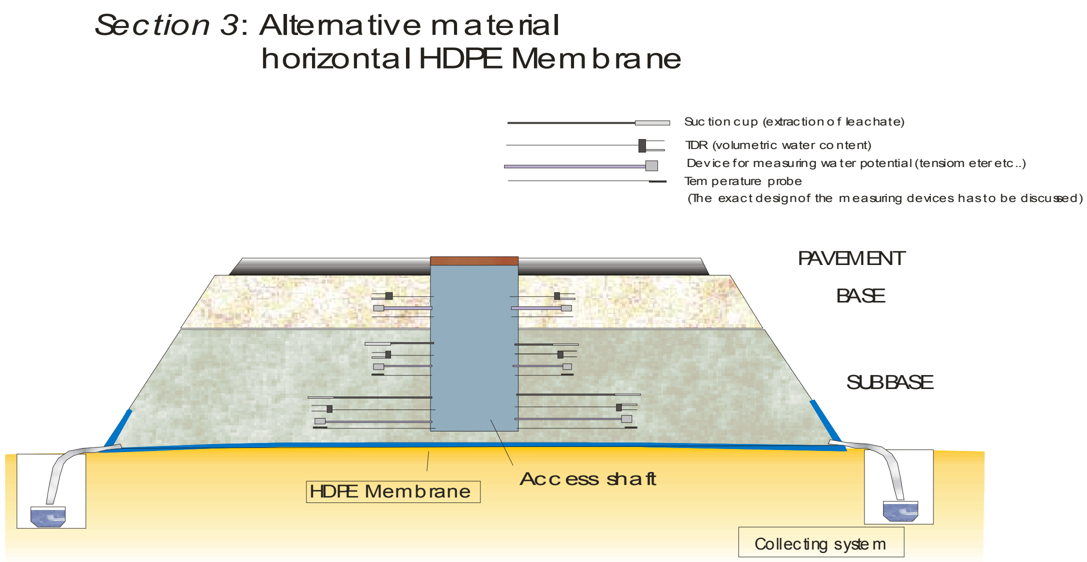



**Figure 10.3: Section 3 of the trial embankment (figure is not to scale)**

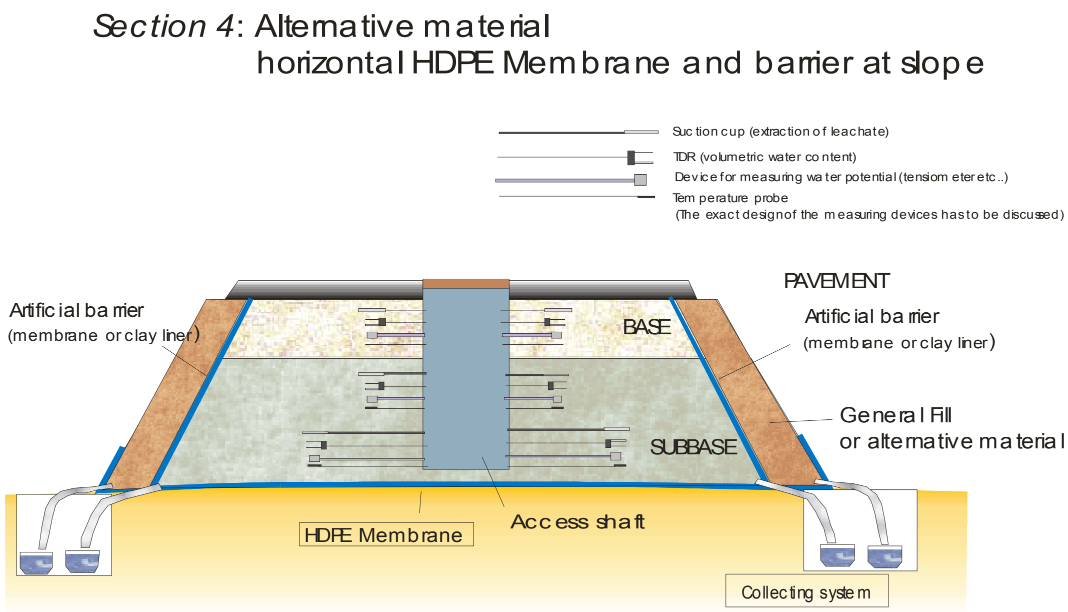



**Figure 10.4: Section 4 of the trial embankment (figure is not to scale)**

The pavement may have to be aged artificially through cracks to enable water flux in a reasonable timescale, but at least one section should be subjected to the normal ageing cycle without any artificial cracking.

