FINAL REPORT FOR PUBLICATION

STATUS P

AMADEUS

Advanced Models for Analytical Design of European Pavement Structures

RO-97-SC.2137

Project co-ordinator : BRRC

Partners :

LNEC
UNL-FCT
BUGH
CEDEX
ISTU
LAVOC
PRA
IBRI
DTU
VTI
TUD
DDC
KTI Rt
NTUA
TRL
VTT

Project Duration : 1 January 1998 to 30 June 1999

Date : March 29th, 2000

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

TABLE OF CONTENTS OF THE FINAL REPORT

March 29th 2000

ABSTRACT

The structural design of a pavement and the prediction of its long term performance are two complementary and closely linked tasks. They indeed are both based on similar models (empirical or mechanistic). Such models now in use in several countries are considered as essential tools in planning the construction and maintenance of a road network.

The AMADEUS[*] research project is a major step in the development of a European advanced pavement design method. It concerns the review and evaluation of pavement design models that are already in use for practical applications and for research projects. The purpose of this activity is to propose guidelines for potential users of advanced models and set up the plans for a design procedure, already outlined in the frame of the COST 333 action. The new procedure will integrate the strong points of existing methods while considering the long-term evolution of the pavement properties in an incremental way.

A first part of this activity consisted of making an inventory of existing design models or software packages which were available and selecting those that are most relevant to our purpose and to the consortium.

In a second part of the work, a detailed programme was proposed in order to organise the evaluation of these software packages by different teams formed among the partners of the AMADEUS consortium. It was decided that the evaluation would be carried out in 3 phases of increasing complexity.

- Phase 1 to evaluate "simple" response models (calculation of stress, strain and displacement).
- Phase 2 to compare calculated responses with measurements carried out on accelerated tests managed by three partners (DTU, LAVOC and CEDEX).
- Phase 3 to compare the long term damage predictions made by means of the models with the actual behaviour observed on German road sections monitored by BASt over long periods of time (up to 20 years).

The work was divided between four teams with the team leaders being responsible for summarising their team's assessment of the models. These were combined to produce a detailed assessment report and information from this report has been used to compile a users guide. This guide will help potential users in choosing design tools suited to their specific problems.

This co-operation finally resulted in a plan for developing a more comprehensive harmonised pavement design method.

---

[*] (AMADEUS is the acronym of "Advanced Models for Analytical Design of EUropean pavement Structures")

EXECUTIVE SUMMARY

In a time of increasing exchange of goods and persons, the improvement of mobility is one of the main challenges of the future. Currently, the majority of this mobility is supported by the road infrastructure, consequently many billions of EURO's are spent annually in the European road sector. Recent data, taken from the International Road Federation IRF and COST 333 sources, are presented in Appendix A to give an idea of the road expenditures involved.

A large part of these amounts is devoted to maintaining and constructing the primary network in which more than 80% consists of flexible and composite roads, structure types that were considered in this project. In order to guarantee the safety and quality of this vast network over the long term and within acceptable budgetary limits, performance assessment tools should be made available to the decision-makers. This requirement, which has been known for many years, was repeated in different sessions of the last PIARC conference in 1999.

The need of a more comprehensive mechanistic pavement design model has been recognised by the Directorate for Transport of the European Commission. To meet these objectives, two actions involving co-operation between several European countries, COST 333 and AMADEUS, were supported by the Commission.

The AMADEUS project was initiated by a Consortium of 15 partners already involved in the COST 333 action, with the purpose to evaluate existing advanced pavement design models. A sound basis of information and knowledge in this field was already available from the work carried out by COST 333.

AMADEUS (“Advanced Models for Analytical Design of EUropean pavement Structures”) was intended to provide a thorough and well-documented evaluation of existing, advanced, design models and to recommend whether these models are suitable as design elements for a comprehensive mechanistic design method, in which a large number of distress phenomena are integrated. Spreading best practice of these methods will foster the use of the available, advanced methods.

AMADEUS was started in January 1998 under the co-ordination of BRRC, the Belgian Road Research Centre. It was supported at the international level as part of the European Commission Fourth Framework Transport RTD Programme.

The main objectives of AMADEUS were :

to evaluate existing, advanced, analytical pavement design models by comparing their predictions using standard inputs. The ability of these models to deal with different materials, pavement construction, climate and traffic characteristics would be considered,

to issue recommendations and guidelines to promote appropriate use of these design models,

to set up the elements for a comprehensive design method integrating a number of distress phenomena with their evolution and mutual interactions.

An essential part of the project consisted in modelling the behaviour of selected pavement structures by using different computer codes and/or models. A deliberate choice of existing advanced analytical models based on clearly different approaches was made. The evaluation of these methods would identify the points on which each tool allows a definite breakthrough. It would also serve to determine their technical and practical shortcomings.

The first tasks of the action consisted in :

- selecting the design tools to be used in the evaluation,
- selecting the cases to be studied and the relevant input data and characteristics,
- planning the evaluation procedure,
- forming different evaluation teams within the AMADEUS consortium, for practical reasons.

The evaluation started in June 1998, proceeding along three progressive phases :

- Phase 1 to train users and compare response models on simple theoretical structures.
- Phase 2 to compare different models on the basis of the responses measured on three accelerated loading tests.
- Phase 3 to predict long term pavement performance on four monitored road sections and compare the results with experimental results.

The evaluation and its further interpretation led to the following main conclusions.

- Starting from the strong points of the different evaluated methods, guidelines for practical use of these models have been set up and presented under the form of a practical guide which is one of the main Deliverables of the project.

- The final part of the project consisted in setting up the plans for a comprehensive and practical design procedure for Europe. The proposal makes use of :

  - the information collected by COST 333,
  - the conclusions of the COST 333 action,
  - the experience gained by using existing models,
  - new advanced models presenting potential improvement with respect to the currently used models.

- The new method should be able to make a better prediction of pavement performance, taking into consideration the material and structural alterations (for example ageing, seasonal variation of material's behaviour, unevenness) that occur during the life cycle of the pavement. This can only be possible if incremental models are used.

- The benefits from the study for the project engineers in pavement design and practionners in pavement management are that the information gathered on the different existing design tools completed by the results of the evaluation performed by expert teams will give them a sound basis of information to select the products that are the most adequate for their particular needs and requirements.

- The developers of these tools could seize the opportunity of this action to be informed of existing programme bugs and make the necessary corrections.

  Developers will also receive information concerning the improvement and completion of the existing products.

Finally, the set of reports and Deliverables of the project will be a source of information for training purposes. Future users of pavement modelling can use this information to calibrate and assess other models or design tools.

