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Tielaitos

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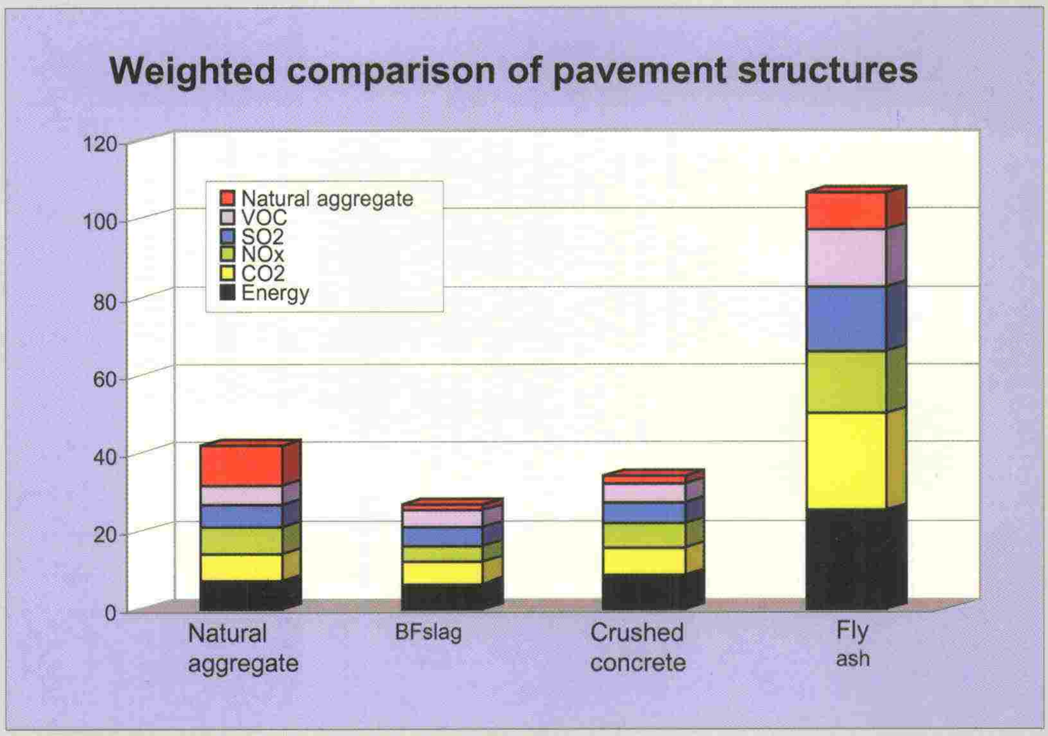

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ABSTRACT

A two-stage study "Life cycle analysis of road construction and earthworks" was part of a more extensive Finnish research project "Assessment of the applicability of secondary products in earthworks". In the first stage of this work a life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was developed. Additionally, a database containing the environmental burdens of the most significant construction materials and unit operations was constructed. In order to evaluate the applicability of the procedure, the use of coal ash, crushed concrete waste and granulated blast-furnace slag in road construction was evaluated in case studies. The use of these secondary products was also compared with the use of natural materials in corresponding applications.

In the second stage the assembled data for utilisation was transferred as a practical model by creating an inventory analysis program to calculate and compare the life cycle impacts of the most common road constructions and foundation engineering methods. The analysis model includes all the significant life-cycle stages covering the production and transportation of materials, their placement in the road structures and the use of the construction. The situation after the use of the construction is not included because the structures most commonly remain in place after they have been withdrawn from service.

The environmental loadings dealt with in the program have been limited to those assessed as being the most important. These loadings are the use of natural raw materials and secondary products, energy and fuel consumption, emissions of carbon dioxide, nitrogen oxides, sulphur dioxide, VOC, carbon monoxide and particles, dust emissions, compounds leaching into the soil and noise. Water usage, land use, waste, COD- and nitrogen effluents and accident risks were also analysed during the first phase. It was, however, concluded that either the significance of these loadings is low or the data available is insufficient for the analysis.

The results of case studies indicate that the production and transport of the materials used in road constructions produce the most significant environmental burdens. Production of the bitumen and cement, crushing of materials and transport of materials are the most energy consuming single life-cycle stages of the construction. A large part of the emissions to atmosphere originates from energy production. In the expert assessment, consumption of natural materials and leaching behaviour of recycled materials were also regarded being of great significance.

PREFACE

Today the functional characteristics of materials and structures used in roads are being actively studied. Substitute materials are also being presented for use in road and earth constructions. It is possible to design alternative constructions using these substitute materials.

All constructions must meet the functional requirements specified for roads. In selecting materials and structures it is also necessary to take the economy and environmental impact of the constructions into consideration. In modern design not only are construction costs calculated, but emphasis is also placed on the life-cycle costs of a construction. These costs are calculated on an annual basis. Environmental effects are factors that are also present throughout the entire life cycle.

Improving the preconditions for using industrial secondary products as substitute materials has been the goal of the Technology Development Centre's (TEKES) Environmental Geotechnology program, among others. An extensive research project "Assessment of the applicability of secondary products in earthworks" included in the program studied how the technical and environmental characteristics of secondary products affected their applicability in earthworks. The project also looked into methods of examining these characteristics and the criteria used in approving the level of environmental risk. Guidelines on procedures used to indicate the applicability of secondary products in earthworks were compiled on the basis of the results of the project.

As part of the research project the life-cycle environmental impact of road and earth constructions was studied. During the study an Excel-based computer application was compiled for calculating the life-cycle environmental effects of road and earth constructions and comparing alternative constructions. If the materials, layer thicknesses and material transport distances of a construction are known, it is possible to calculate and compare the environmental impact of alternative constructions. The environmental loads that were studied were the use of raw materials and energy, atmospheric emissions, substances leaching into the soil, noise and inert waste.

The materials that were compared were natural aggregates and certain substitute materials with the most potential, such as fly ash, crushed concrete and blast-furnace slag. Environmental loading related to different types of pavement was also examined. The parameters of the materials can be modified in the application, and new materials can be added.

The study was financed by TEKES, Finnra, Lohja Rudus Environmental Technology Oy, Helsingin Energia and SKJ-Yhtiöt. The study was carried out by the Technical Research Centre (VTT) Chemical Technology under the co-ordination of Ulla-Maija Mroueh. VTT Communities and Infrastructure also participated in the study.

CONTENTS

1 INTRODUCTION

Life cycle impacts are being used increasingly as a selection criterion for products and materials both in industry and in other activities. Assessment and calculation methods have developed since the early days of LCA, and the scope of its application has grown enormously.

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

The special features of the construction sector are the large volumes of materials used, the long service lives of the finished products, the need to examine constructions as a whole rather than comparing alternative materials, and the significant effect of the constructions' longevity and need for repair on their life cycle environmental loadings. The development of methods for the environmental impact assessment of materials and constructions and for their comparison on an ecological basis is regarded as being important especially in the building construction industry. The development of an internationally accepted life cycle assessment methodology for the analysis and comparison of building products and projects is also an area of research covered by Tekes´s (The National Technology Agency) "Environmental Technology in Construction" programme (1994 - 1999). This study is part of the sub-programme entitled Environmental Geotechnology, the aims of which include the reduction of industrial waste by developing recycled fills from industrial by-products.

1.1 Road construction

About 70 million tonnes of natural mineral aggregate are used each year in Finland for road construction and earthworks (Table 1). In addition to road construction, a large number of carparks, market squares and other similar constructions are also built. The length of the road network, excluding forest car tracks, is over 200 000 km, of which about 78 000 km are public roads maintained by Finnra (Finnish National Road Administration), about 20 000 km are streets, some 1 300 km of which are in Helsinki alone, and 120 000 km are private roads.

Each year, Finnra commissions major road projects involving the construction of tens of kilometres of new roads as well as highway improvement projects requiring the reconstruction of hundreds of kilometres of existing roads. In 1998, 400 km of road structure and alignment improvement projects were carried out, 160 km of pedestrian and bicycle ways were built, and about 60 km of overtaking lanes were constructed. About 3 200 km of roads were resurfaced in 1998 and about 4 000 km in 1997, requiring the use of some 2.4 million tonnes of asphalt. On top of all this come street and other works.

Table 1. Volumes of natural materials used in road construction in 1994 (Rathmayer 1997).

Material	Estimated use, t/a
Crushed gravel	20,000,000
Crushed rock	26,000,000
Gravel and sand, unscreened	6,000,000
Gravel and sand, screened	17,000,000

Most of the materials used in road construction are naturally occurring mineral aggregates and soils. Because the need for materials is large, depletion of the best materials, the need for resource conservation, and lengthened transport distances have all increased the need to introduce substitute materials for natural sand and gravel. Good quality coarse-grained fills can be obtained, for example, by blasting and crushing rock. Substitute materials have also been sought from materials currently classified as being of fine grade (fined-grained mineral soils, tills, peat), which generally have to be treated, for example, by stabilisation, screening, crushing or pelletisation.

Industry, construction and other similar activities give rise to large quantities of different kinds of mineral wastes and by-products, some of which have already been shown to be suitable for use as recycled fills. Usage of these materials requires that they be proven to be technically suitable and environmentally friendly. The content of pollutants must be low or they must be bound to the material so that their migration into the environment is minimal.

The industrial by-products used up to now have been mainly fly and bottom ash, blast-furnace slag and some other steel and metal industry (eg. ferrous or non-ferrous) slags (Table 2). The use of crushed concrete waste began a few years ago and has since grown considerably. Some organic or predominantly organic products, e.g. shredded tyres, are already being used as recycled fills. Asphalt pavements are being recycled into materials for new pavements. Moreover, on-going research and test construction projects are seeking to clarify and improve the prerequisites for usage of several other materials.

Table 2. Industrial by-products used in earthworks in Finland and their estimated annual consumption, 1997 – 1998 (Finergy 1999, SKJ-Yhtiöt Oy 1998, Kivekäs, L. 1999, Suomen rengaskierrätys 1999, FFIF 1999).

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

* The crushing capacity in 1999, the estimated amounts of concrete waste are: 400 000 t of demolition waste, 100 000 t of construction waste, 70 000 t waste from concrete production

1.2 Experiences of the life cycle assessment of road constructions

Even though the environmental impact assessment procedures for construction materials and construction works have been developed in recent years both in Finland and in other countries, we still have rather limited experience of the life cycle assessment of road constructions. In Sweden, IVL (Institutet för Vatten- och Luftvårdsforskning) has made a provisional life cycle analysis of road construction (Stripple 1995) for the Swedish National Road Administration as well as an as yet unpublished manual for the life cycle assessment of road construction. The aim of the Swedish National Road Administration is to obtain a life cycle assessment procedure for general use. Taking account of life cycle impacts in the selection of materials has also been set as an aim in the environmental programmes of the national road administrations of Finland and Denmark (Anon 1996a, Anon 1996b).

A provisional analysis of the environmental impacts of road construction and road building materials (Koski 1995) has been made in the Finnish National Road Administration's TPPT programme (Road Pavement Research Programme). Häkkinen and Mäkelä (1996) have compared concrete and asphalt surfacings in road constructions. Cement and bitumen producers have made life cycle assessments of the production of their materials, and the life cycle data of Finnish cement is available (Häkkinen & Mäkelä 1996, Vold & Ronning 1995). Pan-European life cycle data on bitumen has been assembled in an internal industry report (Blomberg 1998) based on data produced by four production plants. The product data of individual plants can, however, differ markedly from this averaged data.

In addition, life cycle cost analyses of road constructions (Kalliokoski 1995, Ruotoistenmäki et al. 1997) have been or are being made in Finland. The aim of life cycle cost analysis is to assess and compare the total costs of different structural solutions, including all actions necessary over their entire service life. The design model, which is the goal of the latest project, is intended to take account of environmental impacts as well as the cost and traffic effects of alternative constructions. The environmental impacts will be assessed on the basis of the data generated in this study.

Industrial by-products suitable for use as recycled fills have been compared with each other or with naturally occurring raw materials in a few separate studies (Schuurmans-Stehmann 1994, Broers et al. 1994, Dartsch 1993). The issues covered by the studies included possibilities of reclaiming old road materials, the use of fosfogypsum from the fertiliser industry for road construction purposes, and the use of fly ash as a substitute materials for cement. The use of coal fly ash and a desulphurisation product in road construction has been compared with the use of conventional raw materials in connection with the test construction project carried out in Tekes's Environmental Geotechnology Programme (Eskola & Mroueh 1998).

Road constructions differ markedly from the more customary subjects of life cycle analyses. Existing life cycle models are poorly applicable to the treatment of constructions because they do not examine the structure as a whole. Changing some component or material in the construction generally has an effect elsewhere in the structure. In road construction the use of mass raw materials, land use and the possible release of pollutants into the soil have greater significance than in most other applications of life cycle assessment. The impact assessments and effect-scoring systems normally used are not necessarily the best possible, because they weight impacts which do not have as much significance in road construction as they do in other applications.

The service life of a road construction cannot be unambiguously defined because its duration is also affected by factors independent of the structure itself, e.g. community planning and infrastructural development. As the loadings caused by maintenance as well as construction are significant, a sufficiently long service life, at least 40-50 years, should be selected.

The environmental loadings caused by traffic during the service life of the road were found to be great in comparison with the loadings caused by the construction and maintenance of road structure itself. On the other hand, the loadings of traffic and road construction are weighted in different ways, so direct comparison is not completely unambiguous. If the effect of the road structure on the environmental loadings of traffic could be estimated, it might be significant with regard to energy consumption and atmospheric emissions. On the basis of current knowledge, however, the effect of alternative constructions is extremely difficult to estimate.

There are many uncertainties associated with the data available on environmental loadings and technical functionality. This is especially true in the case of by-products and other materials of which we still have little practical experience. For this reason it is important to assess the effects of uncertainties and changes of initial assumptions.

2 OBJECTIVES AND SCOPE OF THE STUDY

The basic aim of the study is to provide a clear and functional procedure for the life cycle impact assessment of road constructions and for the comparison of alternative structural solutions. The assessment procedure should take account of the special features of road constructions. It was hoped that the assessment procedure would be so simple and easy to use that in future it could also be used by planners and designers. However, the assessment should cover the main life cycle phases of the constructions as well as the most important environmental impacts, and it should also meet the other basic requirements set for life cycle analysis. The study focused especially on the comparison of industrial by-products and conventional materials in the sphere of road construction, but there was also a desire to apply the procedure to the environmental impact assessment of other constructions as well.

A comparative procedure based on effect-scoring that would complement the inventory process for road constructions was set as one aim of the study, because it was hoped to that in future the assessment procedure would also be suitable for use in connection with other planning systems, e.g. the life cycle cost analysis being developed for road constructions. These systems require that the results can be presented as simple, mutually comparable numerical values. In addition, there was a desire to simplify the assessment in cases where the user is not fully conversant with environmental impacts. Another aim was to obtain a wider view of the significance of the environmental loading data being dealt with, and thus to make it easier to set system boundaries.

The study was carried out in two stages so that in the first stage a proposal was made for a procedure suitable for the life cycle impact assessment of road construction. In order to evaluate the applicability of the procedure, the use of coal ash, crushed concrete waste and blast-furnace slag in road construction was evaluated in case studies. The use of these industrial by-products and waste materials was compared with the use of natural materials in corresponding applications. The necessary data was also collected during the studies. Excel-based formulae for each work stage were used as the inventory procedure.

The aim of the study's second stage was to transfer the assembled data for utilisation as a practical model by creating an inventory analysis program to calculate and compare the life cycle impacts of the most common road constructions. The data obtained in the first stage of the study was augmented to the extent necessary for this purpose.

3 METHODOLOGY

The methodology used in the study is life cycle assessment adapted to meet the requirements of road construction. In the life cycle assessment the material and emission flows have been determined at all stages of the life cycle, and the most important environmental impacts with regard to the goal of the study as well as their associated factors have been identified. The basic phases of the assessment are goal definition and scoping, inventory analysis, i.e. calculation of the material and emission flows, impact assessment and, if necessary, improvement assessment (Fig. 1). In this case, as the main aim is the comparison of alternative constructions, the task of assessing possible improvements has been left to the user.