The HDPE membranes at the base of the embankment are included to enable infiltrating water to be collected and to prevent the capillary rise of water from the foundation. It is not proposed that membranes be used in this location for mitigation of pollution from the alternative materials except for very sensitive locations (see Chapter 8).

### 10.2.3 Measuring devices

The design and the amount of the measuring devices in Figures 10.1 to 10.4 is only schematic. The exact design should be optimised in a way that vertical and horizontal water, heat fluxes and the mechanical behaviour can be properly recorded.

The measurement of following parameters is proposed:

*Meteorological conditions:*

The quantification of the evaporation is needed for calculating the water balance.

- quantity and quality of rainfall (online)
- temperature of air, road surface (online)
- temperature gradient within the road structure (online)
- relative humidity (online)
- solar radiation (online)
- wind velocity (online)

*Water dynamics within the construction and (partially) underneath:*

- Water content (vol-%): possible equipment:
  TDR probe (online),
  neutron probe,
  capacity probe,
  or similar devices

- Water potential: possible equipment:
  Tensiometer
  gypsum blocks
  or similar devices

- Collection and quantification of surface run off

- Leachate collection [quantitative (online) and qualitative (partly online)]

*Mechanical performance:*

- bearing capacity equipment: FWD

- deformation under cyclic load (online)

- observation and measurement of surface deformation due to frost heave

It is proposed to install the measuring probes in each section from an access shaft into the different construction layers. The probes would be installed during construction, after the placing of each layer of fill.

## 10.3 CONCLUSIONS

With the construction of a trial embankment the knowledge of the following topics could be increased:

- The movement, quantity, change of quantity and quality of moisture in road constructions under real field conditions in different typical scenarios could be investigated.

- The gap between laboratory and field testing regarding the chemical and mechanical behaviour in a short, mid and long time performance will be bridged.

- Lysimeter, climate chamber and laboratory leaching tests could be calibrated.

This will allow completion of the scientific basis for the establishment of environmental and mechanical requirements in regulations.

# 11. CONCLUSIONS

In most European countries, usage of alternative materials in road construction is relatively low at present. An exception is the Netherlands, where a shortage of natural aggregates has led to routine use of some alternative materials. There will be increasing pressure, driven by national governments, to increase the use of alternative materials by means of taxes on material sent to landfill and on the use of natural aggregates and by the setting of targets for the use of alternative materials. However, this is balanced by environmental concerns about contamination of surface and ground waters by leaching from alternative materials, leading many environmental regulatory authorities to adopt a ‘precautionary principle’ approach and apply strict guidelines on the use of such materials. In order to reconcile these conflicting approaches, better understanding of the way alternative materials behave in road construction and test methods to assess their mechanical and environmental performance are needed. The ALT-MAT project has addressed these issues and provides a toolkit of test methods for assessing the suitability of alternative materials for use in unbound granular applications in road construction.

A programme of inter-laboratory tests showed that alternative materials behave in a different way to natural materials in tests such as the Los Angeles and Micro-Deval abrasion tests. Test results for alternative materials should therefore be viewed with caution. However, the gyratory compaction method shows good results and should be optimised. This test simulates compaction of pavement layers with a heavy steel roller in the field.

Alternative materials often give better mechanical performance in the field than would be expected from the results of tests such as the Los Angeles or Micro-Deval. Design should therefore be based on performance-related tests such as cyclic-load triaxial or gyratory compaction. Work needs to be done to relate these tests to measurements of field performance made with the FWD and similar tests.