THE PARTNERSHIP

The participating organisations in the project are national highway research institutions, universities and other road research organisations. They are part of or have strong relations with their national governmental highway administration organisations. Besides they have operational relations with organisations that develop design models.

In the preparatory work performed under COST 333, a team of 15 partners has been built to start co-operation in performing the challenging tasks of this European Road Research Programme.

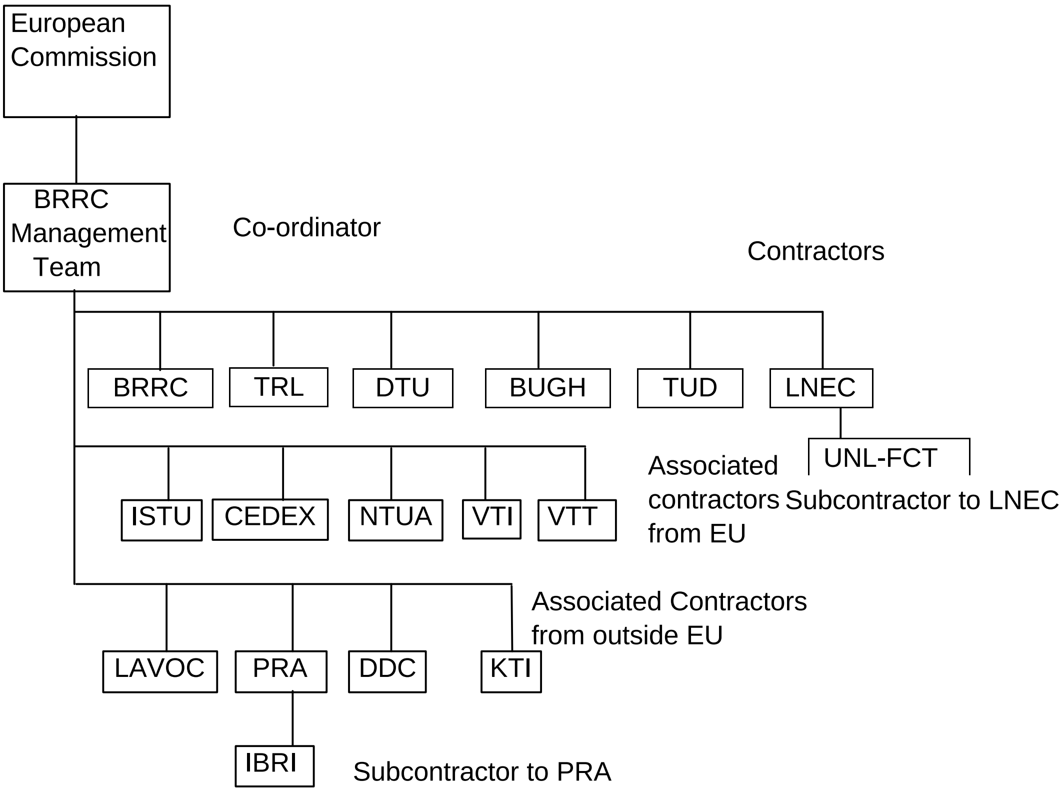
Six Contractors and nine Associated Contractors, under the co-ordination of the Belgian Road Research Centre (BRRC) carried out the project (see Table 1 and Appendix B for more information).

Table 1 : Countries and institutions participating in AMADEUS.

Country code	Organisation	Acronym	Status
AT	Institute for Road Construction and Maintenance Vienna University of Technology	ISTU-TU WIEN	AC
BE	Belgian Road Research Centre	BRRC	Co-ordinator CO
CH	Laboratoire de Voies de Circulation; Ecole Polytechnique Fédérale de Lausanne	LAVOC-EPFL	AC
DE	Bergische Universitaet GH Wuppertal	BUGH	CO
DK	Technical University of Denmark	DTU	CO
ES	Centro de Estudios de Carreteras	CEDEX	AC
FI	Technical Research Centre of Finland	VTT	AC
GB	Transport Research Laboratory Highways Agency	TRL	CO
GR	National Technical University of Athens	NTUA	AC
HU	Institute for Transport Sciences Ltd	KTI Rt	AC
IS	Public Road Administration / Icelandic Building Research Institute	PRA IBRI	AC SC
NL	Technical University Delft	TUD	CO
PT	Laboratório Nacional de Engenharia Civil Universidade Nova de Lisboa - Faculdade de Ciências e Tecnologia.	LNEC UNL-FCT	CO SC
SE	Swedish Road and Transport Research Institute	VTI	AC
SI	Engineering Company for Public Roads	DDC	AC

CO = Contractor.
AC = Associated Contractor.
SC = Sub-Contractor.

The project contract structure is depicted below.



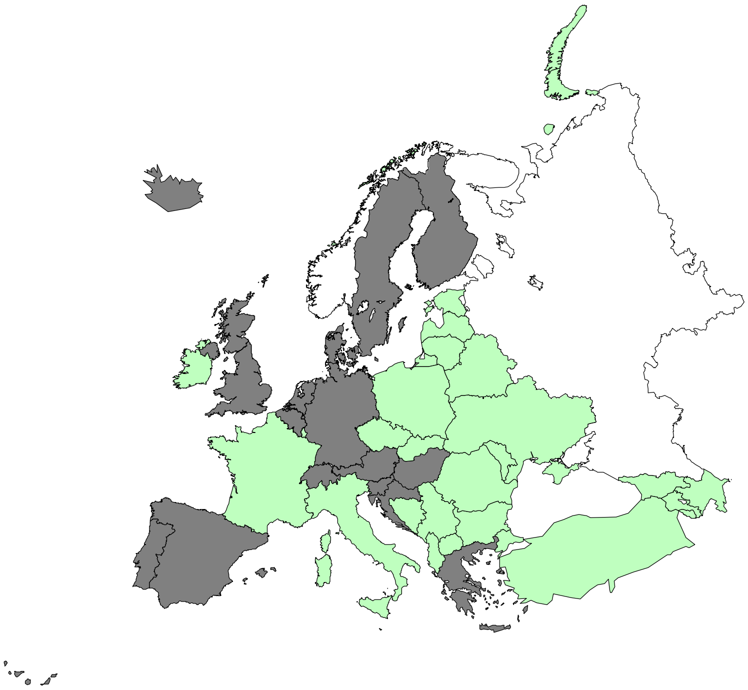


Figure 1 : Countries involved in AMADEUS projects.

1. INTRODUCTION

A number of advanced pavement deterioration and response models have been developed in the recent years. These models describe only a limited number of failure phenomena and sometimes require large computational facilities. Hence, some of them have not been incorporated into daily design activities and are relatively unknown to most potential users in Europe.