The following general procedural guidelines on life cycle assessment have been applied for the most part in the study: SETAC's (Society of Environmental Toxicology and Chemistry) 'Code of Practice' (1993), Nordic Guidelines on Life-Cycle Assessment (Lindfors et al. 1995) and ISO standards (ISO 14040, ISO 14041).

An Excel-based inventory analysis program suitable for routine calculation work was created for the life cycle assessment of road construction. The program can be used to analyse constructions made from the most commonly used materials, and it can be extended to other materials as well, if desired.

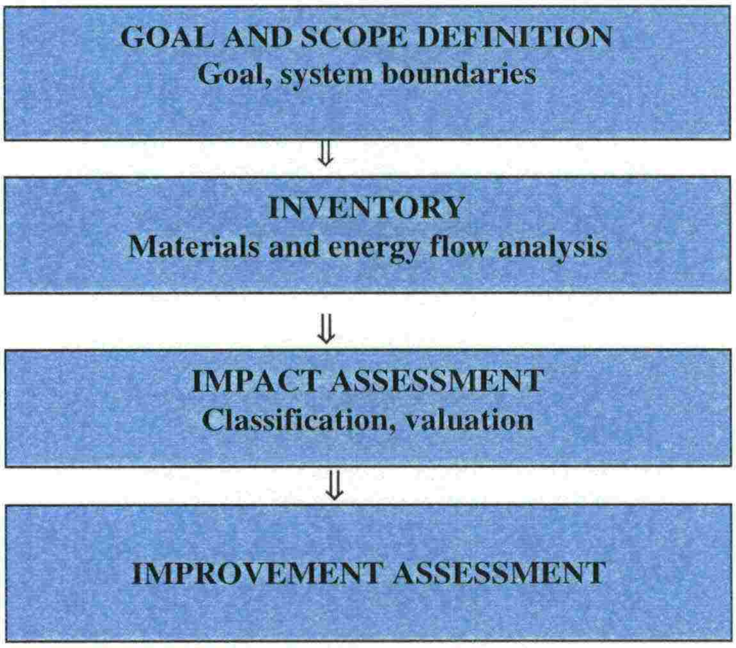

Figure 1. Main phases of a life cycle assessment (SETAC 1993).

The inventory analysis program created in the study is suitable for the routine calculation of the environmental loadings of the most common road constructions, and for their comparison. The starting points, system boundaries and data sources for the inventory are presented in sections 4–5. The inventory analysis program contains the necessary data on the following structural courses in order to calculate the life cycle impacts of road constructions:

Embankment materials:	Sand, crushed rock, blast-furnace slag
Lower sub-base:	Sand, blast-furnace slag
Sub-base:	Sub-base: fly-ash, fly ash and cement, crushed concrete, air-cooled blast-furnace slag (crushed and uncrushed), granulated blast-furnace slag, gravel, crushed aggregate
Base course:	Crushed concrete, crushed blast-furnace slag, crushed aggregate, bitumen stabilisation
Pavements:	AB16, AB20, ABK, SMA*.

* AB16 - asphalt concrete of maximum grain size 16 mm, AB20 - asphalt concrete of maximum grain size 20 mm, ABK - asphalt concrete in bound base layer, SMA - stone mastix asphalt

The environmental loadings of pavement structures can be calculated for selected materials and courses within the construction, and the results presented by principal work stage or as the total loading. The main stages for which the results can be separately presented are the masses of materials, production of materials, transport of materials, construction work, road maintenance and leaching of substances into the soil.

The inventory analysis program also includes the following alternative subgrades: soil replacement, soil stabilisation (cement and lime), deep stabilisation (cement and lime), vertical drainage + drainage course + temporary loading berm, embankment piling.

If necessary the program can be extended to include new materials, structural components and alternative subgrades. It also has a worksheet enabling the comparison of pavement structures. The environmental loadings of alternative constructions can be compared as such, in relation to a fixed reference or as effect scores. The program includes a number of standard graphical presentations.

4 SYSTEM BOUNDARIES

4.1 Functions and work stages

The analysis includes all the significant life-cycle stages covering the production and transportation of materials, their placement in the road structures and the use of the construction. The situation after the use of the construction is not included in the analysis because the structures most commonly remain in place after they have been withdrawn from service. The structure is examined as a whole because in road construction the selection of a material often influences the quality and quantity of other materials used, the work methods employed, the need for maintenance, etc.. Pavement and foundation structures are treated as separate entities, which are combined as and when necessary. This procedure facilitates the analyses in the case studies.

The environmental loading data is calculated for each individual structural component and work stage, so that it is possible to examine flexibly the alternative constructions under study at any given time. The principal road construction and usage phases on which basic data is included in the analytical model and which are taken into account when comparing structures and materials are given in Fig 2. Only the stages of production and use of the alternative construction being examined are selected for the analysis.

If industrial by-products are used in the constructions, the degree to which the environmental loadings of alternative disposal in a landfill could be reduced by using them can also be roughly estimated. This requires that landfill disposal is a real alternative to utilisation.

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

- site clearance
- functions associated with road use, e.g. road markings, the installation and use of traffic signs and lights.
- regular or seasonal maintenance, e.g. snowploughing, road salting and sanding.
- traffic emissions. In a comparison of alternative constructions, traffic emissions are only significant if it is possible to determine the effect of using a material or structure on them. As yet there is insufficient data to accomplish this.

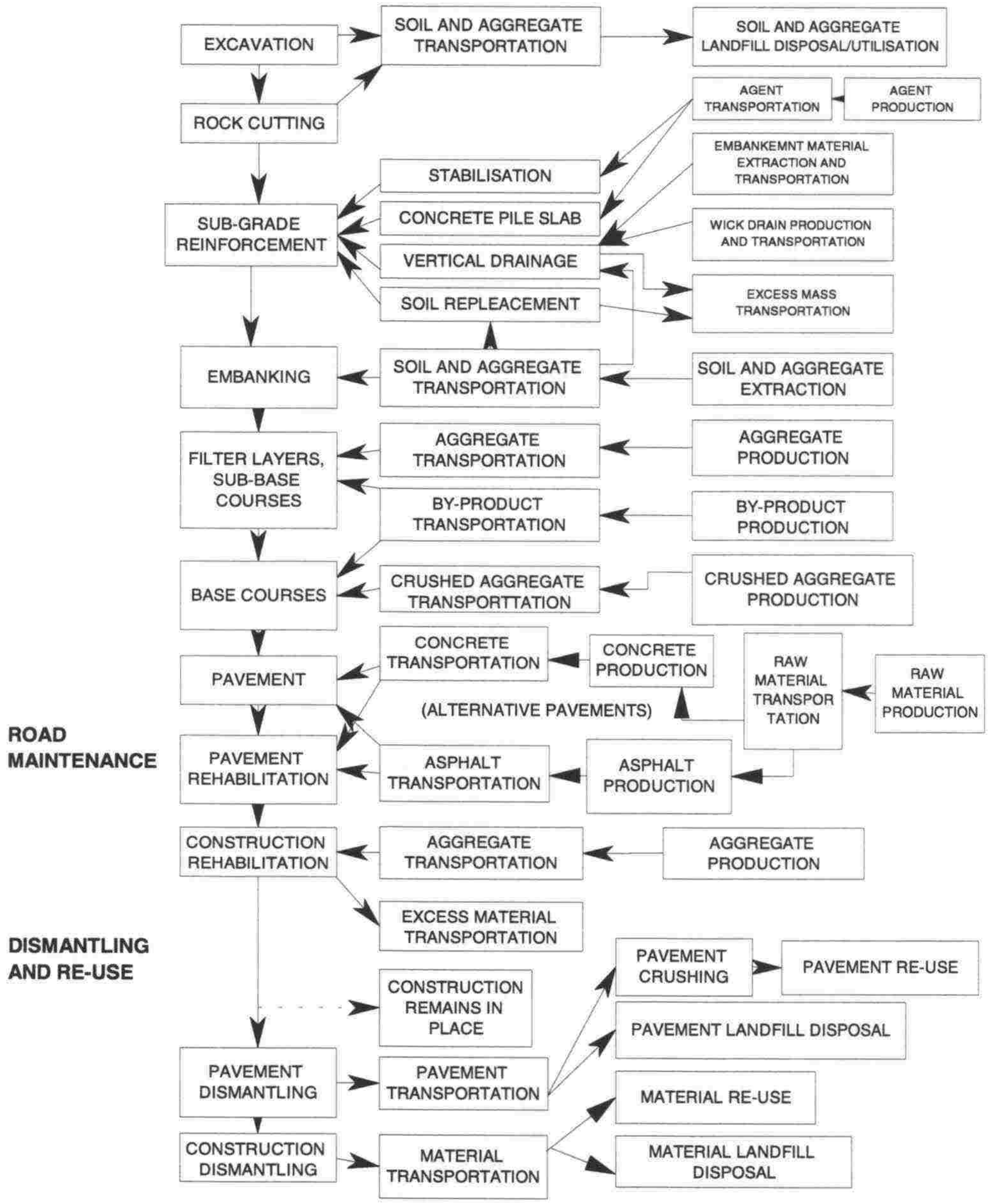

Figure 2. The principal road construction and usage phases which are taken into account when calculating environmental loadings of the structures.

4.2 Environmental loadings

The environmental loadings assessed as being essential during the life cycle of road constructions are selected on the basis of the case studies for inclusion in the analysis. The included environmental loadings, which are classified into four impact categories, are presented in Table 3.

A provisional assessment of the significance of several other environmental loading factors was also made. Some of these factors were included in the first case study. The possibilities of assessing accident risks less commonly included in life cycle assessments were also clarified, because civil engineering has traditionally been a rather accident-prone field. For example, in 1982-86 there was an average of 0.192 fatal accidents per 1 000 workers, compared with a national average of 0.045 over the same period. Dangerous tasks include excavation, asphalting, the maintenance, repair and installation of machines and equipment, and the transportation of earthmoving equipment (Reinikka 1987, Hyödynmaa & Herranen 1987). However, it was found that there is insufficient data to assess the accident risks of different work stages.

Table 3. Environmental loadings examined in the life cycle assessment of road construction.

Impact category	Environmental loading	Results, unit
Resource use	Use of natural resources	t/ construction selected*
	Industrial by-products	t/ construction selected
	Energy	kWh/construction
	Fuels**	m^3/construction
	Land use	verbal estimation of the significance of land use
Effluents to soil and waters	Leaching of metals (e.g. As, Cd, Cr, Cu, Mo, Ni, Se, Pb, Zn)***	mg/m^2 of construction selected
	Leaching or migration of organic compounds from materials***	mg/m^2 of construction selected
	Cl, SO_4***	mg/m^2 of construction selected
Emissions to air	CO_2	kg/construction selected
	NO_x	
	SO_2	
	VOC	
	CO	
	Particles	
Wastes	Inert waste	t/km
Other loadings	Noise	noise x time/km

* The entire construction or, if necessary, a specific length, e.g. one kilometre, of the construction can be selected as the functional unit. Only constructions that meet the same performance requirements and are designed for the same site are compared in the assessment.

** Fuel means diesel oil used to power machines and vehicles or oil used as a raw material in industry. Included in energy consumption, but because of its significance can also be presented separately.

*** The substances included in the analysis are selected according to the material used (significant mainly for certain industrial by-products).

Table 4 gives the impact categories that were excluded from future assessments together with estimates of the quantity and significance of emissions ruled out of the analysis.

Table 4. Impact categories excluded from the studies.

Impact category	Sub-category	
Use of resources	Water usage	Used to maintain the optimum water content of materials. The quantities of water used vary from 300 to 3 000 t/km, depending on the materials used. Water does not require any pre- or after-treatment, and the consumption of fuel caused by its use is small in comparison with the total amount.
Discharges to water	COD	Emissions occur in the manufacture of bitumen and cement, but not in the road construction process itself. The maximum emission over the life cycle of the road pavement structures examined was about 30 – 50 kg/km. There could be a significant life cycle COD discharge when large quantities of cement are used, especially from cement-stabilised subgrade structures, 200 – 1 000 kg/km.
	N to water	Emissions occur e.g. in the manufacture of bitumen and cement. The maximum life cycle emission estimated for the road constructions examined was about 1.5 kg/km.
Atmospheric emissions	Heavy metals (As, Hg, Cd, Cr, Tl, Pb, Zn)	Emissions are released when generating energy from solid fuels. The emission quantities are comparable with those released in the consumption of non-fuel energy. With the exception of mercury, they are released into the atmosphere with particulate emissions. The quantities are small but the substances are relatively hazardous. The emission factors are less reliable than those of other atmospheric emissions.
	CH_4	Emissions are released along with other hydrocarbons e.g. in connection with the use of vehicles. Greenhouse gas. The quantities released over the life cycle of a road construction are about one-thousandth of the level of carbon dioxide emissions, but the greenhouse effect is estimated to 20 – 50 times greater than that of carbon dioxide.
	PAH	Small quantities of PAH emissions are released in energy production; the emissions are significant only in small-scale combustion. PAH compounds are also present in the exhaust gases of diesel vehicles. In addition, PAH emissions are released in connection with asphalting, in which case they can pose an occupational health risk for asphalt workers. Assessing the emission quantities from asphalting is difficult as the measurements are made for occupational health purposes.
Wastes	Inert waste	Inert wastes are generated in connection with the production of limestone for use in cement manufacture and, for example, when unsuitable material has to be removed in connection with subgrade preparation.
	Ordinary waste	Packaging wastes and wastes generated in connection with the production of materials, etc. The quantities are relatively small and difficult to estimate.
	Hazardous waste	Wastes generated during the use and maintenance of vehicles, e.g. waste oil; quantities difficult to estimate.
Other impacts	Accident risks	Accident risks arise in connection with all functions and work stages. With the exception of traffic accidents caused by transportation, the availability of data on accident risks is poor.

4.3 Material production chains

The production chains of industrial by-products were limited so that the environmental loadings of the by-product production process were not included in the analysis. By-products are defined in waste legislation as wastes for which no loadings are allocated in life cycle analyses. An alternative to the use of most by-products as recycled fill is disposal of the inert waste in landfills. The production chains of natural resources begin with their extraction from the ground.

The following boundaries were imposed on the production chains of the most important materials:

Fly ash	Starting point: production plant silo. Separation of fly ash from flue gases and its transfer to the silo were excluded from the analysis.
Crushed blast-furnace slag	Starting point: stockpile into which the molten slag is poured to cool.
Granulated blast-furnace slag	Starting point: stockpile. Cooling water for the slag coming from the blast furnace was excluded from the analysis.
Crushed concrete waste	Origin: mixed concrete waste brought to the crushing plant. Transportation from the work site to the crushing plant was excluded from the analysis.
Blasted and crushed rock	Starting point: rock quarry
Sand and gravel	Starting point: sand pit
Cement	Starting point: extraction of the cement's raw materials
Lime	Starting point: extraction of raw materials
Rubber	Starting point: production of crude oil

4.4 Other boundaries

Functional unit

When comparing constructions, the functional unit should always be structures of the same length that meet the same performance requirements and are designed for the same site. Constructions designed for different sites are not compared, because they must meet different technical requirements and thus possess different performance characteristics. In the theoretical case studies, a one-kilometre-long section of the construction under study was selected as the functional unit. In practical cases the entire construction can also be the functional unit.

Period of analysis

The period of analysis should include the entire life cycle of the material or product from raw material extraction to withdrawal from service and final disposal. In the life cycle assessment of a road construction the period of analysis must be sufficiently long to include the impacts of its service life. For this reason 50 years was chosen as the period of analysis.

Machines and equipment

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

Situation after use

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

Landfill disposal

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

5 DATA QUALITY

5.1 Data sources

Because of the local nature of the effects of road constructions, primarily local or material-specific data was used. Use was also made of general Finnish knowledge, which was supplemented by international sources of data where necessary. The most important data sources are given in Table 5.