The following existing CEN mechanical tests for granular materials are evaluated to be suitable for alternative materials:

| Test method | Reference |
|---|---|
| Methods for sampling | EN 932.1 |
| Methods for reducing laboratory samples | prEN 932.2 |
| Determination of particle size distribution | EN 933.1 |
| Determination of the resistance to wear (Micro-Deval) | EN 1097.1 |
| Methods for the determination of resistance to fragmentation | EN 1097.2 |
| Determination of water content by drying in a ventilated oven | prEN 1097.5 |
| Determination of particle density and water absorption | prEN 1097.6 |
| Method for determination of loss on ignition | EN 1744.1 |
| One of the standards prEN 13286.2-13286.5 Test methods for laboratory reference density and water content: | |
| Standard proctor | prEN 13286.2 |
| Vibrocompression with controlled parameters | prEN 13286.3 |
| Vibrating hammer | prEN 13286.4 |
| Vibrating table | prEN 13286.5 |

Limiting values for the parameters should be set on a national basis, having due regard to the local climate and experience with the relevant materials. In some cases, it may be necessary to determine site-specific limiting values for particular materials.

For alternative materials tests using vibration (e.g. vibrating table) instead of impact (e.g. proctor) are recommended. The nuclear gauge is not recommended for the determination of the in-situ density of MSWI ash. A test method for the self-binding capability of alternative materials is needed, as is an improved method to describe the material composition of alternative materials.

European or international standardisation is less advanced within the field of assessment of the environmental properties of alternative residues. Standardisation work is, however, in progress, and several standard CEN tests for characterisation of alternative materials may be expected to emerge over the coming years. In the meantime, a number of national standards, pre-standard CEN tests or Nordtest recommended leaching test methods are available to assess the leaching properties of alternative materials under different circumstances. Several of these tests were selected and applied in this project. Comparison of the results of these tests with lysimeter and climate chamber tests indicates that column tests provide the most detailed simulation of the actual leaching behaviour of the materials under normal circumstances. If there is any chance that the pH of the material might change significantly in the field, for example by carbonation of oxides/hydroxides or oxidation of sulfides, pH-static tests should be used to estimate the effect of the anticipated pH change. Simulation leaching tests at high liquid to solid (L/S) ratios (e.g. availability tests) are of limited value in road construction applications, unless the road does not have a relatively impermeable surface layer (e.g. gravel roads in rural areas).

Impact assessments and predictions should be based on scenario calculations, i.e. a description of the physical lay-out of the site in question, the flow of water through the site in conjunction with a description of the composition of the leachate formed as a function of L/S or time, the latter derived from laboratory or lysimeter leaching tests.

Among the useful tools for assessment of the environmental properties of alternative materials used in road construction, we particularly recommend the following:

- Draft prENV12920 Characterisation of waste: Methodology guideline for the determination of the leaching behaviour of waste under specified conditions;
- Column leaching test NT ENVIR 002;
- Batch compliance test prEN 12457-3.
- The pH-dependency of the leaching behaviour is investigated, e.g. using a pH-static leaching test.

Most of these leaching procedures are currently being developed as European Standards by CEN/TC 292.

When effects of climate are to be predicted in larger systems, then lysimeters and climate chamber tests can be used. The conditions for lysimeter tests will resemble natural conditions more closely than laboratory leaching tests, since they will be exposed to the natural climatic conditions. In most cases, laboratory leaching tests can be used to give a conservative estimate of environmental effects, since laboratory tests in most cases will overestimate actual leaching. The results from the lysimeter and climate chamber tests suggest that the pH which is developed in the material over time is the most significant factor in the composition of the leachate. It is thus essential to understand the mineralogy of an alternative material and its likely behaviour in a road pavement in order to make sensible predictions about its leaching behaviour. If the pH is likely to change with time, as a result of oxidation, carbonation or hydration reactions, pH-static leaching tests should be carried out at an appropriate range of pH values.

A model has been adopted to predict the impact of leaching from alternative materials in road construction on the quality of groundwater. The model is site specific and is based on the allowable increase in concentration of contaminants in the groundwater. For each contaminant, a critical length of time is estimated based on its relative mobility; highly mobile ions such as potassium are allocated a shorter critical time than less mobile metals such as chromium. The critical length of time can be converted to a critical L/S ratio on the basis of the road geometry, contributing area of the road to the groundwater catchment and the rate of infiltration into the road. The cumulative amount leached at this L/S ratio is derived from leaching test results; if it is less than the allowable cumulative amount leached, the material may be used in the road construction. The model, which is based on flux considerations, is conservative in that it does not account for the attenuation of contaminants during transport from the application through the unsaturated zone and the aquifer to the point of groundwater extraction.