Current pavement design models treat the pavement and its foundation as a set of continuous, horizontal, isotropic, linear elastic layers extending infinitely in horizontal directions. This is a simplification of the actual behaviour of pavement materials and the pavement geometry. These models do not take into account anisotropic, visco-elastic, non-linear or time-dependant behaviour of materials. Neither do they take into account non-uniform distribution of the tyre pressure, dynamic wheel loads and pavement boundaries.

1.1 Justification of the project - Current situation and State of the art

FEHRL, the "Forum of European National Highway Research Laboratories" has started a Strategic European Road Research Programme (SERRP). One of the topics in this programme is the development of an advanced, mature design methodology, based on fundamental understanding of the physical processes. Preliminary activities were dealt with in COST 333 : "Development of new Bituminous Pavement Design Method", which started in 1996. AMADEUS is the continuation of COST 333.

A number of other FEHRL projects are related to the activities of COST 333 and AMADEUS such as :

- COST 323 “Weigh in motion of road vehi
- COST 324 “Long term pavement performance of pavements”.
- PARIS “Performance Analysis of Road Infrastructure”
- WAVE “Weigh in motion of Axles and Vehicles for Europe”.
- COST 334 “Effects of wide single tyres and dual tyres”.
- COST 336 “Use of falling weight deflectometers in pavement evaluation”.
- COST 337 “Unbound granular materials for road pavements”.

Eleven European Union countries, together with four non-member states are directly involved in AMADEUS. All these countries are participating in FEHRL.

Pavement design methods can be classified into three basic categories: empirical, analytical and mechanistic. The ultimate goal of the pavement design methodology was outlined in the frame of the COST 333 action. This is the development of a mechanistic/analytical method, based on full understanding of the behaviour of the materials in the road pavement structures. This mature method will be able to accurately predict the performance of different pavement structures and materials under specified traffic and climatic conditions. Currently used design methods are either empirical or analytical or a blend of the two.

There is a range of empirical methods. At one extreme an empirical method may be based solely on engineering experience, in which case it may have evolved over time with regular reviews as more experience is accumulated. At the other extreme an empirical method may be the result of the systematic collection of performance data over a period of time and a statistical correlation of design variables with this performance information.

Analytically based methods use empirical data obtained from in-service roads to calibrate analytically determined pavement design criteria. The most frequently used methods employ a pavement response model to calculate the stresses and/or strains at locations in the pavement structure that are considered to be the source of deterioration. These calculated values are compared with permissible values to achieve the required life.

Recently a number of mechanistic models have been developed. They can deal with some aspects of non-linear, viscous/plastic behaviour of materials, with anisotropy, dynamic loads, granular (non-continuous) materials etc. However, these advanced methods are not yet applied in current daily pavement design practice. They need to be critically assessed under defined conditions.

1.2 Links with COST 333 Action

COST action 333 ("Development of New Bituminous Pavement Design Method") was started in 1996 through an initiative of FEHRL, as part of the Strategic European Road Research Programme (SERRP).

The main objective of the Action was set to contribute to the development of a new European design method for flexible and composite pavements, based on the latest research findings and the latest developments in pavement modelling.

COST 333 was a concerted European research Action that focused towards information gathering, identification of requirements and selection of design elements. This would be a first step towards the development of a coherent, cost-effective and harmonized pavement design method that can be applied throughout Europe. The work plan of COST 333 is summarised in table 2.

Table 2 : Work plan of COST 333.

Task	Sub-Task	
1. Information gathering	1.1	Terminology Requirements for pavement components
	1.2	Review of design methods
2. Requirements for a pavement design method	2.1	Traffic
	2.2	Climatic effects
	2.3	Soils
		Granular materials
		Bituminous materials
		Cement bound materials
	2.4	Models
3. Extension of the action		Input from accelerated load trial Input from AMADEUS
Conclusions		Selection of design elements Final report

The review of the requirements and deterioration mechanisms of the main pavement components, together with the review of current pavement design methods, performed under task 1 of COST 333, demonstrated the discrepancy between the actually observed modes of pavement deterioration and the modes of pavement deterioration on which current pavement design methods are based.

This conclusion stressed the need for development of a new, improved European pavement design method. The new method should use advanced models, and should be able to make a better prediction of pavement performance, taking into consideration the material and structural alterations (for example ageing, seasonal variation of material's behaviour, unevenness) that occur during the life cycle of the pavement.

Under task 2, the requirements for this new method were set, addressing separately the main elements that form a pavement design method: traffic and climate input, materials input, response models and performance models.

The major task in the AMADEUS project consisted in running existing software for pavement design, to predict the response and performance of pavement structures submitted to variable conditions of traffic and environment.

Therefore, the knowledge on relevant traffic and climatic conditions, material properties and behaviour laws, gathered under COST 333, formed an essential information that was made available for the specification of data to be treated in the AMADEUS project. On the other side, the preliminary results from the evaluation of pavement design models performed under the AMADEUS framework, were a key input to the selection of design elements within COST 333. Together, the outcome of the two projects led to the production of an outline comprehensive pavement design procedure corresponding to the general frame presented in figure 2.

1.3 Description of an ideal design procedure

The different elements making part of a full pavement design procedure taking into account the initial conditions and their evolution through an incremental process have been identified and analysed in the frame of COST 333 action. The links between these design elements were discussed and are described in the form of a flow chart shown in figure 2. This diagram contains the following items :

1. Initial conditions and structures.
2. Geometry.
3. Traffic.
4. Material properties.
5. Climatic and environmental conditions.
6. Response model.
7. Stresses, strains and displacements.
8. Performance models.
9. Structural change.
10. Current condition.
11. Complete history of the pavement.

One of the tasks of AMADEUS was to define more precisely the function and contents of these eleven design elements. This was developed in the "elaboration” work package.

Another main task of AMADEDUS was to examine the coverage of these different elements by the existing models and software products presently available to the design engineers, in the perspective of the requirements set up for an improved pavement design method outlined in COST 333.