5.1.1 Production of materials

The environmental loadings of mineral aggregate and gravel production were assessed mainly on the basis of information provided by material suppliers and Finnra. The environmental loadings caused by the storage, loading and crushing of industrial by-products (crushed concrete waste, blast furnace slag, foundry sand and fly ash) were assessed on the basis of information provided by their suppliers. The emissions of electrically powered equipment were calculated using the average emission factors of Finnish power production (Pirilä et al. 1999).

5.1.2 Transportation

It was assumed that the materials used in road construction would be transported by lorry. The quantities to be transported were estimated on the basis of information provided by Finnra, other road builders and designers, and material producers. Transportation and exhaust gas emissions were estimated using the emission factors of Mäkelä et al. (1996).

5.1.3 Road construction

The masses, volumes and weights per unit volume of road paving materials during storage and transportation were calculated on the basis of information provided by Finnra, material suppliers and TS data cards.

The operating times of work machines were calculated on the basis of TS data cards. The energy consumption and emissions of machines were calculated on the basis of the emission factors proposed by Puranen (1992).

Table 5. Principal data sources used to calculate the environmental loadings of the road structures.

Work stage	Data source
Storing and loading of fly ash	Helsinki Energy (Oasmaa 1996)
Transport of fly ash and its placement into road constructions	Lohja Rudus (Rämö 1997)
Landfill disposal of fly ash	Helsingin Energia (Oasmaa 1996) Blomster 1989 City of Vantaa (Markkanen 1996) City of Helsinki (Arovaara 1996)
Blasting of rock	Lemminkäinen (Ruostetoja 1996)
Excavation of sand and gravel	Lohja Rudus (Rasimus 1996)
Crushing of aggregate	Lemminkäinen (Ruostetoja 1996) Finnra 1994 Finnra 1995
Transport of aggregate	Lohja Rudus (Rasimus 1998)
Road construction	RIL 156 1995
Blast furnace slag	SKJ-Yhtiöt (Mäkikyrö 1998)
Crushed concrete	Lohja Rudus (Määttänen 1998)
Cement	Häkkinen and Mäkelä 1996 Finncement (Lundström 1998)
Asphalt	Häkkinen and Mäkelä 1996 IVL (Stripple 1995)
Concrete	Häkkinen and Mäkelä 1996 Lohja Rudus Oy (Kostiainen 1999)
Lime	Häkkinen and Mäkelä 1996
Lumber	Häkkinen et al. 1997
Reinforcing steel	Häkkinen and Mäkelä 1996
Repaving	Finnra (Komulainen 1998)
Remixing	Finnira (Eerola 1998) Design of pavements/ Finnra 1997 Elg-yhtiöt (Elg 1998) JJ-Asfaltti Oy (Karvonen 1998) Valtatie Oy (Mannonen 1998) VTT Chemical Technology (Siltanen 1998)
Tack-coating	VTT Building Technology (Apilo 1998)
Deep stabilisation	Betoni-Tekra Oy (Pietikäinen 1999) Junttan Oy (Sohlman 1998)
Vertical drainage	Kaitos Oy 1998 Geotechnics Holland BV 1998 Containerships 1998
Leaching of impurities	VTT Chem. Technology (Wahlström et al. 1999)

5.1.4 Road reconstruction

Road reconstruction is assumed to concern only the wearing course and to occur at specific intervals as resurfacing and remixer stabilisation works. The user of the inventory analysis program can select the number of reconstruction measures on a case-by-case basis. The data used in calculating the environmental loadings of road reconstruction comes from Finnra and firms carrying out road reconstruction works.

5.1.5 Leaching

The quantities of substances leaching out of materials and migrating into the soil during placement were estimated primarily on the basis of leaching studies carried out by the Technical Research Centre of Finland. The research method was primarily the CEN high-speed shaking test (pr EN 12457). The solubility of natural materials has not been studied in Finland. Moreover, foreign data comparable with data obtained by the solubility research methods used in Finland have only been available from a couple of narrow studies. For this reason the solubilities of foundry sand and a few of the natural mineral aggregates used in road construction were tested in connection with the study (Appendix 1).

The following data was used to estimate the quantities of soluble substances:

Fly ash	The average solubility of coal fly ash was calculated on the basis of tests performed by VTT on fly ash from several different coal-fired plants.
Crushed concrete waste	VTT (Wahlström & Laine-Ylijoki 1996)
Blast-furnace slag and foundry sand	VTT (Appendix 1)
Natural aggregates	VTT (Appendix 1)

5.1.6 Land use

Land use is an environmental loading that essentially belongs to road construction. The development of land use assessment methods is problematic, because the consequences of land use exist on many levels and it may not be possible to identify them precisely. Moreover, the effects are often dictated by local and site-specific factors. It has not been possible to develop a simple calculation and assessment method that would be both applicable to different types of sites and capable of translating the effects of land use into a mutually comparable form.

The most important factor in road construction is generally the surface area beneath the structure itself. However, the significance of this should, in the first instance, be assessed as a part of community planning. The extraction, processing (e.g. crushing) and storage of raw materials and, for instance, the land surface area that would have been required for landfill disposal as an alternative to the utilisation of by-products are more important in the comparison of constructions.

The applicability of land use assessment methods proposed in the literature was assessed in connection with the study, but it was found that the development of assessment criteria suitable for comparative purposes would require wider study (Laine-Ylijoki et al. 1999). In the future the assessment criteria could be based, for example, on effect scoring or on a weighted analysis of material-specific land use.

5.2 Data deficiencies and uncertainties

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

It is necessary to make many assumptions when calculating the operating times of work machines, because the work stages can be carried out in many different ways using machines of different ages and efficiencies. It was assumed in the calculations that the machines were of average efficiency and used in normal summer conditions.

The release of dust emissions from materials during the different stages of production, transportation and construction is a significant environmental loading factor due to the comfort and heath risks that they pose. However, little measurement data on the release of dust emissions was found and its conversion into a comparable form was problematic. No data on dust emissions during the transportation of mineral aggregates and ash was found. Also with regard to the release of dust emissions during construction, data on only some materials was found. The estimated quantities of dust emissions can be regarded as a best guess.

In practice, small particulate matter (SPM) can be more significant than the total amount particles. SPM emissions remain airborne for a very long time and are carried long distances by winds. Moreover, they pose a more serious health risk than bigger dust particles. Because SPM emissions have attracted attention only recently, there is even less data available on them than on total emissions of particles. For example, fly ash, which is extremely dusty when dry, contains particles smaller than 2.5 µm (approx. 5%) and particles smaller than 10 µm (10–20 %) (Sloss 1996). It was not possible to assess SPM emissions due to the lack of data.

The quantities of substances leaching out of recycled fills are simulated on the basis of laboratory-scale leaching tests. In practice, numerous factors, e.g. the condition of the structure and its surface as well as environmental conditions affect leaching from construction materials. There can also be significant differences between the same material when produced under different conditions. For example, the quantities of pollutants leaching out of fly ash can vary considerably, depending on the quality of the coal and the combustion conditions. There is little leaching data on natural mineral aggregates. The quantities of impurities leaching from most mineral aggregates are probably small, but regional and site-specific variations can occur in minerals.

6 CASE STUDIES

In the first stage of the study the use of conventional materials and industrial by-products were compared in a theoretical road construction (Eskola et al 1999). The alternative pavements and subgrades were examined separately.

6.1 Alternative constructions

6.1.1 Pavement structures

The pavement structures were designed on the basis of the following assumptions:

- The structural courses are laid directly on the subgrade after removal of the topsoil. The subgrade is frost-susceptible sand till.
- The structure to be studied is main road cross-section IN-10.5/7.5. The dimensions of the cross-section are presented in Figure 3. The target bearing capacity of the structure (pavement structure class 1 AB) on top of the pavement is 420 MPa.
- The frost conditions are assumed to be of medium severity and the design freezing index 30 000 h°C. According to Finnra's design code, the combined thickness of the courses should be at least 900 mm in such conditions.
- The loading design of the case study constructions is done as conventional bearing capacity design.

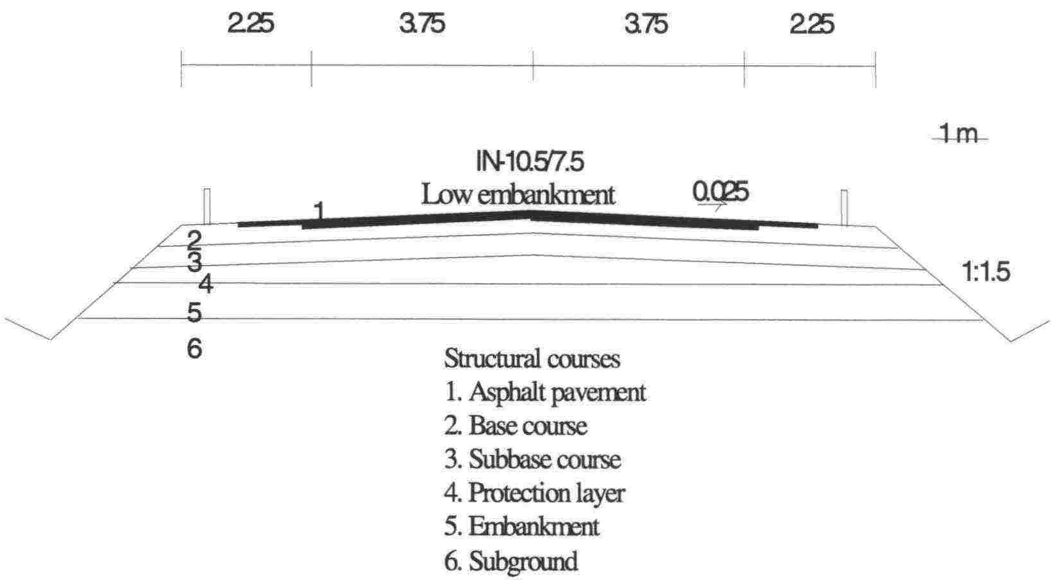

Figure 3. Dimensions of the cross-section selected for analysis and the structural courses on a low embankment.

Table 6. Structural courses of the case study constructions and the materials used in them. The constructions and the abbreviations hereafter used to denote them were as follows:

Natural aggregate – *reference construction built solely out of natural mineral aggregate, R1*
Ash 1 – *fly ash construction, FA1*
Ash2 – *fly ash construction comparable with other constructions in terms of pavement thickness, FA2*
Ash3 – *fly ash construction 2 without cement, FA3*
Concrete1 – *crushed concrete construction, CC1*
Concrete2 – *crushed concrete construction in which the pavement thickness is reduced by using thicker crushed concrete courses than in Concrete 1, CC2*
Blast-furnace slag – *construction in which crushed blast-furnace slag and sand are used, BFS.*

Structural layer	**Natural aggregate**	**Ash1**	**Ash2**	**Ash3**
Pavement	160 mm AB 20/120	50 mm AB 16	160 mm AB 20/120	160 mm AB 20/120
Base course	250 mm Crushed stone 0-35	150 mm Crushed stone 0-35 BST	150 mm Crushed stone 0-35	150 mm Crushed stone 0-35
Sub-base	250 mm Gravel	650 mm Fly ash + cement 2%	350 mm Fly ash + cement 2 %	350 mm Fly ash
Lower sub-base	250 mm Sand	200 mm Sand	200 mm Sand	200 mm Sand
Total thickness	**960**	**1050**	**860**	**860**
Embankment	500 mm Sand	500 mm Sand	500 mm Sand	500 mm Sand

Structural layer	**Concrete1**	**Concrete2**	**Blast-furnace slag**
Pavement	160 mm AB 20/120	80 mm AB 20/120	160 mm AB 20/120
Base course	100 mm Crushed concrete 0-50	200 mm Crushed concrete 0 - 50	100 mm Crushed blast-furnace slag
Sub-base	350 mm Crushed concrete	200 mm Crushed concrete	250 mm Granulated blast-furnace slag
Lower sub-base	550 mm Sand	450 mm Sand	200 mm Granulated blast-furnace slag
Total thickness	**960**	**930**	**860**
Embankment	500 mm Sand	500 mm Sand	500 mm Sand

The life cycle environmental loadings were calculated for the case study constructions listed in Table 6. Because the same structural requirements can be met using different structural solutions, two different alternatives in terms of pavement thickness are presented for the fly ash and crushed concrete constructions. In addition, a fly ash construction in which cement was not used as a mix additive was inventoried. With the aid of alternative by-product constructions it was possible to assess the effects of the pavement course thickness and the use of cement on the life cycle environmental loadings.

6.1.2 Subgrades

In the alternative subgrades examined, the natural ground was assumed to be weakly bearing and compressible soft clay extending to a depth of 5 metres. The ground beneath the clay is bearing. Constructions most commonly used on shallow and deep layers of weak soil were examined as alternatives. To make comparisons easier, the depth of weak soil was assumed to be the same in all the constructions. The alternatives were as follows:

Shallow layer of weak soil:	Soil replacement	Removal of the weakly bearing material and replacement by sufficiently bearing fill.
	Soil stabilisation	Stabilisation of the clay layer using cement (100 kg/m^3)
Deep layer of weak soil:	Deep stabilisation	Deep stabilisation using cement (120 kg/m^3)
	Vertical drainage	Vertical strip drains at 1-metre intervals

6.1.3 Landfill disposal

Landfill disposal was examined as an alternative to the utilisation of fly ash and crushed concrete waste. In these case studies it was assumed that the fly ash would be disposed of in basin structures made of blasted rock using the so-called sandwich method. It was assumed that the crushed concrete waste would be disposed of as such in the landfill. The thickness of the landfill layer was assumed to be 10 metres.

6.2 System boundaries

The system boundaries were as described in section 4. The functional unit selected for the case studies was a one-kilometre-long section of road, the structural design of which is given in Figure 3. With regard to the subgrades, the functional unit was 17 metres wide, 5 metres deep and 1 kilometre long. In the landfill disposal alternative the functional unit was the quantity of by-product used in the alternative road construction.

Average distances from Helsinki Metropolitan Area to sources of sand, gravel, crushed rock and fly ash were used as the transport distances. Average transport distances in Finland were used for other raw materials. The transport distances were as follows:

Crushed rock	10 km
Crushed concrete	10 km
Sand and gravel	50 km
Cement	100 km
Fly ash	10 km
Asphalt	10 km
Blast-furnace slag	50 km

Road maintenance was assumed to take place in accordance with the average Finnish road maintenance strategy (Häkkinen & Mäkelä 1996). In these theoretical case studies it was not possible to determine the effect of the structure and structural materials on road maintenance, and thus the calculations were limited to only one maintenance alternative, which describes the contribution of road maintenance to the total life cycle loadings of the construction.

6.3 Environmental loadings of pavement structures

The environmental loadings were calculated for each alternative construction by work stage on the basis of the material quantities used in the structure and the environmental loadings of each stage. The construction work stages of the main structural types examined when calculating the environmental loadings of the pavement structures are given in the charts of Appendix 2.

6.3.1 Consumption of raw materials

The consumption of natural materials, the by-product quantities and the consumption of water in the alternative pavement structures are given in Figure 4. The consumption of raw materials in the landfill alternative for the fly ash and crushed concrete waste was also calculated in these case studies. In the by-product constructions the consumption of natural materials is primarily influenced by the extent to which different materials of the structural courses can be replaced by recycled fill. The differences between the alternative constructions are reduced by the fact that a 0.5-metre sand embankment and asphalt pavement are assumed in all the constructions. The need for water is greatest in the fly ash constructions because fly ash has to be wetted before laying to obtain the optimum moisture content in the fly ash mix.