Unbound granular layers in road construction will generally be partly saturated for most of the year, with limited periods of full saturation. In order to measure the movement of water through road constructions, it is necessary to know the relationship between water content and suction, and the relation of both to the hydraulic conductivity. A number of methods are available, all of which are appropriate in certain circumstances. The choice of method is affected by factors such as the electrical conductivity, chemical composition and heterogeneity of the materials. Alternative materials differ markedly from natural aggregates in this respect, so these properties should be determined at the start of any investigation so that the most appropriate methods can be chosen. Specific calibration curves may be required for alternative materials, especially for nuclear methods.

One of the materials which causes problems for electromagnetic measurements of water content is MSWI bottom ash, because of its high electrical conductivity. A new test method was developed for this material, involving vibrocompression and freezing of samples and use of a pressure chamber for suction measurements. The methods worked well, and are recommended for general use on sensitive materials. Two different MSWI bottom ashes were investigated, both as young and aged materials. The MSWI behaved like a silty soil, with high water retention even at high suctions. The water content of both ashes increased with age, but the shape of the water retention curves remained the same.

Inspection and monitoring of existing roads showed that alternative materials gave as good and sometimes better support to the road pavement layers as natural reference materials. The sites investigated ranged from the north of Sweden to south-west France, and hence covered a wide range of climatic conditions. The materials studied included crushed concrete, air-cooled blast furnace slag, MSWI bottom ash and demolition rubble (mixture of brick and concrete). The performance in the field was often better than would have been predicted from laboratory test results. For some materials, notably crushed concrete and air-cooled blast furnace slag, an increase in stiffness with time was recorded, due to the self-binding properties of the material.

Chemical tests revealed that leaching had caused a perceptible increase in the concentration of certain constituents in the subgrade below the alternative materials. This was noted in Denmark and France below MSWI bottom ash and in the UK below demolition rubble. The phenomenon was recorded in both clay and sand subgrade. The increases were limited to a few constituents in each case, and the resulting concentrations were well below national limits for contamination. Leaching tests and groundwater sampling indicated that the alternative materials did not appear to be having any significant effect on groundwater quality.

Mitigation methods to counter possible adverse environmental effects of the use of alternative materials were considered. These may be either source-based or pathway-based, it being generally impracticable to move the receptors. Source-based methods include ageing of materials such as steel slag and MSWI ash. This allows harmful constituents to hydrate and carbonate, avoiding expansion reactions after the material is placed, and the pH of the materials to drop from often undesired highly alkaline values to near neutral.

Pathway-based methods include covering the road surface with a layer of dense, impermeable asphalt or placing low permeability materials on the slopes above the alternative material. The aim is to reduce the contact between water and the alternative materials, and hence reduce the leaching of harmful constituents. These measures should be combined with an effective drainage system.

A further way to reduce contact between percolating water and the alternative material is to stabilise it using bitumen or cement as a binder. This may enable the material to be used in a higher value application such as roadbase, for which the unbound material may not be suitable.

ALT-MAT is principally about test methods rather than material suitability, but the project included an assessment of the materials used in the study. The materials were chosen in each country on the basis of their availability, past use and potential for use in road construction. Natural reference materials were tested as a control. It should be noted that the conclusions apply only to the samples tested, and cannot be extrapolated to all materials of the same type.

**Austria:** Two types of MSWI bottom ash were investigated. They did not meet the mechanical requirements for use as sub-base or base materials. The materials could be improved by decreasing the amount of material <0.063mm. At present, the use of MSWI bottom ash is not permitted in road construction. The leaching properties could be improved by separation of the non-ferrous metals, a longer period of storing, and washing of the ashes. These measures would also improve the physical properties of the material.

**Denmark:** Crushed concrete was suitable for unbound road base. MSWI bottom ash was suitable as unbound sub-base. Under forthcoming environmental legislation, the MSWI would be suitable below the road pavement but not under the shoulders of the road.