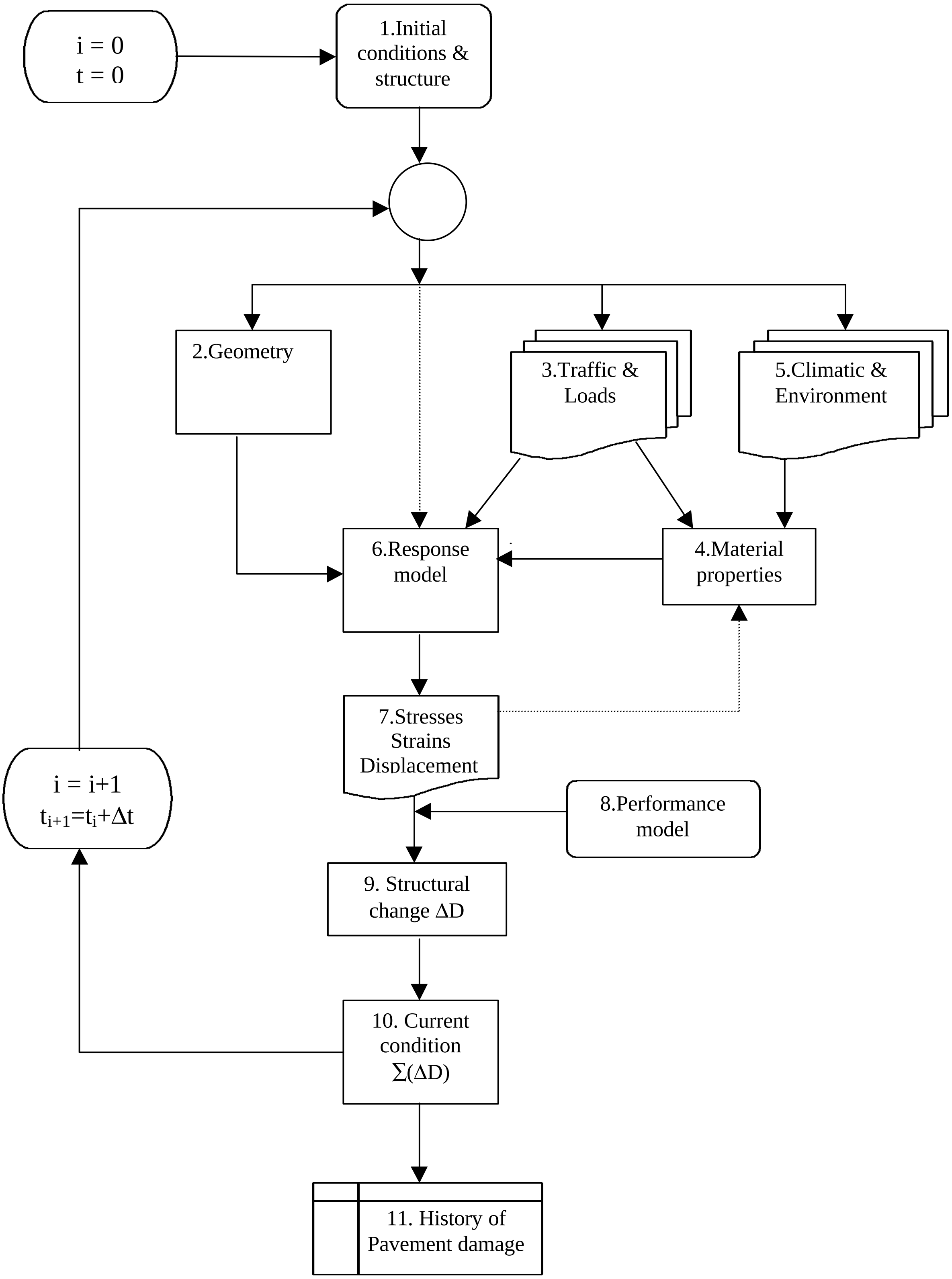


Figure 2 : Flowchart of an incremental pavement design procedure.

1.4 Summary of the proposal

1.4.1 Goals and objectives

The need of a more comprehensive mechanistic pavement design model has been recognised by the Directorate for Transport of the European Commission. To meet these objectives, two actions involving co-operation between several European countries, COST 333 and AMADEUS, were supported by the Commission.

COST 333 "Development of new bituminous pavement design method" was a concerted European research Action that focused towards information gathering, identification of requirements and selection of design elements. This would be a first step towards the development of a coherent, cost-effective, harmonised pavement design method.

The AMADEUS project was initiated by a Consortium of 15 partners already involved in the COST 333 action, with the purpose to evaluate existing advanced analytical pavement design models. A sound basis of information and knowledge in this field was already available from the work carried out by COST 333.

A number of advanced pavement deterioration and response models have been developed in the recent past. As these models describe only a limited number of failure phenomena and as they are relatively unknown to most potential applicants in Europe and sometimes require large computational facilities, some of them have not been incorporated into daily design activities.

The main objectives of AMADEUS were :

- To evaluate existing, advanced, analytical pavement design models by comparing their predictions using standard inputs. The ability of these models to deal with different materials, pavement construction, climate and traffic characteristics would be considered.
- To issue recommendations and guidelines to promote appropriate use of these design models.
- To set up the elements for a comprehensive design method integrating a number of distress phenomena with their evolution and mutual interactions.

AMADEUS was intended to provide a thorough and well-documented evaluation of existing, advanced, design models and to recommend whether these advanced models are suitable as design elements for a comprehensive mechanistic design method, in which a large number of distress phenomena are integrated. Spreading best practice of these methods will foster the use of the available, advanced methods.

1.4.2 Approach

The work of AMADEUS project was planed over 18 month period, following the work package (WP) or task distribution presented in table 3a and along the time schedule presented on table 3b. Figure 3 shows how the manpower resources were distributed over the six work packages.

WP2 “Elaboration” started by making an inventory of existing design models and software tools. An internal workshop was organized to present selected products and exchange experiences and ideas with the producers and developers. Then partners could progressively get familiar with the design models and their implementation. Six evaluation teams were formed among them to perform the evaluation (task 4) of the models.

In WP3 “Specification” the partners decided to split the evaluation into three progressive phases. This task consisted in setting up the terms of the cases to analyse with the models during execution of the three evaluation phases.

WP4 “Evaluation”, was an essential part of the project consisting in modelling the behaviour of selected pavement structures by using different computer codes and/or models. A deliberate choice of existing advanced analytical models based on clearly different approaches was made. The evaluation of these methods would identify the points on which each tool allows a definite breakthrough. It would also serve to determine their technical and practical shortcomings.

Starting from the strong points of the different evaluated models, guidelines for practical use of these models were set up in task 5. Therefore the knowledge of the existing loading and environmental conditions, material properties and behaviour laws are essential information that were made available through the COST 333 action.

Table 3a : Structure of the AMADEUS work-plan in terms of tasks.