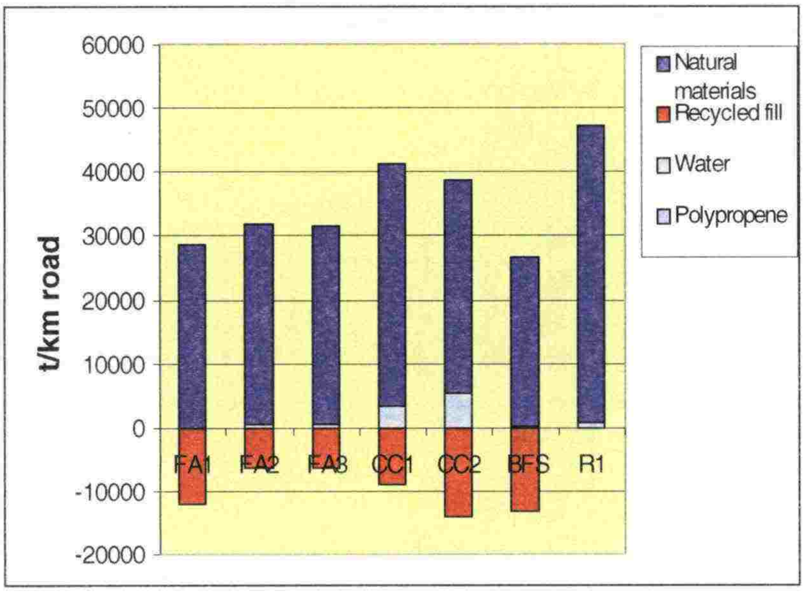

Figure 4. Consumption of raw materials in the pavement structures: FA1 – FA3 – fly ash constructions, CC1 and CC2 – crushed concrete constructions, BFS – blast furnace slag construction, R1 – natural aggregate construction.

6.3.2 Consumption of energy and fuels

The energy consumption of the alternative constructions by main work stage is presented in figure 5.

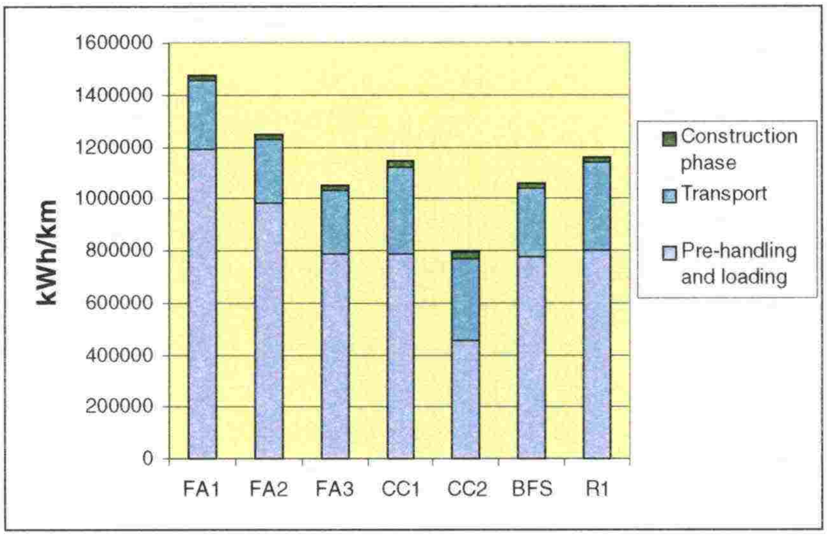

Figure 5. Energy consumption of the alternative structures.

Energy consumption includes the energy used by machines, vehicles and raw material manufacturing processes as well as the internal energy of organic materials. The fuel aspect of total energy consumption, which includes the use of diesel and fuel oil, is calculated separately. Construction machines and transport equipment were assumed to be powered by diesel oil. The energy consumption and exhaust gas emissions of work machines were calculated on the basis of the machines' operating times using the emission factors of Puranen (1992). Emission quantities were assessed on the basis of the work done by the machines, i.e. on the energy (E) consumed by them.

Most of the energy is consumed in the pre-handling and loading phases, which include the heavily energy-consuming manufacture of cement and asphalt. In the FA1 construction, for example, asphalt accounts for 57% of energy consumption, the manufacture of cement for 25%, and everything else for only 18%. In the reference construction, asphalt account for 67% and everything else for 33%. Thus the fly ash constructions containing cement (FA1 and FA2) have the highest total energy consumption, and the crushed concrete construction with a relatively thin asphalt pavement (CC2) has the lowest. Fuel consumption breaks down in approximately the same way as energy consumption, of which it forms a large part.

6.3.3 Atmospheric emissions

Exhaust and flue gas emissions

The atmospheric emissions of the alternatives expressed as kilograms per functional unit are presented in Figure 6. Because, with the exception of some process emissions, the atmospheric emissions originate from the consumption of fuels, they break down among the alternative constructions, structural materials and work stages in the same way as energy consumption. The emissions of all the alternative pavement structures are of the same order of magnitude. The fly ash constructions containing cement (FA1 and FA2) have the highest emissions. The reference construction has the next highest emissions. The emissions of the landfill disposal alternatives are about one tenth of the corresponding road constructions.

Dust emissions

The dust emissions of material handling and processing are calculated separate from exhaust gas and process-generated particulate emissions, because there are significantly greater uncertainties associated with the calculation of dust emissions. Dust is released in all of the mineral aggregate and by-product handling and processing stages, e.g. quarrying of aggregate, crushing, loading and transportation of materials, unloading of materials into heaps or directly into the construction. Transport vehicles also cause dust from the ground or asphalt to become airborne. Finely divided materials such as fly ash are particularly dusty. However, dust emissions from all materials can be reduced by wetting prior to handling and by using different kinds of dust separators, covers and sealed containers (Matilainen 1986).

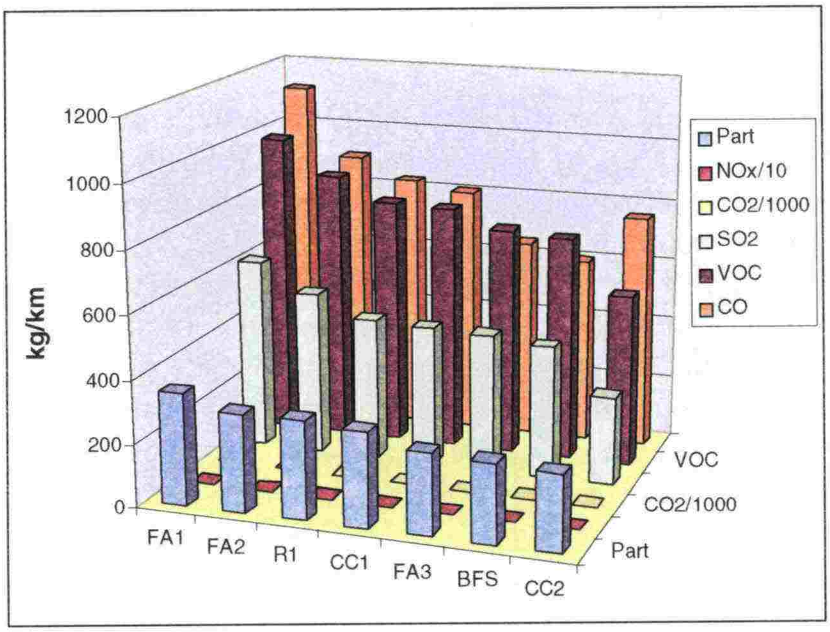

Figure 6. Atmospheric emissions of the alternative constructions.

It turned out to be difficult to assess the dust emissions of the work stages because the data available on dust emissions was scant and its reliability was found in most cases to be poor. For example, it was hardly possible at all to take account of fly ash dust emissions. Dust emission data obtained by work stage as well as those work stages in respect of which no dust emission data was found are presented in Table 7. Of the various work stages, the crushing, transportation and loading of materials caused the highest dust emissions. The principal dust emissions of the alternative pavement structures (excluding particulate emissions from traffic and energy production) are presented in Table 8.

Table 7. Dust emissions (Himanen et al. 1989, Muleski et al. 1986, EPA 1988).

Work stage	Dust emission	Particle size
Quarrying/drilling	0.4 g/t bedrock 0.04 g/t bedrock	<30 μm <10 μm
Quarrying/blasting	n.a	
Gravel and sand excavation	n.a	
Crushing of aggregate	1.21 kg/t	<30 μm
Storage of mineral materials in silos or heaps	n.a	
Loading with excavator	29 g/t	<30 μm
Transportation of aggregate in lorries	36.1 g/km (road) 8.6 g/km (street)	2–40 μm 2–40 μm
Unloading aggregate from lorries	0.17 g/t	<30 μm
Transfer of aggregate on a conveyor belt	0.17 g/t	<30 μm
Storage of fly ash (mixtures) in silos or heaps	n.a	
Loading of fly ash (mixtures)	2 g/t	<30 μm
Transportation of fly ash	n.a	
Road construction using conventional aggregates	n.a	
Road construction using fly ash	Information available 'only' from monitoring of suspended particles	

Table 8. Principal dust emissions (kg/functional unit) in the alternative structures.

	FA1	FA2, FA3	CC1	CC2	BFS	R1
Crushing	-	5 400	-	-	-	9 200
Loading	720	940	990	900	500	1 500
Transport	2 300	2 200	3 200	2 900	2 600	3 300

6.3.4 Substances leaching into the soil

Water-soluble substances present in the materials can be carried away by run-off water into the environment of the site and from there into the groundwater. The amount of leaching depends on the composition of the material, the amount of water passing through the material, and the manner in which it is laid. Covering with a material possessing poor water permeability, e.g. asphalt or even moisture barriers, reduces the amount of water filtering through the structure. Leaching may also be reduced by consolidation of the finished structure (Ranta *et al.* 1987).

The amount of leaching cannot be assessed solely on the basis of compositional data, because the solvency of metals, and also damage to the environment, depends on the kind of compounds in which the metals are present. Laboratory-scale leaching tests are used as the research method. The quantity of pollutant leaching out of the construction over a certain time period can be assessed on the basis of the test results by calculating the amount of water passing through the construction in proportion to the quantity of material (the so-called L/S ratio) The leaching from the material corresponds to the amount dissolved in the leaching tests at the same L/S ratio. The formula and assumptions used in the calculation are presented in Appendix 1.

Some foreign solubility data were used in the case studies, but this was replaced in later calculations by Finnish data. Sulphates, calcium, chlorides and, of the heavy metals, molybdenum, chromium and vanadium leach the most out of the fly ash. There is some leaching of sulphates and chromium from the crushed concrete. Vanadium leaches out of blast-furnace slag, and there is some leaching of sulphate compounds due to the effect of short-term washout from the structures' top surfaces. Lack of data meant that it was not possible to take account of the substances leaching out the natural materials and cement nor the solubility-reducing effect of cement pollutants.

Table 9. Pollutants leaching out of the alternative constructions compared with the maximum permitted emission from materials/square metre over a hundred years used in VTT's assessment of applicability of materials.

Substance	Ash FA1	Ash FA2 / FA3	Concrete CC1	Concrete CC2	B-F slag BFS	Dutch ref. value
Sulphate, mg/m²	692 000	446 000	546 000	761 000		2 225 000
Chloride, mg/m²	84 600	44 600	13 800	20 800		1 500 000
Arsenic, mg/m²	84	69			<0.1	435
Barium, mg/m²	7.7	7.7				6 300
Cadmium, mg/m²	0.06	0.05			0.4	12
Chrome, mg/m²	250	140	92	131	<0.1	1 500
Copper, mg/m²	4.4	2.7	51	65	<1	540
Mercury, mg/m²	0.3	0.2				4,5
Molybdenum, mg/m²	1 260	1 260			<0.1	1 140*
Nickel, mg/m²	19	12			<0.1	525
Lead, mg/m²	0.15	0.15			4	1 275
Selenium, mg/m²	45	28				15
Vanadium, mg/m²	615	615			5	2 400
Zinc, mg/m²	3	2			<10	2 100

The quantities of substances leaching out of the constructions containing by-products were calculated per functional unit and product kilogram during the first 50 years. The quantities of pollutants leaching out of the alternative constructions are compared in Table 9 with the maximum permitted emission from materials per square metre over a hundred years, which serves as the basis of the Dutch design values used in VTT's assessment of the applicability of materials (Besluiten 1995). The reference value is defined so that the pollutant content in a one-metre-thick reference soil layer beneath the construction may rise by a maximum of one per cent over a hundred years. Only the quantities of substances leaching out of by-products are presented in the table. The data on the solubility of natural materials used in VTT's studies and in the study of Kälvesten (1996) are presented in Appendix 1.

6.3.5 Noise

Noise emissions are usually reported as a sound level, i.e. as the A-weighted sound pressure level (L_{pA}), which is defined as: $L_{pA} = 20\ \lg(p_A/p_0)$, where p_A is the A-weighted sound pressure and p_0 the reference pressure (=µ20 Pa). The sound level unit is the decibel (dBA). Design values are given for the noise level in a Council of State Decision 1992/93.

The detrimentality of noise is usually assessed in relation to the closest susceptible point to the disturbance, or the distance from the disturbance at which the above-mentioned design noise values are satisfied is calculated. Noise levels of work machines and stages at a distance of 7 metres from the source are presented in Table 10 (Matilainen 1986, Naturvårdsverket 1983).

Table 10. Noise levels of work machines and stages at a distance of 7 metres from the source.

Machine	Noise level dBA	Average noise level (dBA)
Drilling rig	98–101	100
Blasting	125–136	130
Hydraulic hammer	87–92	90
Conveyor belt	84	84
Crushing plant	100	100
Hydraulic excavator	82–100	89
Earth-moving machine	91	91
Lorry	84	84
Bulldozer	80–89	84
Road roller	84–101	92
Asphalt layer	74–89	81
Road grader	85–89	87

It was not possible in this study to determine the total noise of the alternatives because the work stages occur in different places and the work machines are used at different times and for periods of different lengths. However, the alternatives were compared as follows: the noise level of each work stage was reported as the work time at which the so-called noise time (dBA • h) for each work stage was achieved. The noise times for each structural course were combined and these results were compared with each other. It was assumed that the work stages take place successively. The results are presented in Figure 7.

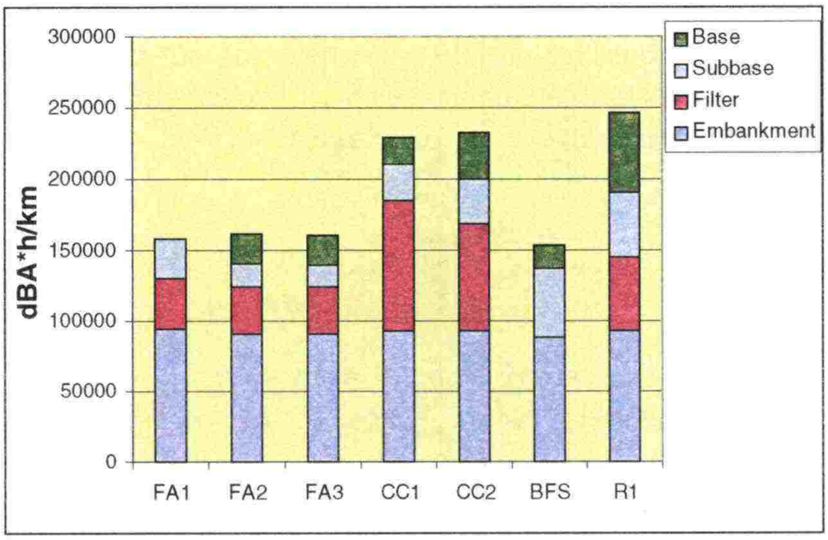

Figure 7. Noise times by structural course in the road t construction alternatives.

6.3.6 Loadings caused by road maintenance

The environmental loadings caused by road maintenance over a period of 50 years were assessed on the basis of the report by Häkkinen and Mäkelä (1996). Road maintenance was assumed to take place in accordance with the Finnish road maintenance strategy (Häkkinen & Mäkelä 1996, Appendix 3) and the loadings were calculated by proportioning them to the road width. This approximate estimate of the environmental loadings of road maintenance is presented in Table 11. The program has subsequently been improved to allow the roadkeeping strategy to be defined and for the environmental loadings of road maintenance to be calculated accordingly.

Table 11. Environmental loadings caused by road maintenance over a period of 50 years compared with the loadings caused by road construction.