**Finland:** Ferrochrome slag and blast furnace slag can be used in most parts of the road construction, but not in the road base of high standard roads. No environmental concerns for either material were reported. The concentrations in leachate from climate chamber tests were very low for most metals.

**France:** Two types of MSWI bottom ash were investigated. They gave very high values in Los Angeles and Micro-Deval tests, indicating they were not suitable for high quality end uses. However, inspections of two existing roads in which MSWI ash had been used as unbound sub-base showed that they were giving satisfactory performance 20 years after construction. No environmental problems were reported.

**Sweden:** Crushed concrete and air-cooled blast furnace slags were investigated. Both were satisfactory as unbound sub-base. Crushed concrete may also be satisfactory as a base course material. An increase in stiffness with time was noted for both materials. Use of air-cooled blast furnace slag high up in the road pavement may cause icing on the road surface in cold climates, especially in early winter. In these cases no significant influence on the surrounding environment was encountered with either of the materials.

**Switzerland:** Recycling glass, VRG-slag (glass-like, not crushed) and VRS-slag (mineral-like, crushed) were investigated for use as bitumen-bound materials in the road pavement. The mechanical properties of the materials were satisfactory, but there were some problems with particle shape for the slags. All three materials suffered problems with poor adhesion to the bitumen binder. There were no problems with leaching of contaminants. However, the slags should not be used in the wearing course as they contain metals, which would be released by attrition.

**United Kingdom:** Steel slag from EAF plant and demolition rubble, consisting of a mixture of brick and concrete, were investigated. The steel slag is acceptable as an unbound sub-base material provided it has been aged. The demolition rubble was satisfactory in most respects for unbound sub-base, however it failed to meet exceeded the criteria for frost resistance. This test may be too severe for many parts of the United Kingdom, where temperatures are rarely below zero for any length of time. In-situ tests on a site where the demolition rubble was used as a combined sub-base and capping layer indicated that is was performing satisfactorily. No leaching problems were encountered for the demolition rubble, but leaching tests on the steel slag had high concentrations of molybdenum.

Two areas where further research was needed were identified; performance tests for mechanical behaviour and measurement of the movement of water through road constructions.

The results from several countries show that alternative materials appear to give better performance in-situ than would be expected from the results of standard laboratory tests. Investigation of alternative materials in tests such as the Los Angeles and Micro-Deval show that their behaviour is significantly different from that of natural aggregates. The usefulness of such tests as indicators of in-situ performance must therefore be questioned. Priority should be given to performance-related tests such as cyclic-load triaxial and gyratory compaction. Research is required to develop these tests and relate them to in-situ measures of performance such as the FWD test. The related research project COURAGE, dealing with the mechanical behaviour of unbound granular materials, came to a similar conclusion.

It became apparent during the project that there were very few reliable data on the movement of water into, through and out of road pavements. As a consequence, the fluxes of contaminants are not known and conservative leaching tests and models are used to estimate environmental impact. The new model developed during ALT-MAT will improve this considerably, but it is still based on a number of fairly conservative assumptions on water movement into and out of road construction. Measurement of the actual quantities of water and contaminants is therefore required to calibrate the model and to enable the development of more accurate models in the future. Water movement in roads also affects the mechanical behaviour of the road materials. This area was agreed as a priority for further research by the projects ALT-MAT, POLMIT and COURAGE. A programme of laboratory and field tests is proposed, leading to the development of a hydrogeological model which can be used as a predictive tool for the environmental impact of alternative materials in road construction.

Overall, the results of the ALT-MAT project are very positive and provide support for the use of alternative materials in road construction. The case studies show that the materials perform as well as natural aggregates, and often better than suggested by standard laboratory tests. Methods for testing the mechanical and hydrodynamic properties of alternative materials and their leaching behaviour are listed, and a model for assessing the environmental impact on groundwater quality on a site-specific basis is presented. It is important that highway authorities and environmental regulatory authorities are made aware of this toolkit of methods and apply them in a national context. This can be achieved through the national seminars, publication of the final report in book form and on the ALT-MAT website, articles in technical journals and presentations at suitable conferences and seminars.

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