Contents	Leader	Task No	Sub Task	Contents
WP1 Management	BRRC	1		Management
WP2 Elaboration	BRRC	2.1		Inventory of issues
		2.2		Inventory of models
		2.3		Demonstration workshop
		2.4		Detailed elaboration
WP3 Specification	BUGH	3		Specification of conditions for model testing
WP4 Evaluation	BRRC	4.1	4.1.1	Simple structures
			4.1.2	Accelerated load tests
			4.1.3	Long term performance
		4.2		Analysis and collation
		4.3		Recommendations
WP5 Design Guidelines & Future developments	TRL	5.1		Guidelines
		5.2		Plans for integrated model
WP6 Dissemination	LNEC	6		Disseminate results to potential users

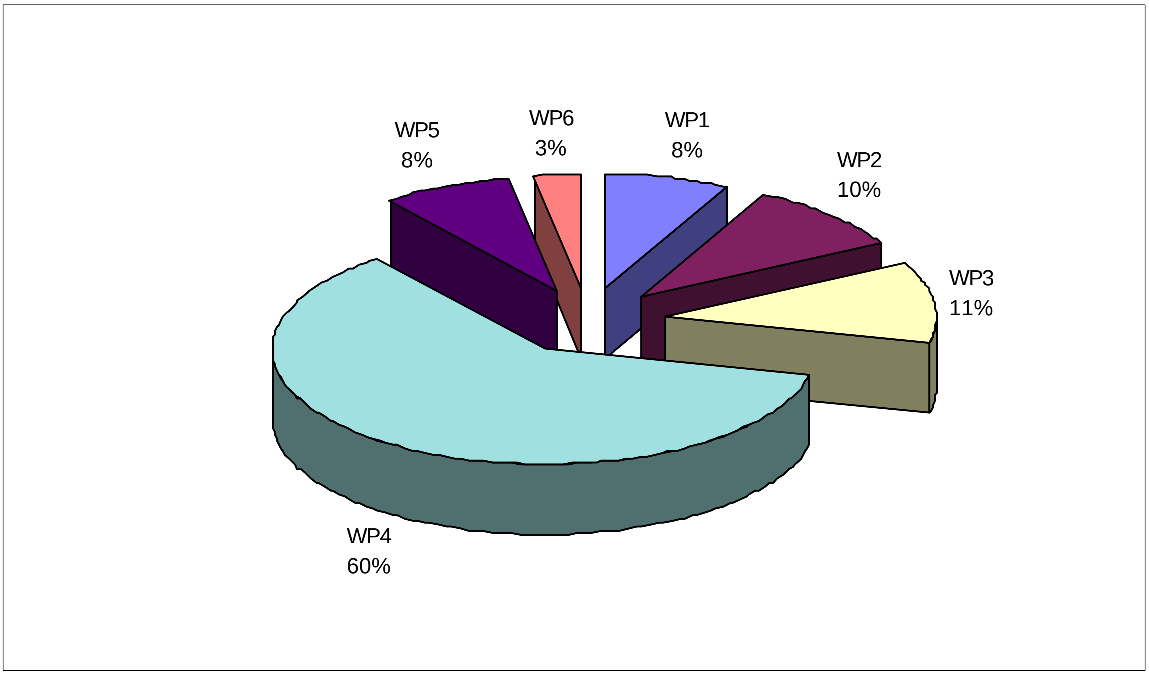


Figure 3 : Distribution of manpower in the AMADEUS tasks.

Table 3b : AMADEUS Initial time planning of the tasks

Year		1998												1999					
WP	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
I		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
II	2.1	⬛	⬛	⬛															
	2.2	⬛	⬛	⬛															
	2.3			🟥															
	2.4				🟥														
III			⬛	⬛	⬛														
IV	4.1				⬛	⬛	⬛	⬛	⬛	⬛									
	4.2							⬛	⬛	⬛	⬛	⬛	⬛						
V	5.1												⬛	⬛	⬛	⬛	⬛		
	5.2														⬛	⬛	⬛	⬛	⬛
VI					⬛								⬛	🟥					🟥
Deliverables				1,2	3								4	7		5			6,7
Links with COST 333			1	2				3					4						

Deliverables:

1. Detailed project elaboration report (Task 2.4)
2. Consortium Workshop (Task 2.3)
3. Specifications and data to be treated (WP3)
4. Model evaluation report (Task 4.2)
5. User's guide (Task 5.1)
6. Project plan for the comprehensive design method (Task 5.2)
7. Dissemination and presentation at RISC’99 Conference (WP6)

Links with COST 333:

1. AMADEUS mentions where input data are not available
2. COST 333 gives additional information on the request
3. AMADEUS informs COST 333 on the results of the models evaluation
4. AMADEUS model evaluation report available for COST 333

2. ELABORATION

2.1 Requirements

The review of the requirements and deterioration mechanisms of the main pavement components has demonstrated that there is some discrepancy between the modes of pavement deterioration perceived by the members and also verified in recent or undergoing studies on pavement performance, and the modes of pavement deterioration on which current pavement design methods are based.

In the frame of COST 333 action an inquiry was made in 1997 by Mike Nunn and Darren Merrill (TRL) on current design methods used in Europe. As shown in table 4 the two criteria that are generally taken for structural pavement design, i.e. fatigue cracking and permanent deformation, of the subgrade are located far below in the ranking of the observed pavement deteriorations.

Table 4 : COST 333 inquiry on pavement design practices.

Ranking of the observed deterioration
1. Rutting in asphalt
2. Loss of skidding resistance
3. Surface cracking
4. Longitudinal unevenness
5. Wheel-path cracking
6. **Cracking from bottom of base**
7. Ravelling
8. **Rutting in subgrade**
9. Frost heave/ low temperature cracking/ studded tyre wear

In fact, some frequently observed deterioration mechanisms, such as rutting originating in the bituminous layers, and cracking initiated in the surface, are not directly taken into account in current pavement design methods. It is recommended that more research effort is put into developing new improved models for pavement design, which provide better explanation to the observed deterioration mechanisms.

As a first step in this research, the evaluation of existing advanced design models to be performed under the AMADEUS project should lead to the definition of which features can be addressed by the use of these models, and to the identification of new areas where further development of these models should be performed.

2.2 Review of models and softwares

Prior to carrying out a detailed study of the existing models and software products, the members of the AMADEUS consortium considered as essential to define the role of the eleven design elements identified by COST 333 as parts of a comprehensive design procedure. These definitions would help in classifying the different existing products while clarifying the main lines along which the evaluation would proceed during task 4.
One of these elements, the response model, is of particular importance because it is the heart of any design method and the principles on which these elements are based determine to a large extend the final result as well as the field of application of a given model.

In the following sections we will give a more precise description of what a response model is, after that a short definition will be given of the eleven design elements and the way incremental procedure might be implemented**.**

This preliminary work will then be used as the basis for a classification of models and their later evaluation.

2.2.1 Response models

A response model is the computing algorithm which will supply the response of the structure to a given load in terms of stresses, strains and displacements. It is an essential element in the pavement design procedure described above.