Loadings	Maintenance	Construction	Share of road maintenance from total loadings of road construction
CO_2 (kg/km)	33 900	263 000–562 000	6–3 %
SO_2 (kg/km)	4.1	280–610	0.7–1.5 %
NO_x (kg/km)	140	2 600–3 800	3.7–5.4 %
CO (kg/km)	20	600–1 100	1.8–3.3 %
VOC (kg/km)	210	550–980	21–38 %
Fuel consumption (l/km)	18 200	63 000–100 000	18–29 %
Energy consumption (kWh/km)	183 300	790 000–1 470 000	12–23 %

6.3.7 Land use

Land use can cause very different consequences for the landscape, soil, waters, fauna and flora. Road construction affects both the landscape and living environment of people and animals. The excavation of sand and gravel damages the soil and alters the landscape. These excavations have impacts not only on the soil, waters, flora and fauna but also on the recreational usage of the areas concerned. The crushing of aggregate causes changes in the structure and potential use of land, as local ground materials are removed and deposited elsewhere. Landscape changes and the destruction of aesthetically valuable rocky areas are also a consequence of rock blasting and crushing (Kylä-Setälä & Assmuth 1996).

In road construction the most significant factor for land use is the surface area of land beneath the structure, which in the constructions of the case studies is 20 000 m^2/km. The protected zones on either side of the road also require one and half times the surface area of the road itself. It is difficult to estimate the land use required by the excavation of sand and gravel in the theoretical case studies, because in practice some of the mineral aggregate comes from road construction sites, and some from elsewhere. Moreover, gravel excavation sites and the possibilities to obtain gravel vary greatly.

In the case study alternatives only the material-specific need for landfill space was assessed. Assuming that the masses are disposed of in a ten-metre-thick layer, the need for landfill space is as follows: FA1L 1 200 m^2/unit, FA2L 640 m^2/unit, CC1L 350 m^2/unit and CC2L 570 m^2/unit.

6.3.8 Comparison of environmental loadings

The environmental loadings of the alternative pavement structures are compared in Table 12 and Figure 8. For comparison, Table 12 also shows the traffic emissions over a period of 50 years, assuming a traffic volume of 7,000 vehicles per day, of which 1,000 are heavy vehicles.

The table and figure clearly shows that there are differences between the environmental loadings of the pavement structures in the case studies, but the differences are not generally very great. Because the constructions are examined as a whole, the use of asphalt accounts for a relatively large proportion of energy consumption and atmospheric emissions. This evens out the differences between the constructions with regard to these loadings. The same type of levelling effect is also evident in the other loadings.

Table 12. Comparison of environmental loadings of the alternative pavement structures. For comparison also estimated traffic emissions over a period of 50 years are shown.

Effect category	Unit	FA1	FA2	FA3	CC1	CC2	BFS	R1	Traffic
Raw materials	t/km road								
-natural aggregate		28 700	31 200	31 000	37 800	33 200	20 000	46 300	
-by-products		12 000	6 410	6 410	8 860	14 100	13 100	-	
Total		40 700	37 600	37 400	46 650	47 350	33 060	46 300	
Water	t/km road	-	450	450	340	540	250	760	
Fuel consumption	m³/km	100	83	65	76	63	63	80	12 700
Energy consumption	MWh/ km	1 470	1 250	1 050	1 150	793	1 060	1 160	120 200
Emissions									
-CO	kg/km	1 120	900	650	800	760	600	830	459 000
-NO_x	kg/km	3 800	3 400	2 900	3 300	2 600	2 800	3440	354 000
-particles	kg/km	360	310	260	300	250	260	315	22 000
-SO_2	kg/km	610	530	440	450	280	425	460	4 000
-CO_2	t/km	562	449	346	373	263	338	380	31 500
-VOC	kg/km	980	870	740	790	550	720	800	86 000
-dust (2–40 µm)	kg/km	3 020	8 540	8 540	4 200	3 800	3 100	14 000	
Leaching to soil	kg/km								
-sulphate		9 000	5 800	5 800	7 100	9 900	n.a		
-chloride		1 100	580	580	180	270	n.a.		
-molybdenum		29	17	17	n.a	n.a			
-vanadium		8	8	8	n.a	n.a	<0.013		
-chrome		3.2	1.7	1.7	1.2	1.7	<0.013		
-copper		0.057	0,035	0.035	0.66	0.85	0.052		
-aluminium		n.a.	n.a.	n.a.	0.097	0.11	n.a.		
-cadmium		0.0009	0,0006	0.0006	n.a	n.a	0.0052		
Land use									
Noise	dBA•h •1 000	158	161	160	229	232	153	246	

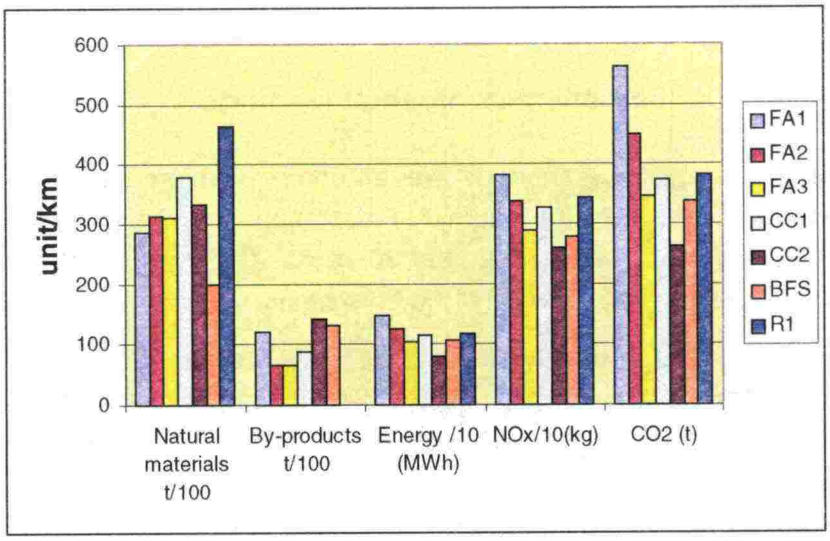

Figure 8. Comparison of selected environmental loadings of alternative pavement structures.

When comparing the environmental loadings, it must be remembered that we are dealing with theoretical constructions in these case studies. In real situations the calculation must always been made for each individual construction. For example, a change in the thickness of the asphalt course, the use of unpaved structures or the use of cement has a significant effect on the total loadings and also on the differences between the constructions. The difference between the FA2 and FA3 fly ash constructions illustrates the effect of using a relatively small amount of cement (2 % of the material used in a 350 mm thick sub-base) on energy consumption and emissions.

6.4 Environmental loadings of the alternative foundation engineering methods

The consumption of raw materials in the alternative subgrades and the quantities of soil masses to be replaced are presented in Table 13. The sand needed for vertical drainage of the temporary loading berm can be used later in the pavement structure.

Table 13. Consumption of raw materials and removed soil masses per functional unit in the alternative foundation engineering methods.

	Massive soil stabilisation, t/km	Soil replacement, t/km	Deep stabilisation, t/km	Vertical drainage
Cement	8 500	-	2 860	-
- limestone [1]	10 200		3 400	
- clay [1]	3 400		1 140	
Sand till	-	170 000	-	-
Sand (can be used in pavement structure)	-	-	-	78 750 t/km (temporary loading berm)
Vertical strip drains	-	-	-	85 000 m/km
Polypropylene[2]	-	-	-	5 780 kg/km
Clay (to landfill)	-	127 500	-	-

[1] raw material for cement [2] raw material for the vertical strip drains

A summary of the environmental loadings of the alternative foundation engineering methods is presented in Table 14 and Figure 9. Energy consumption and atmospheric emissions are high in the soil stabilisation and deep stabilisation alternatives, in which plenty of cement is used. Compared with the alternative pavement structures, the energy consumption of soil stabilisation and deep stabilisation are greater by factors of about 10 and 4, respectively.

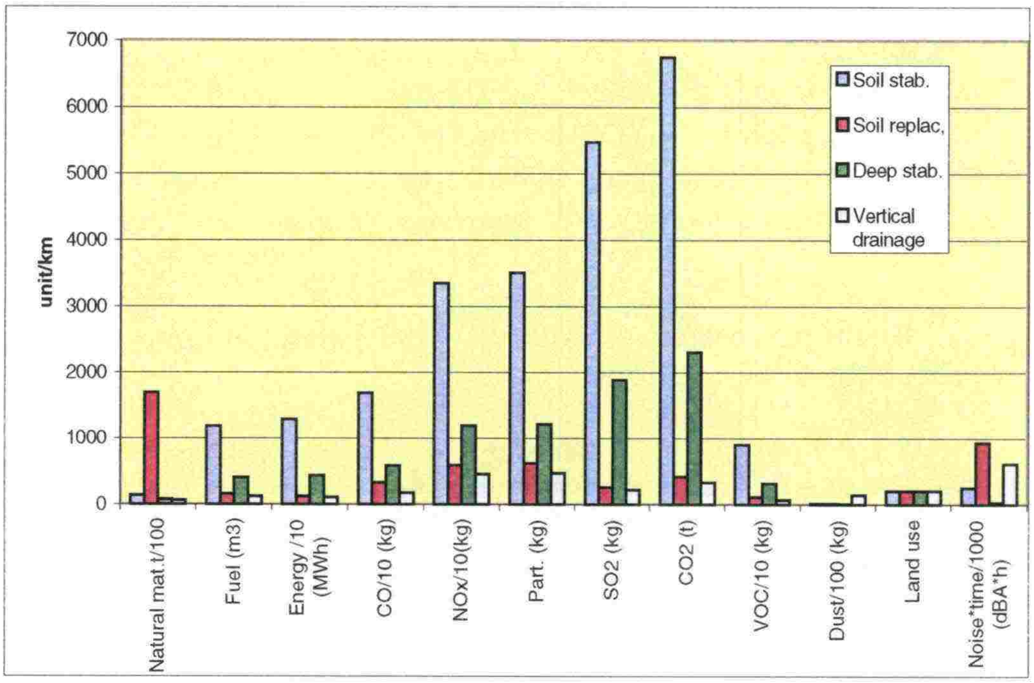

Figure 9. Environmental loadings of the alternative ground improvement and foundation engineering methods.

7 ENVIRONMENTAL IMPACT ASSESSMENT

7.1 Uncertainties of the results

Because it is necessary to make many assumptions when assessing the environmental loadings, the uncertainties and ranges of the results are quite large. However, the fact that the same assumptions have been made when examining the various alternatives improves the reliability of the results. For example, machines of the same sizes and transportation distances of the same lengths have been used. For this reason the assumptions made have a greater effect on the absolute values of the results than on the outcome of the comparisons.

The effect of using cement and asphalt on total emissions can be assessed on the basis of the alternative constructions in the case studies, for instance by comparing the FA2 fly ash construction containing cement with the otherwise similar FA3 construction without cement. The difference between the CC1 construction (160 mm of asphalt) and the CC2 construction (80 mm of asphalt) illustrates the effect of the asphalt course. The constructions are not absolutely the same in other respects, but the differences in energy consumption and atmospheric emissions are mainly caused by the differences in the thickness of the asphalt pavement.

The effect of transport distances on the energy consumption and emissions of the FA3 fly ash construction is examined in Figure 10. The quantities of different materials contained in the FA3 construction are as follows:

Fly ash	6 540 t/km
Sand	22 940 t/km
Crushed aggregate	4 480 t/km
Asphalt	3 600 t/km.

Lengthening the transport distance of fly ash from 10 km to 50 km increases the loadings by 0.5–8 %. Shortening the transport distance of sand to 10 km reduces fuel consumption by 23% and energy consumption by 14%. CO emissions are reduced by 24%, SPM emissions by 21%, NO_x emissions by 18%, CO_2 emissions by 11% and VOC emissions by 7%. The transport distance of sand has hardly any effect on SO_2 emissions.

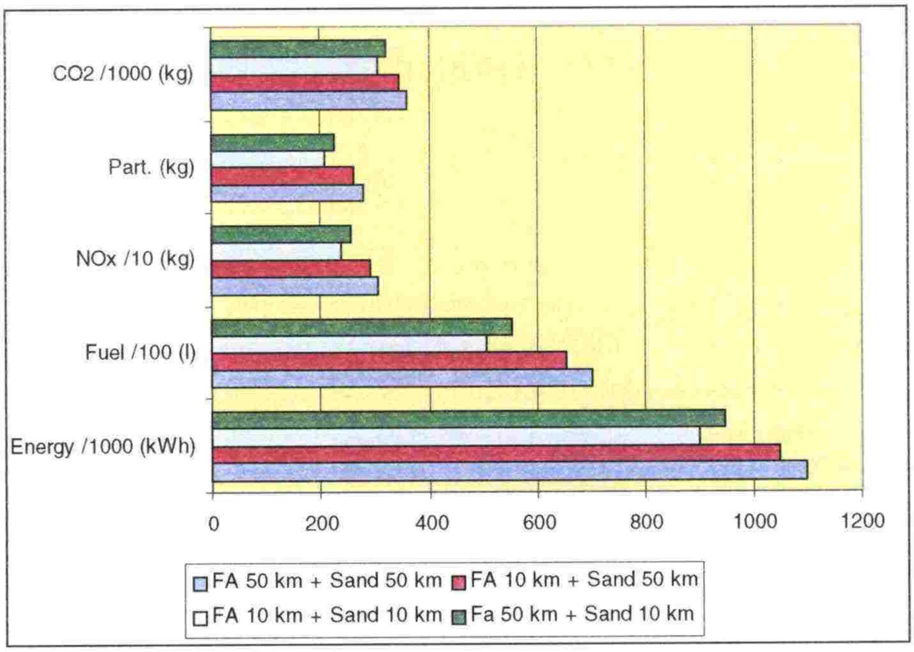

Figure 10. The effect of transport distances on the energy consumption and emissions of the FA3 fly ash construction (constructions presented in table 6).

The effect of the transport distance on emissions and on fuel and energy consumption is considerable, especially when large quantities of material are transported. Lengthening the transport distance from 10 to 50 km can affect the level of individual loadings by as much as 30%. In addition to the transport distance, also the amount of material transported at one time has a considerable effect on the loadings. The effect of variation in the quantity of material carried at one time has not been assessed in this report.

7.2 Assessment of the significance of environmental loadings

The aim of the life-cycle environmental impact assessment is to convert the inventory results into a form that can be more easily interpreted and compared. The impact assessment procedure is performed in three stages: classification, i.e. sorting the environmental loadings into impact categories on the basis of potential impacts, characterisation, i.e. weighting the emissions and other environmental loadings within the category according to possible impact potential, and valuation, i.e. weighting the environmental loadings or impacts in relation to each other. After the loadings are weighted, for example the leaching of impurities into the soil, the use of natural materials and emissions of carbon dioxide are proportioned to each other so that they can be compared directly. Similarly, the weighting can be performed on the impacts so that, for instance, impacts on the greenhouse phenomenon, acidification and the use of resources can be compared with each other.

The advantage of the valuation methods is the simplicity of result interpretation. The final outcome is either one environmental loading index or an impact matrix of mutually comparable effect scores. Further exploitation of the results does not require any expertise on the part of the user, and they can be added as such, for instance, to expert systems requiring effect scores. If the environment is assigned a significance factor in relation to other examination perspectives, the environmental impact index can be further compared with, for example, a cost index or an index describing technical durability.

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

7.2.1 Applicability of the assessment methods to the comparison of road constructions

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

The requirements of an assessment procedure suitable for the comparison of road constructions include the following:

- The significance of the special features of road constructions, such as land use, the consumption of natural raw materials and the migration of pollutants into the soil, should be taken into account.
- Procedural clarity and simplicity – the fundamentals of the procedure should be easily understandable – and the procedure itself as widely applicable as possible.
- It should be possible to add the procedure to an assessment as an optional stage so that the results are presented as both environmental loadings and, if desired, as effect scores.

The methods of comparison used in life cycle assessment programs, i.e. comparison on the basis of environmental costs, the weighting of environmental loadings on the basis of expert assessments, and comparison with target values (distance-to-target comparison), were provisionally examined as possible alternatives. The methods of comparison used in life cycle programs were found to be quite poorly applicable, because the weightings in road construction are not the same as in more conventional consumer goods applications.

Environmental cost assessment is supported by the understandability of the cost estimate obtained as the end-result and its comparability with other economic assessments. Finnra has already estimated the environmental costs of traffic emissions. The costs associated with factors such as land use and the consumption of natural raw materials, which are significant in road construction, are not included in those estimates. The assessment of environmental costs is a complex procedure and there are many uncertainties associated with it.

In the distance-to-target method the absence of unambiguous target values with regard to many loadings is a problem. One solution is to create an "average construction", with which alternatives can be compared. However, as the design of constructions is site-specific, the creation of a universal model construction is also problematic.

7.2.2 Comparison of environmental loadings on the basis of expert assessments

On the basis of the considerations described above, it was decided that a draft proposal based on expert assessment would be made for an effect score comparison procedure. Two questionnaires were made in order to obtain the background information to be used in the assessment. The questionnaire respondents were asked to rate the comparative detrimentality and significance of the environmental loadings caused in road construction (these are listed in Table 14). The first questionnaire (34 respondents) was made at a seminar in which the participants were representatives of research institutes, firms, road builders and environmental agencies, all of whom were familiar with the use of industrial by-products in road construction. The second questionnaire was limited to the members of one research group at VTT Chemical Technology (8 respondents).

In both questionnaires the respondents were asked to rate (score) the environmental loadings on a comparative basis. The average scores (on a scale of 0-100) assigned to the environmental loading factors and the averages converted into relative values on a scale of 0-10 are presented in Table 14. The assessments made by the respondent groups were fairly consistent, although the range of scores given was wide. Of the environmental loading factors considered by the respondents, the use of natural raw materials, emissions of heavy metals into the soil and the consumption of fuel and energy were regarded as being the most significant. The importance attached to the leaching of heavy metals into the soil was underlined, perhaps more than expected, in both questionnaires. The fact that this was a topical issue for many of the respondents may have contributed to this somewhat unexpected result. Inert waste, the use of water and noise were regarded as being of the least importance. The dispersion among the loadings in between these two extremes was greater and the order of importance was not particularly clear in all respects.

Table 14. Assessment by two expert groups of the comparative importance of the environmental loadings caused by road construction.

Environmental loading	Expert group 1			Expert group 2		
	Rank	Mean of scores	Relative scores, scale of 0-10	Rank	Mean of scores	Relative scores, scale of 0-10
Consumption of natural materials	1	76	10	*2*	67	10
Heavy metals to soil	2	67	9	*1*	68	10
Fuel consumption	3	58	7.5	*4*	49	7
Energy consumption	4	56	7.5	*6*	42	6
Ordinary waste	5	52	7	*13*	27	4.0
CO_2 to atmosphere	6	51	6.5	*9*	35	5
NO_x to atmosphere	7	50	6.5	*3*	50	7.5
Land use	8	47	6	*10*	32	4.5
Cl to soil	9	45	6	*8*	37	5.5
SO_2 to air	10	44	6	*14*	27	4.0
SO_4 to soil	11	44	6	*11*	29	4.0
Particles to atmosphere	12	43	5.5	*7*	40	6
VOC to atmosphere	13	40	5	*5*	43	6
N effluents	14	39	5	*12*	28	4.0
COD effluents	15	39	5	*16*	25	3.5
CO to atmosphere	16	38	5	*15*	26	4.0
Inert waste	17	30	4	*17*	18	2.5
Use of water	18	29	4	*19*	9.3	1.5
Noise	19	24	3	*18*	8.4	1.0

Despite its simplicity, the procedure used provided a relatively good picture of the importance of the environmental loadings caused by road construction. The questionnaire results could be used to make a provisional comparison of road constructions and also in the development of the assessment procedure as a whole.

7.2.3 Comparison of the case study constructions

The provisionally compiled comparative scores were tried out in a comparison of the case study pavement structures described in section 6. The results of the comparison are presented in Figure 10. The environmental loadings of the constructions were converted into relative values using the reference construction made of natural materials as the base level. It was not possible to calculated as precise a relative value for leaching as it was for other loadings, because there were large differences in the availability and representativeness of the solvency data on the materials. Land use was completely omitted from the comparison at this stage because the calculation principles still need to be more precisely defined.

After the relative environmental loading levels had been calculated, the impact categories were proportioned to one another by multiplying the effect scores by the comparative scores obtained on the basis of expert assessment (these are presented in Table 14). The scores given by the 34 respondents of the first questionnaire were used as the comparative scores.

The comparison of the case study constructions on the basis of the final calculated scores is presented in Figure 11. The results give an approximate picture of the environmental impacts of case study constructions. Because the construction and the transport distances always affect the outcome of such comparisons, the results as such cannot be generally applied to the comparison of materials. When comparing the alternative constructions it is notable that in all respects the differences between the constructions are not particularly great, and that the differentiating factors act in opposing directions.

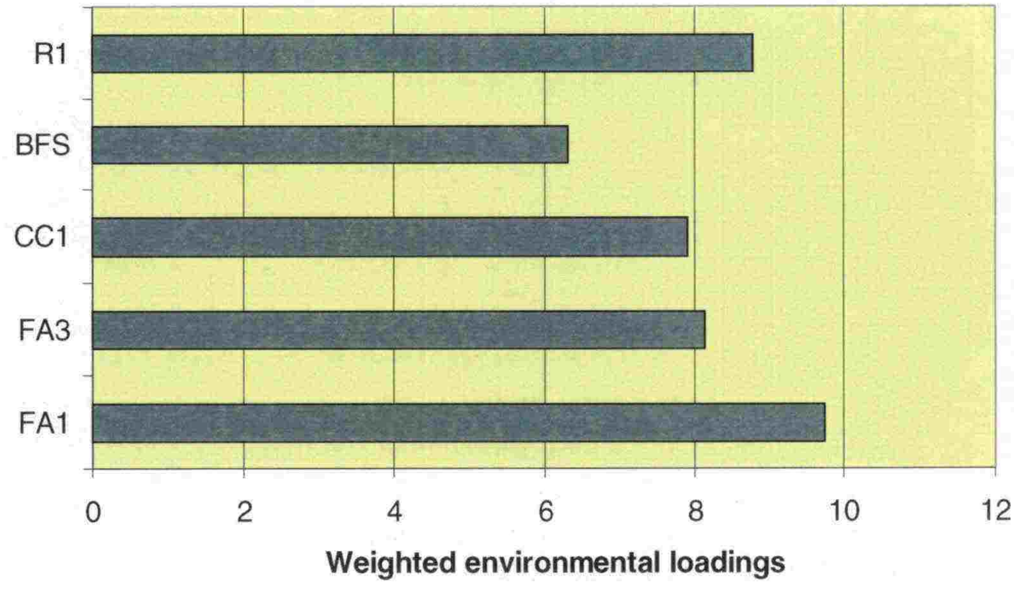

Figure 11. Weighted comparison of the constructions' environmental loadings using the scores of table 14. The constructions are presented in table 6.
R1 – natural material construction
BFS – blast-furnace slag construction
CC1 – crushed concrete construction 1
FA1 – fly ash construction 1.
FA3 – fly ash construction 23

8 APPLICABILITY OF THE INVENTORY ANALYSIS PROGRAM

In the second stage of the project the suitability of Excel-based life-cycle analysis program for calculation of environmental loadings of various constructions was tested.

Most of the data needed for calculations is included into the program. Only the dimensions of the construction, materials and thicknesses of the structural courses and transport distances of materials are required as input data. The environmental loadings of constructions or structural courses can be presented in numerical form or using various standard graphical presentations included into the program. The program also enables comparison of pavement structures as such, in relation to fixed reference construction or as effect scores. Some graphical model presentations are shown in figures 12 – 15.

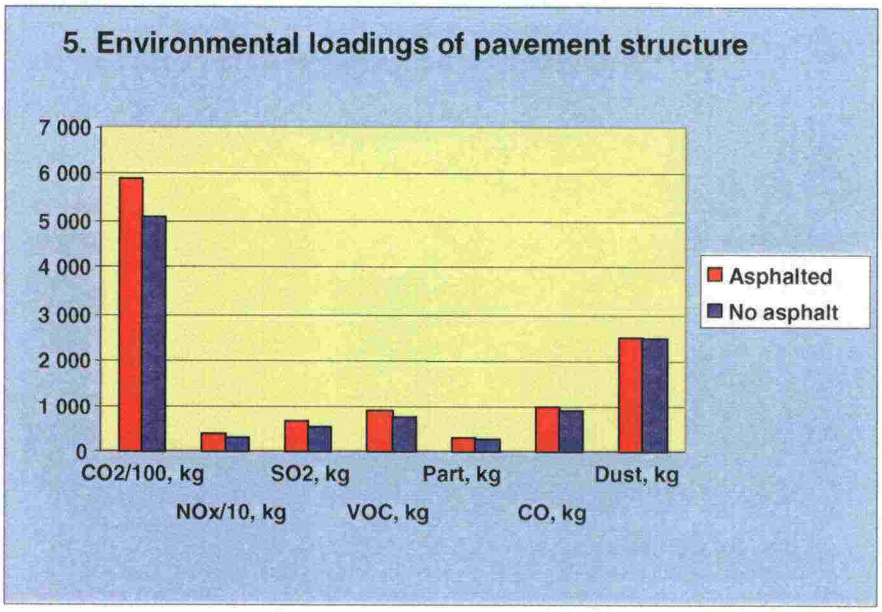

Figure 12. Fictive model presentation of the calculation program. Total environmental loadings of the pavement structure.

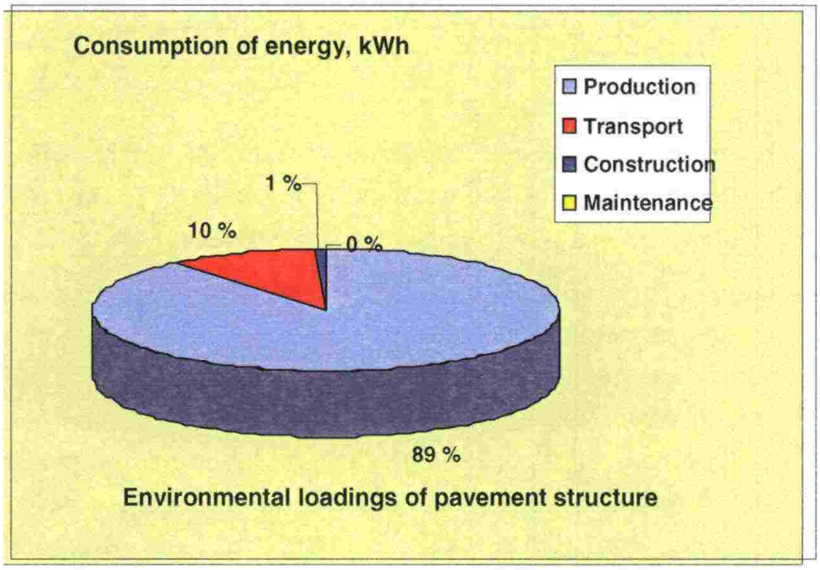

Figure 13. Fictive model presentation of the calculation program. Selected environmental loadings of the life-cycle stages of pavement structure.

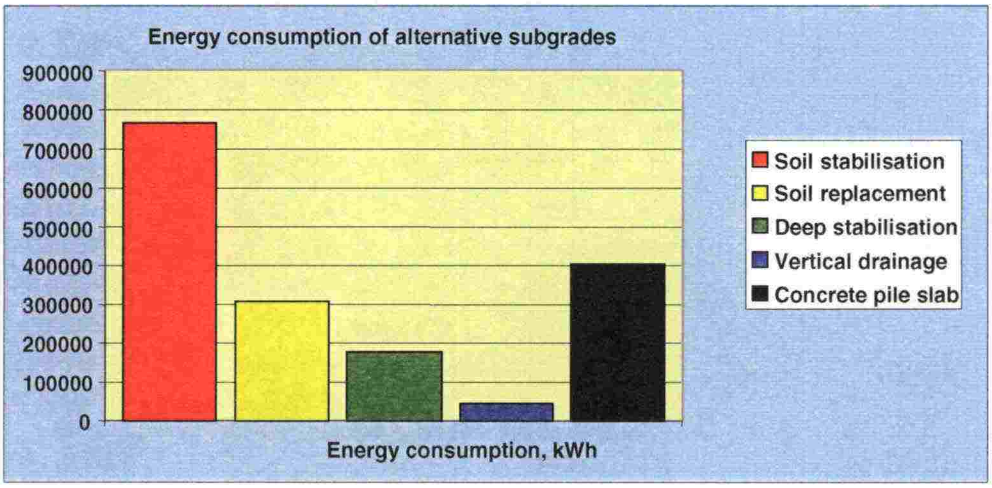

Figure 14. Fictive model presentation of the calculation program. Selected environmental loadings of alternative subgrades.

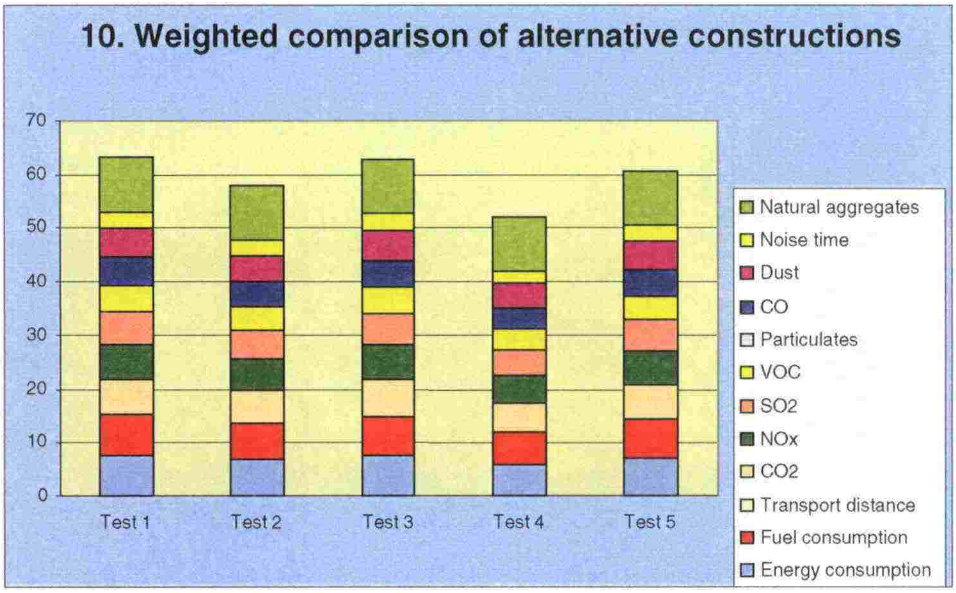

Figure 15. Fictive model presentation of the calculation program. Weighted comparison ot the alternative constructions.

For testing of the life-cycle inventory program the environmental loadings of five actual road planning cases were calculated (Laine-Ylijoki et al 2000). In this report the results of case 1, comparison of crushed concrete and natural aggregates in pavement structure, are presented. The materials of structural courses and transport distances of the materials are presented in table 15. The dimensions of the structure were the following:

Length of the road	4 100 m
Width of the road	10.5 m
Width of asphalt pavement	10 m

Table 15. The materials of alternative constructions of road case 1.