According to the type of traffic loads and climatic conditions, the type of damage concerned, the structure considered and the nature of the component materials, different types of response models can be used.

A short review presented hereafter will help in the understanding of the different approaches that are available and how they were progressively developed

Semi-infinite half space

In 1885 Boussinesq solved the equations for the response of a semi-infinite elastic solid. His basic assumptions were:

1. Static equilibrium.
2. Compatibility (continuous solid material).
3. Hooke's law.

Based on these assumptions, he established a fourth order differential equation that he solved for a point load perpendicular to the surface and for the center line of a circular load. Boussinesq's closed form solutions are very simple and allow the calculation of stresses, strains, both normal and shear, as well as displacements at any point of the halfspace under a point load or at the center line of a circular load.

Boussinesq was aware that the equations might not be valid for non-solid materials and had developed a theory for stresses in a granular medium, assuming the shear modulus to be proportional to the hydrostatic stress (Boussinesq, 1876).

In 1934 Fröhlich showed that the vertical stress was more "concentrated" than the stress predicted by Boussinesq's equation. Fröhlich suggested that the major principal stress should be calculated from:

$$\sigma_1 = \frac{nP}{2\pi R^2}\cos^{n-2}\Theta$$

where P is the point load,
R is the distance from the point load,
Θ is the angle with vertical, and
n is the "concentration factor", with n = 3 one obtains Boussinesq's equations.

Veverka (1973) showed that the conditions of equilibrium and of compatibility required a variation of modulus with depth if the concentration factor was different from 3:

$$E = C \times z^{\frac{n-1}{2}}$$

where E is the modulus,
z is the depth, and
C is a constant.

From the vertical stresses measured under a plate load on a granular material, Veverka found stress concentration factors, n, of 3 – 5.

Van Cauwelaert (1980) used Veverka’s stress measurements in an analysis where he assumed the granular material to be cross anisotropic, and found the modulus in the vertical direction to be two to three times the modulus in the horizontal directions.

In a granular material there are forces between the grains and displacements of the grains (translation and rotation). “Stresses” and “strains” only exist as average values over a large number of grains. Harr (1977) has shown that the distribution of the expected value of the vertical normal stress within a two-dimensional representation of a particulate medium, subject to a vertical line load, will follow a normal distribution, and has formulated a method of “probabilistic stress distribution”.

In 1978 Cundall presented a computer programme “BALL” for dealing with the mechanics of particulate materials, using the Distinct Element Method (DEM). The programme operates in small increments of time, and considers the forces and movements of each individual grain, using an explicit integration of the equations of motion. In 1997 Ullidtz used DEM to show that stresses and strains in a particulate medium could be quite different from those in a solid, and that elastic and plastic deformation, including failure, could be modeled quite realistically with DEM.

Layered systems

No closed form solutions, like Boussinesq’s equations, exist for a layered system, like a pavement. The different approaches used to deal with layered elastic systems may be divided into: the Method of Equivalent Thicknesses (MET), Layered Analytical Models (LAM) and Finite Element Models (FEM). DEM has not yet been developed to a point where it can be included in a pavement design procedure.

Method of Equivalent Thicknesses. In 1949 Odemark presented a simplified method for dealing with a layered system. Odemark transforms the layered system to semi-infinite halfspaces, on which Boussinesq’s closed form solutions can be used. The transformation is done by calculating the “equivalent thickness” in such a way that the stiffness of each layer is maintained. The algorithm is extremely fast. It may be implemented in a spreadsheet and allows MET to be used in Pavement Management Systems or in simulation of pavement deterioration, where stresses and strains must be calculated millions of times.

Layered Analytical Models are generally based on the work of Burmister (1943). They are often referred to as mathematically exact solutions, where the fourth order differential equation is solved for the given boundary conditions using numerical integration. These models give the response (stresses and strains) in any point of the pavement structure induced by a wheel load, in a multi-layered, linear elastic pavement in which the layers are treated as being horizontally infinite and resting on a semi-infinite subgrade. Originally, layered analytical models of this type only considered linear elastic isotropic layers, uniform circular loading and full bond at the layer interfaces, but now some models can consider complex interactions between the road and tyre, multiple wheel loads and complex material behaviour (cross anisotropy, visco-elasticity).

Finite Element Models are those based on the method of finite elements. This method assumes that a continuum can be divided into smaller more manageable elements. These finite elements, as the name suggests, are finite in size and together form a finite element mesh. Each element has its material behaviour defined. The behaviour of each element can be analyzed separately and the cumulative deformations of the elements brought together to give a resultant deformation for the whole structure. These models can deal with non-linear material behaviour, complex tire contact stresses and virtually any geometric condition, including pavement discontinuities. On the basis of the nodal displacements, stresses and strains can be computed at any location of the structure. A distinction should be made between plane stress/strain two-dimensional methods (2D), axial symmetric methods and three-dimensional methods (3D). Unlike layered analytical methods, FE methods need the definition of a system which is horizontally and vertically limited in space. A second distinction can be made in both models cited above on the basis of the models used to describe the material behaviour.

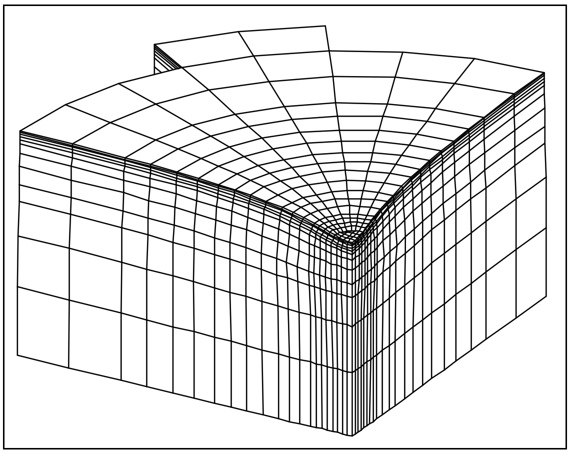


Figure 4 : Finite element mesh for single wheel loads in CAPA-3D.

When moving from MET, over simple layered analytical models, via more advanced analytical models, to axial symmetric and 3D FEM, the complexity increases, not only of the models but normally also of the input parameters required and the operation of the programmes. This increased complexity can only be justified if the response predicted by the more complex models is significantly closer to the actual pavement response, than the response predicted by the simpler models. If the more complex models do *not* improve the agreement with the actual pavement response, then the simpler models are to be preferred.

An important part of the AMADEUS project (phase 2 and 3) has been concerned with the verification of theoretical response models against measured pavement response and performance.

Having in mind the different models described above, a first fundamental distinction between the models can be based on the difference between the method used to solve the problem (multi-layer models or finite element methods).