Structural layer	**Natural aggregate**		**Crushed concrete**	
	Material	Transport length, km	Material	Transport length, km
Pavement 1	0.10 m AB 20	5 urban	0,10 m AB 20	5 urban
Pavement 2	0.06 m ABK	5 urban		
Base course	0.15 crushed rock	10 urban	0.21 crushed concrete	5 urban
Sub-base	0.80 crushed stone	10 urban	0.80 crushed aggregate	10 urban
Lower sub-base				
Embankment				
Total thickness	**1.15**		**1.11**	

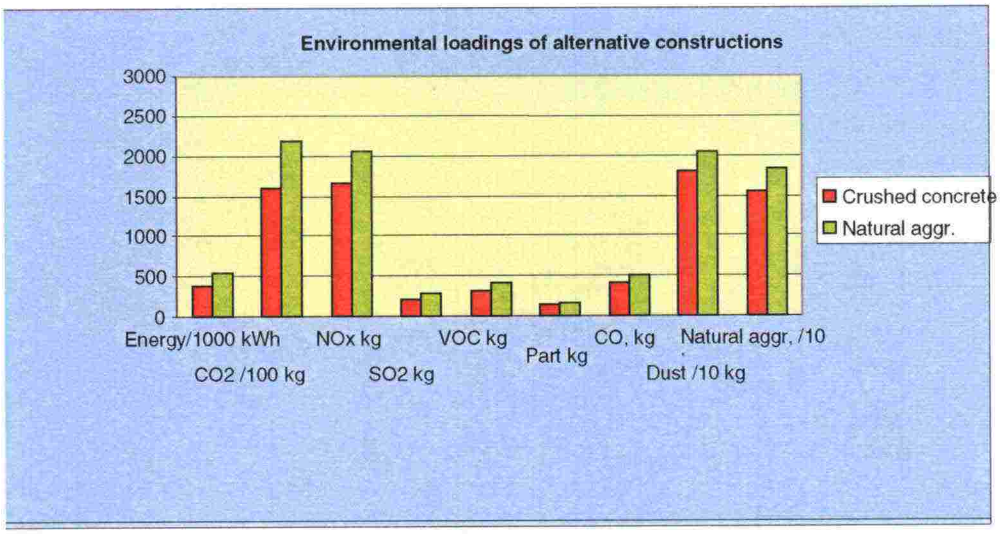

Figure 16. Environmental loadings of the alternative constructions of road case 1.

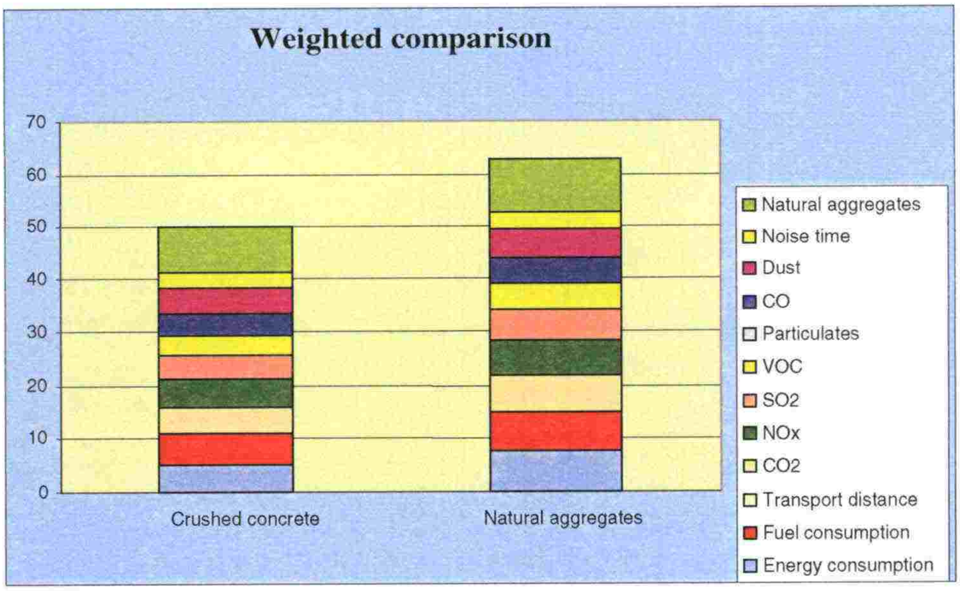

Figure 17. Weighted comparison of the environmental loadings of the alternative constructions of road case 1.

The differences in environmental loadings of alternative constructions of road case 1 were mainly due to the crushing of aggregate and to somewhat thicker pavement course required by "Natural aggregates" alternative (Figures 16 and 17). The quantities of substances leaching out of the constructions were below the Dutch design values used in VTT's assessment of the applicability of the materials (Figure 18).

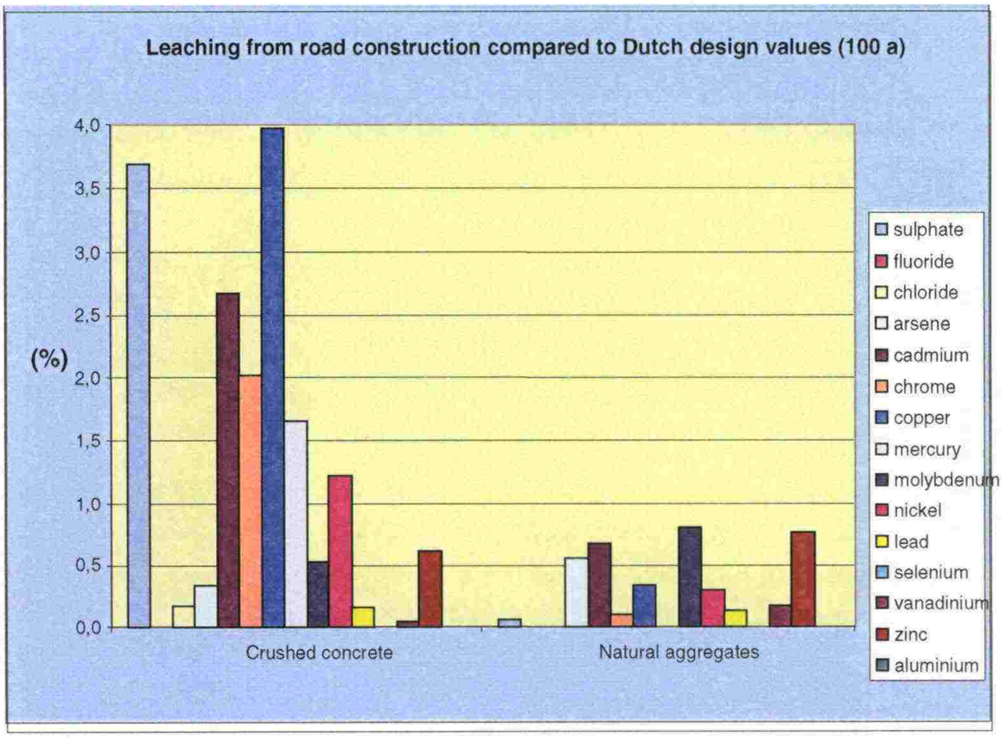

Figure 18. Impurities leaching out of the alternative constructions of road case 1 compared with the maximum permitted emission from materials/square metre over hundred years.

The main objective of the case studies was testing of the calculation program. The calculation of environmental loadings of case studies proved to be a relatively simple and fast task. The use of comparison worksheet enabled straightforward comparison of the alternatives and presentation of the results of calculations.

9 CONCLUSIONS

The Excel-based life cycle inventory analysis program for road constructions which has been developed on the basis of the study's results covers all the work stages from material production to road maintenance as well as the materials most commonly used in the structural courses of road constructions. The environmental loadings of the constructions and structural components made from the materials within the scope of the program can be calculated simply using only the dimensions of the construction and thicknesses of the structural courses as input data.

The simplicity of the inventory analysis program makes it suitable for use by structural designers and other groups not is familiar with LCIA methodology. In the interests of simplicity of use it has been necessary to place some limits on the amount of input data and the selection possibilities. For this reason structural materials that may not be included in the program's data program cannot be directly integrated into it at the touch of a button. However, the program has an extensive basis database and the addition of missing elements is possible by linking a worksheet containing the functions required by the material to the main workfile. The handling of individual materials and the work stages of construction must both be analysed separately because they vary depending on the material and structural course concerned. Special alternatives can also be calculated using the program's data as separate entities without adding them to the program.

The environmental loadings dealt with in the program have been limited to those assessed as being the most important. However, the loading factors in question described the total environmental loadings quite well as long as the life cycle inventory pertains to complete constructions. The environmental loadings regarded as being the most important for road construction in the expert assessment made when creating the inventory analysis procedure were the use of natural materials, energy and fuel consumption, the leaching of heavy metals into the soil, and atmospheric emissions of NOx and CO2.

Perhaps the most important factors absent from the inventory analysis program are COD emissions to water and land use, for which the development of applicable calculation methods requires more extensive research. The development of a land use assessment method suitable for road construction could be continued, for example, as a wider international co-operation project.

The absence of some environmental data and uncertainties associated with the available data complicated some aspects of the inventory calculation. For example, this applies to the utilisation of the by-products in road construction, which is not yet well established. Similarly, of the environmental loadings, data on dust emissions in particular is only available in the case of some materials and work stages. The choice of average emission factors, construction methods and other basic data will always limit the accuracy of the calculations. However, the effects when comparing constructions are not particularly great because the assumptions made in the calculations are largely the same.

The inventory analysis program is limited at this stage to calculating and comparing the environmental loadings of constructions only. Activities associated with the construction, use and maintenance of roads that are presently beyond the scope of the program include bridge construction, land clearance works, road-marking work, the construction and maintenance of equipment necessary for traffic control, road lighting, and regular or seasonal road maintenance work (salting, sanding, snowploughing, etc). The creation of procedures for calculating the environmental loadings of such factors would be important for assessing the impacts of material selections and the total loadings of road usage.

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LEACHING OF NATURAL AGGREGATES

The quantities of substances leaching out of secondary materials were simulated on the basis of laboratory-scale leaching tests. The quantity of impurities leaching out of the construction over a certain time period was assessed by calculating the water passing through the construction in proportion to the quantity of material (the so called L/S-ratio). The leaching from the material corresponds to the amount dissolved in the leaching tests at the same L/S-ratio. The following formula is used for calculation of L/S-ratio:

$L/S = t \times I \times (1\ 000\ l/m^3)/(d \times h)$, where

t = period of leaching beginning from the appearance of first percolate (a)

d = dry volume weight of the material to be investigated (kg/m^3)

h = thickness of the layer (mm)

I = infiltration (mm/year).

In the calculation programme the period of leaching, t, is 100 years and infiltration, I, is 6 mm/a for as. For industrial by-products average Finnish leaching data was used. Because there was no Finnish leaching data for natural aggregates, a few materials were tested during the project (table1).

Table 1. Leaching of metals from natural aggregates and granulated blast-furnace slag, mg/kg. Test method CEN prEN 12457.

Sample	mg/ kg																	
	Cd		Cr		**Mn**		V		**Ni**		Pb		**Zn**		As		**Mo**	
	L/S 2	**L/S 10**	L/S 2	L/S 10	**L/S 2**	**L/S 10**	L/S 2	L/S 10	**L/S 2**	**L/S 10**	L/S 2	L/S 10	**L/S 2**	**L/S 10**	L/S 2	L/S 10	**L/S 2**	**L/S 10**
Crushed rock 0-50 mm	0.0002	0.001	0.004	0.020	**0.026**	**0.130**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	**0.006**	0.030	0.020	0.1
Crushed rock 0-16 mm	0.0002	0.001	0.004	0.020	**0.006**	**0.046**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	**0.006**	**0.030**	**0.024**	0.1
Lower sub-base sand	0.0002	0.001	0.004	0.020	**0.036**	**0.114**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	0.006	0.030	0.020	0.1
Gravel	0.0002	0.001	0.004	0.020	**0.128**	**0.338**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	0.006	0.030	0.020	0.1
Gravel	0.0002	0.001	0.004	0.020	**0.072**	**0.368**	0.010	0.050	**0.004**	0.020	0.004	0.020	0.040	0.200	0.006	0.030	0.020	0.1
Crushed rock 0-16 mm	0.0002	0.001	0.004	0.020	**0.018**	**0.082**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	0.006	0.030	**0.028**	0.1
Crushed gravel 0-50 mm	0.0002	0.001	0.004	0.020	**0.120**	**0.395**	0.010	0.050	0.004	0.020	0.004	0.020	0.040	0.200	0.006	0.030	**0.028**	0.1
Granulated blast furnace slag	0.0002	0.001	0.004	0.020	**0.211**	**0.301**	**0.403**	**1.753**	0.004	0.020	0.004	0.020	0.040	0.200	0.006	0.,030	0.020	0.1
	Detection limit, mg/kg																	
	0.0002	0.001	0.004	0.02	0.002	0.01	0.01	0.05	0.004	0.02	0.004	0.02	0.04	0.2	0.006	0.03	0.02	0.1

APPENDIX 1

The tests used were CEN pr EN 12457 (L/S 2 and L/S 10) and a pH-static test. In CEN pr EN 12457 the leaching of Cd, Cr, Zn and Pb and V was under detection limit (table 1) from all the natural aggregates. The decrease of pH did not significantly increase the leaching of metals from sand. The amounts of Cu, Ni and Zn leaching from crushed rock and crushed gravel increased in the pH-stat test.

For comparison the leaching of heavy metals from three natural materials in the study of Kälvesten is presented in table 3 (1996). The quantities are comparable with the data of table 1. There may, however, be local factors, such as variance of the composition of natural materials, which affect leaching of impurities from certain construction materials.

Table 2. Leaching of metals from natural aggregates and granulated blast-furnace slag. pH-stat test. The leaching values I and II are Dutch draft leaching values for building materials, which are used as reference values.

Sample	**mg/kg**											
	pH	As	Cd	Cr	Cu	Mn	Mo	Ni	Pb	Zn	V	SO_4^{2-}
Crushed rock 0-50 mm	4	<0.04	<0.01	<0.10	**5.00**	**18.26**	<0.05	90.32	0.16	1.83	<0.05	0.96
Crushed rock 0-16 mm	4	<0.04	<0.01	<0.10	**1.34**	**10.51**	<0.05	0.22	0.20	1.34	<0.05	19.11
Lower sub-base sand	4	<0.04	<0.01	<0.10	**<0.10**	**0.83**	<0.05	<0.04	<0.02	0.30	<0.05	30.73
Gravel	4	<0.04	<0.01	<0.10	**6.51**	**7.67**	<0.05	0.34	0.05	0.97	<0.05	14.57
Gravel	4	<0.04	<0.01	<0.10	**<0.10**	**0.83**	<0.05	<0.04	<0.02	0.30	<0.05	30.73
Crushed rock 0-16 mm	4	<0.04	<0.01	<0.10	**0.86**	**17.59**	<0.05	0.18	0.10	2.54	<0.05	21.50
Crushed gravel 0-50 mm	4	<0.04	<0.01	<0.10	**0.97**	**13.60**	<0.05	0.26	<0.02	0.80	<0.05	9.72
Granulated blast furnace slag	5	<0.04	<0.01	<0.10	**<0.10**	**66.61**	<0.05	<0.04	<0.02	0.09	0.33	85.37
Leaching value I		0.88	0.032	1.3	0.72	NA	0.28	1.1	3.8	3.8	1.6	750
Leaching value II		7	0.066	12	3.5	NA	0.91	3.7	15	15	32	22000

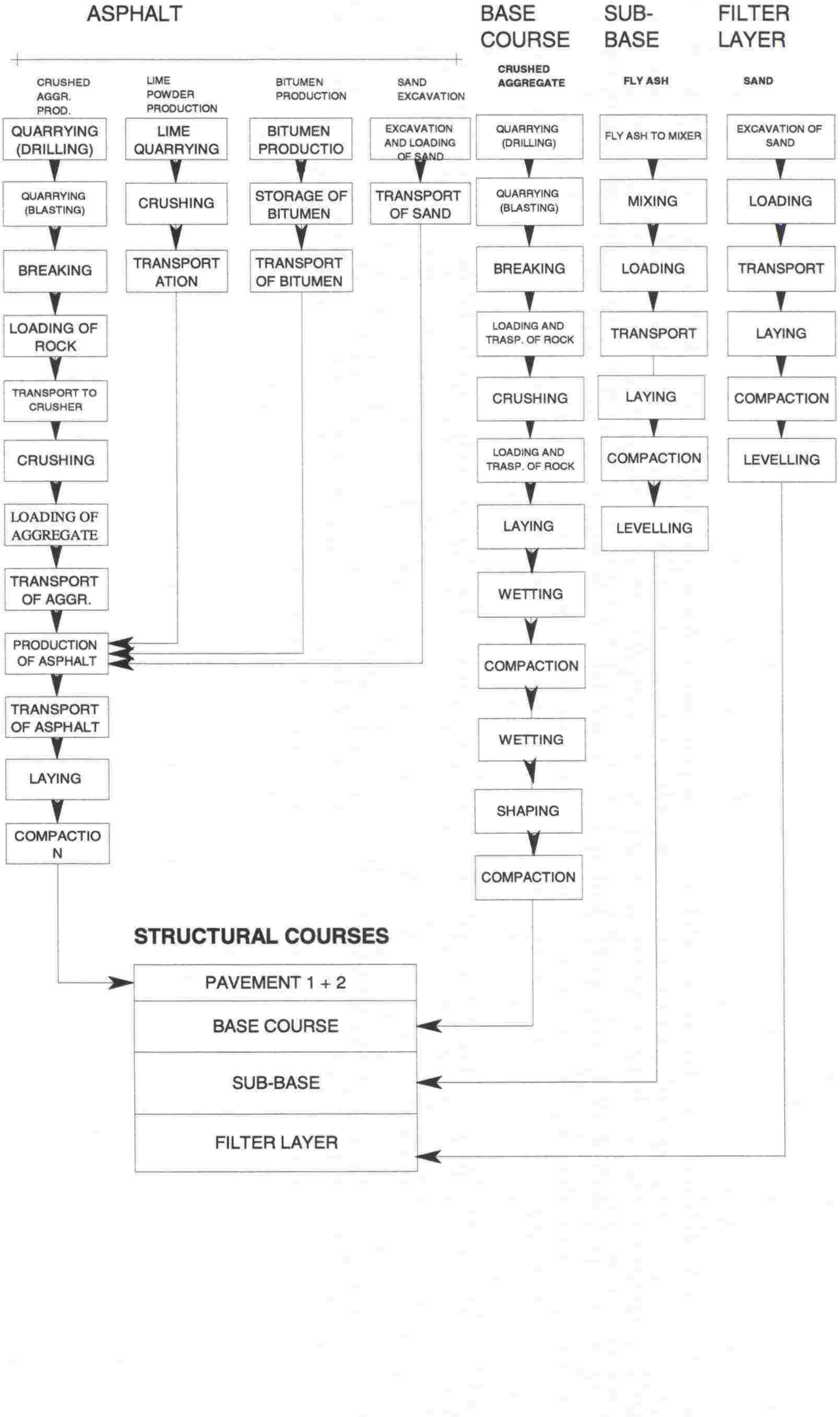
Table 3. Leaching of impurities (L/S 2) from natural aggregates in the study of Kälvesten (1996).

	Crushed rock	**Gravel**	**Moraine**
Cd	0.0002	0.0002	0.0002
Cr	0.002	0.002	0.002
Cu	0.009	0.009	0.009
Ni	0.04	0.06	0.04
Pb	0.002	0.002	0.002
Zn	0.015	0.017	0.013

APPENDIX 2

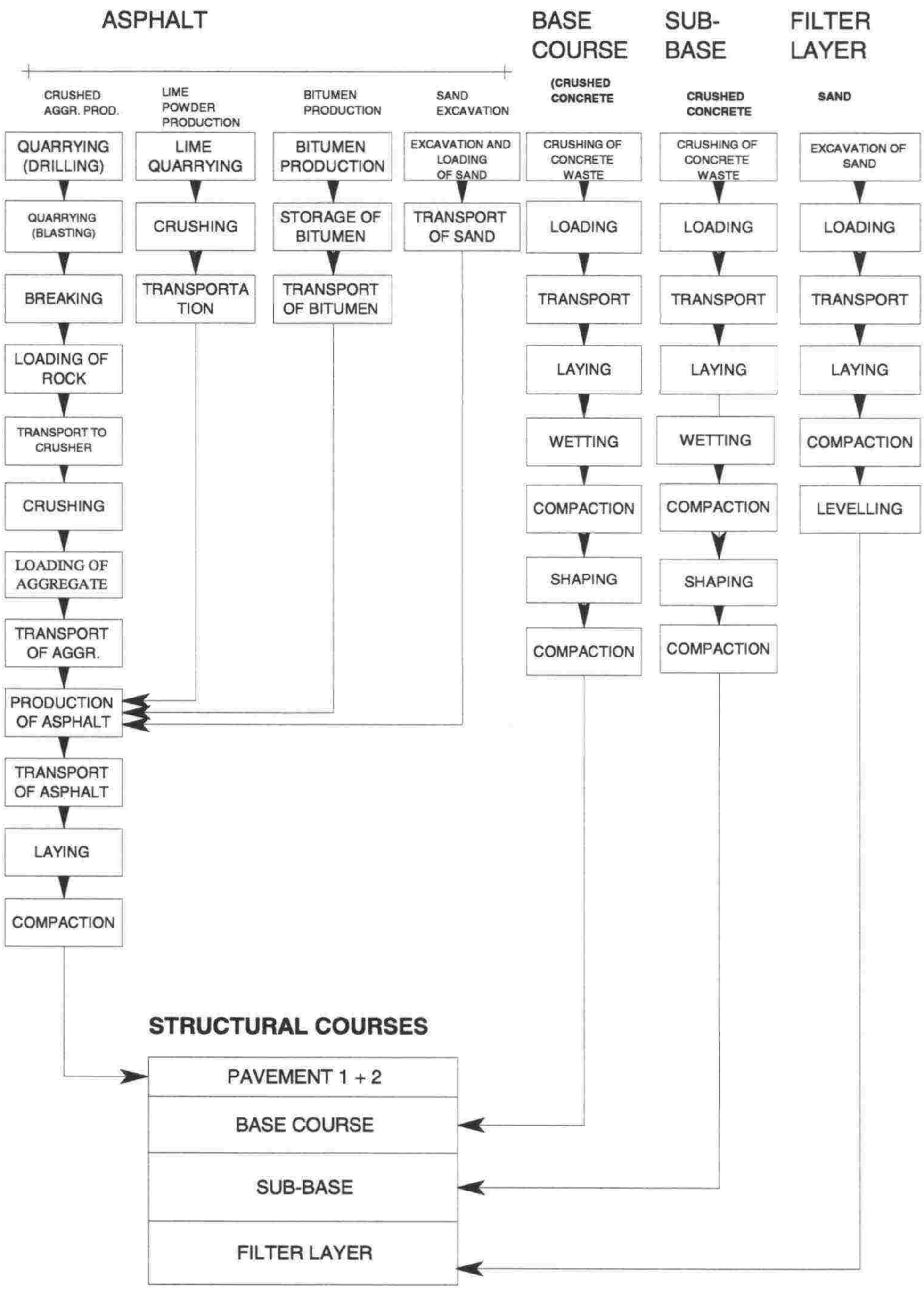
THE CONSTRUCTION WORK STAGES IN CASE STUDIES EXAMINED (CHAPTER 6)

FLY ASH CONSTRUCTION, FA2

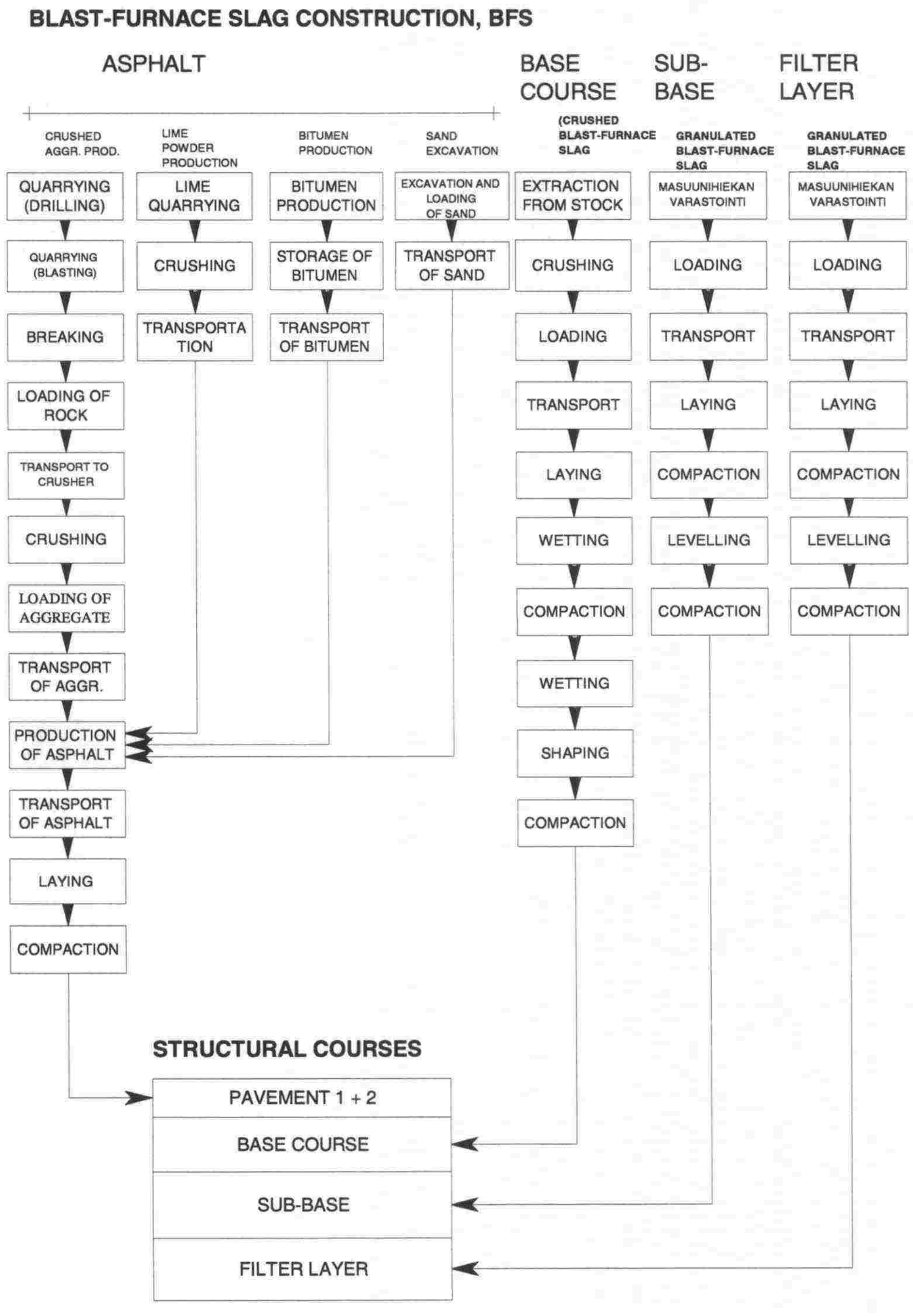


APPENDIX 2

CRUSHED CONCRETE CONSTRUCTION, CC1/CC2

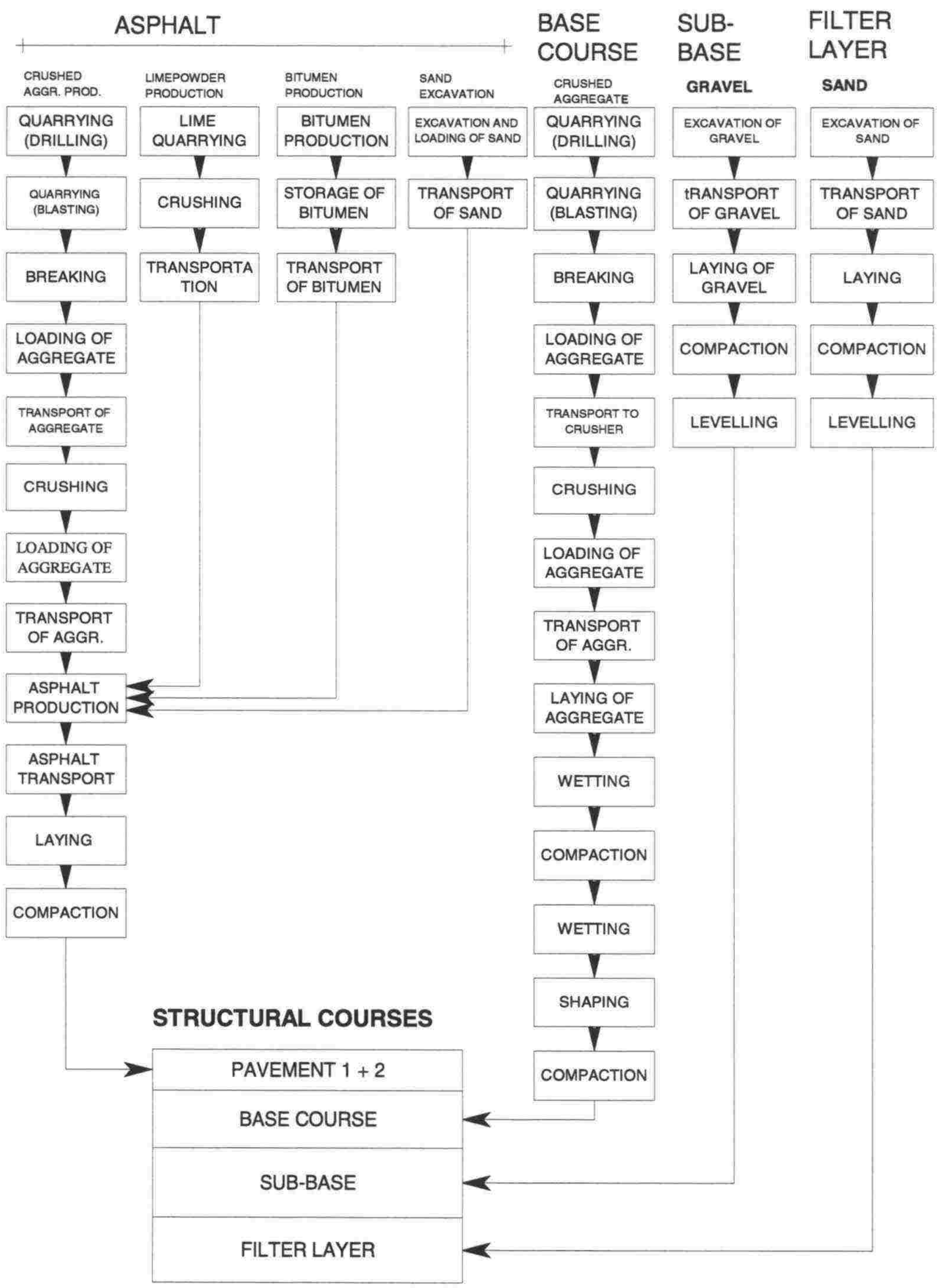


APPENDIX 2


BLAST-FURNACE SLAG CONSTRUCTION, BFS
ASPHALT
BASE COURSE
SUB-BASE
FILTER LAYER
CRUSHED AGGR. PROD.
LIME POWDER PRODUCTION
BITUMEN PRODUCTION
SAND EXCAVATION
(CRUSHED BLAST-FURNACE SLAG
GRANULATED BLAST-FURNACE SLAG
GRANULATED BLAST-FURNACE SLAG
QUARRYING (DRILLING)
QUARRYING (BLASTING)
BREAKING
LOADING OF ROCK
TRANSPORT TO CRUSHER
CRUSHING
LOADING OF AGGREGATE
TRANSPORT OF AGGR.
PRODUCTION OF ASPHALT
TRANSPORT OF ASPHALT
LAYING
COMPACTION
LIME QUARRYING
CRUSHING
TRANSPORTATION
BITUMEN PRODUCTION
STORAGE OF BITUMEN
TRANSPORT OF BITUMEN
EXCAVATION AND LOADING OF SAND
TRANSPORT OF SAND
EXTRACTION FROM STOCK
CRUSHING
LOADING
TRANSPORT
LAYING
WETTING
COMPACTION
WETTING
SHAPING
COMPACTION
MASUUNIHIEKAN VARASTOINTI
LOADING
TRANSPORT
LAYING
COMPACTION
LEVELLING
COMPACTION
MASUUNIHIEKAN VARASTOINTI
LOADING
TRANSPORT
LAYING
COMPACTION
LEVELLING
COMPACTION
STRUCTURAL COURSES
PAVEMENT 1 + 2
BASE COURSE
SUB-BASE
FILTER LAYER

APPENDIX 2

REFERENCE CONSTRUCTION (R1)



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