2.2.2 Full performance and design procedures

- Performance and design procedures are more comprehensive than response models in that they contain a response model that is connected to other models or design elements in such a way that they constitute a tool allowing prediction of performance and pavement design. The flowchart presented on figure 2 is an example of such a flow chart.
- The manner of how the user interface is designed can prevent access to the response model and its output. In the case of a design model, the inputs are used in the response model and the pavement response is automatically checked to see if it satisfies specific design criteria. Often these models include software routines to automatically refine the structure to produce optimum pavement design solutions. Pavement performance models use output from the response model to predict some performance indicator using pavement performance transfer functions. The development of cracking, longitudinal unevenness and rutting can be predicted using such models.

2.2.3 Definition of the design elements

A programme can deal with each of the eleven design elements that were identified by COST 333 and depicted on the flowchart of figure 2, if the following conditions are satisfied:

1. **Initial conditions and structures :** The basic input data set required to run a response model. This consists of the initial material properties, geometry of the pavement structure and traffic loading conditions. All programmes require such a data input set.

2. **Geometry :** This element covers the ability of a programme to deal with changes that occur in the pavement layer geometry during the course of a calculation. This involves changes in layer thickness, internal boundaries, development of cracks, longitudinal unevenness, etc. that result from traffic loading and climatic effects.

3. **Traffic :** The programme can model compound traffic, load spectra and complex wheel configurations.

4. **Material properties :** The programme can select material characteristics from a database or generate the characteristics using models supplied with details of the constituent components of the materials.

5. **Climatic and environmental conditions :** The programme uses detailed climatic data to model a structure in a given location. This is either provided from a database or a detailed description of the climatic conditions is requested.

6. **Response model :** The programme calculates response at a number of locations that can be chosen freely by the user, and this can be used for performance evaluation and/or design purposes.

7. **Stresses, strains and displacements :** A complete set of calculated response parameters, at any location in the structure, can be accessed by the user. The response parameters are :
   - components of the stress tensor (in LE analysis),
   - 3 principal stresses,
   - components of strain tensor,
   - 3 components of displacement.

8. **Performance models :** The programme can select performance criteria or models from a database or generate these models using details of the constituent material components. The main performance criteria concerned are:
   - Cracking due to fatigue of bound layers
   - Rutting and permanent deformation
   - Ageing
   - Low temperature cracking

9. **Structural change :** The programme can calculate increment of damage caused by a small number of loads applied in a particular period under fixed conditions.

10. **Current condition :** The programme can progressively accumulate the incremental damage by adding (linearly or non linearly) the damage occurring in each iteration to the previous damage.

11. **Complete history of the pavement :** The programme can give the complete evolution of the pavement condition over long periods of time is recorded.

Any further evaluation of the design elements of existing models will be made on the basis of these definitions.

2.2.4 Incremental procedure

Condition 11 implies the possibility to repeat many incremental loops in which the effect of the damage on the design elements 2, 4, 8 is taken into account.

In this procedure, called “incremental”, design elements 9 and 10 should include changes in the structural properties of the pavement materials in addition to damage. For example, the stiffness modulus of asphalt will change as fatigue damage occurs and this should be recorded for each iteration. Without this broader definition ageing cannot be handled within the framework defined in figure 2.

2.2.5 Inventory of models

A review of the available, advanced analytical methods allowing the structural analysis of pavement structures was made and a list of potential tools for further studies was set up (see table 5). The review of the model was made by taking into account the analytical approach used (multi-layer or finite element) as well as the coverage in terms of material properties, performance laws and external factors.

Not all the existing tools were retained for the project; a selection of the most promising and practical ones was made, by taking into account criteria and characteristics such as :

- type of model (visco-elastic, non linear, etc.),
- calculation method (multi-layer, finite elements),
- dimensions (2D, 3D),
- required hardware (P.C., work station, main frame),
- required input data,
- full scale validation,
- availability of the software for use in AMADEUS.

2.3 Results of the first inquiry and questionnaire

The inventory of modelling and design programmes was made on the basis of a comprehensive questionnaire that was set up at BRRC and widely distributed in December 1997. This questionnaire was intended to gather information concerning :

- General features and identification of the product.
- Basic principles and type of damage addressed.
- Input data needed to run the model.
- Type of output obtained from the model.

The results of the inquiry are collated and summarised in table 5. The response concerned 17 different models from Europe or outside Europe. They can be distributed into two basic model types : the multi-layer methods and finite element methods. It can be derived from this result that most of the issues and damage features mentioned in the table are addressed by at least one programme, but on the other hand there is no programme or model that is able to take them all into account.

Some of the models referred to in table 5 were not used in the evaluation, due to lack of availability.

Table 5 : Inventory of existing models and design software products.

Software Name	Method Used in response model	Type *	Non Linearity	Rheology	Anisotropy	Interface	Climatic effects	Dynamic loading	Axle spectrum	Tyre characteristics	Stochastic	Crack propagation	Thermal effects	Cumulated damage	Fatigue	Permanent Def
APAS-WIN	Multilayer	3					Y		Y	Y			Y		Y	
AXYDIN	Axi-symmetric FEM	1						Y								
BISAR/SPDM	Multilayer	3				Y	Y		Y						Y	Y
CIRCLY	Multilayer	3			Y	Y			Y	Y				Y	Y	
CAPA-3D	3D-FEM	3	Y	Y	Y	Y		Y		Y		Y	Y	Y	Y	Y
CESAR **	3D-FEM	3	Y	Y	Y	Y	Y	Y		Y	Y	Y		Y	Y	Y
ECOROUTE **	Multilayer	1				Y				Y				Y		
ELSYM 5	Multilayer	1														
KENLAYER	Multilayer	2	Y	Y		Y		Y		Y				Y	Y	Y
MICHPAVE	Axi-symmetric FEM	1	Y												Y	
MMOPP	Multilayer	2	Y				Y	Y	Y	Y	Y	Y		Y	Y	Y
NOAH	Multilayer	3			Y	Y	Y		Y		Y				Y	Y
ROADENT/WESLEA ***	Multilayer	2				Y	Y		Y	Y						
SYSTUS	3D-FEM	2	Y	Y	Y	Y		Y		Y		Y				
VAGDIM 95	Multilayer	3					Y						Y	Y	Y	Y
VEROAD	Multilayer	1		Y					Y	Y	Y					
VESYS	Multilayer	3					Y		Y	Y	Y			Y	Y	Y

* See section 2.4.

** Model not used in the project due to lack of availability.

*** Only the response model “WESLEA” was evaluated in the project.

2.4 Classification of models

A ranking of the models in three categories, or types as shown in table 5, was made based on the principles given hereafter. A first fundamental distinction between the models can be based on the difference, as mentioned above, between multi-layer models and finite element methods (2 or 3D). Noting the difference in the complexity of available software programmes and incorporated models, and their different usage or purpose, although all in context of pavement design, it appeared necessary to distinguish six main elements in a full design procedure (corresponding to the flowchart presented in figure 2):

a) **Input of the response model** : concerns the input data relative to the structure geometry, traffic conditions, climatic conditions and material properties. These data can come from outside information or can be partially included or predicted inside the model (material properties and their dependence on climate for example).
b) **Response model** : computing algorithm which will supply the response of the structure in terms of stresses, strains and displacements.
c) **Output of the response model** : values of the stresses, strains and displacements at any location of the structure.
d) **Inputs for performance model** : data required to apply the material performance laws from which the evolution of the pavement condition can be predicted. This concerns the stresses strains and/or displacements at critical locations of the structure. Other external input data (thermal characteristics, ageing, statistical variations, etc. …) may also be added at this stage.
e) **Performance models** : relations between the inputs described in d) at critical locations of the structure and their influence on the pavement condition. Damage accumulation and comparison with critical conditions must be considered at this stage for pavement design purposes.
f) **Outputs of the full design procedure** : concerns the evaluation of the pavement condition over time. These must be used to make the decision on whether a given structure is acceptable or not. These outputs can also be fed back at point a) as new or modified inputs for applying the response model iteratively over time. In this last case we will have an incremental procedure.

Existing tools can be roughly distributed over three categories depending on their coverage on the six model elements described above.

Type 1: **Response models** : programmes that only provide results of calculations with regard to stresses and strains (items a),b) and c)).

Type 2: **Response + (partial) performance** : programmes that consider the effects of loading, climate, etc. on rutting, crack initiation and progression, etc. but do not provide a full design procedure with results as stated below (items a),b) and c) and partially d) and e)).

Type 3: **Full design procedure** : programmes that are able to provide the user with a recommended pavement structure (layer thickness, necessary materials, etc.) and/or long term performance(LTPP) predictions (items a) to f)).

3. SPECIFICATION

3.1 Planning of the evaluation procedure

Specifications of typical design conditions for testing advanced models were prepared prior to start of the evaluation procedures.

The logical layout of the flowchart of figure 2 was used to define three steps to follow during the evaluation and to decide which elements of each software should be examined at each step of the evaluation.

The conditions used as input had to be representative of European situations relevant to traffic and climatic conditions and to (flexible or composite) pavement structures.

- **Phase 1 : Evaluation of the response models** (type 1 in table 5) under simple conditions. Three layer structures under fixed material properties and loading conditions were used it this case, and the response of the different simple models evaluated as compared.

- **Phase 2 : Medium and advanced models**. Evaluation of the response models (stresses/strains displacements, deflections) for monitored test tracks of CEDEX, DTU and LAVOC including variable conditions of temperature.

- **Phase 3 : Implementation** of type 3 models on real situations related with Long Term Performance Projects (LTPP). The choice of the pavement structures and conditions should preferably match actual situations existing in LTPP studies. Such information was selected in large monitoring projects such as those existing in Germany.

Four to six groups working in parallel performed the exercises included in the three phases of evaluation. This evaluation was completed by assessments based on the following criteria:

- added benefit of using the model,
- input complexity,
- limitations of use,
- existing validation,
- field of application.

For reasons of consistency this information was to be given in a standard questionnaire. Different evaluation group leaders reported the results of the model’s evaluation.

Based on this, a number of models would be selected as the most appropriate for pavement design purposes, taking into consideration the relevant deterioration mechanisms and the agreement with the observed long term behaviour of full scale sections or accelerated loading test results (defined in task 2.4).

3.2 Short description of the models selected for evaluation

Models used in phase 1 only

AXIDIN

AXIDIN is an axi-symmetric, finite element response model for analysis of pavement under dynamic loading. This model was primarily produced as a research tool for interpretation of dynamic, non-destructive test results (Falling Weight Deflectometer) on pavements, however, it may also be applied to the problem of dynamic loads induced by moving heavy goods vehicles.

ELSYM5

ELSYM5 is an axi-symmetric response model based on multi-layered, linear elastic analysis. ELSYM5 was adapted to run on personal computers and is a modification of the LAYER5 model, which was developed at the University of California. ELSYM5 follows other multi-layer models in that the layers are assumed homogenous and extend infinitely in horizontal direction and into the subgrade. Loading is also conventional and can be defined in terms of single, dual or more than two circular loaded areas of uniform, vertical contact stress.

WESLEA

WESLEA is a conventional multi-layered, linear elastic pavement response model developed at the U.S. Army Waterways Experiment Station. Up to 5 isotropic layers can be defined together with up to 50 output points. Slip at the interface between layer can also be specified.

Models used in phase 2 and other phases

CAPA3D

CAPA-3D is a 3D finite element code developed at the Structural Mechanics Section of TU Delft and is under continual development. The complete system consists of a mesh generation facility with pre and post data processing capability, the main finite element code and an analysis data post-processing facility. All these facilities are integrated in a Windows based user interface.

KENLAYER

KENLAYER is a pavement response and performance model, which incorporates non-linear and visco-elastic behaviour. The basis of KENLAYER is a conventional multi-layered, elastic model under a single, circular load area. Multiple loads can be defined in terms of groups of 6 loads with a possible maximum up to 24 groups. Non-linear and visco-elastic behaviour is approximated using an iterative process. Non linear behaviour is restricted to unbound layers while visco-elasticity in the bound layers is characterised by the creep compliance curve.

MICHPAVE

MICHPAVE is a non-linear, axi-symmetric finite element response model. Produced in 1989 at the Department of Civil and Environmental Engineering of Michigan State University, it is a development of the ILLI-PAVE model (Thompson, 1986). The primary use of this software is for modelling the response of flexible pavements and it is intended to be an improvement over conventional multi-layered, elastic programmes.

SYSTUS

SYSTUS is a general, finite element code developed by FRAMATOME. Possibilities with this model include static and dynamic analysis, analysis of large displacements, non-linear behaviour. Interface conditions can be specified to simulate slip, friction sliding or fully bonded conditions. Fracture mechanics capabilities are included and the possibility to have user defined material behaviour.

VEROAD

VEROAD is a linear, visco-elastic multi-layer programme. The theory behind the programme is analytical and based on the ‘correspondence’ principle. This principle states that a visco-elastic problem in the time domain, is an elastic problem in the frequency domain. This enables Fourier transform techniques for the time dependent parts (position of the load and properties of the material) to be applied.

Models used in phase 3 and other phases

APAS

APAS is a modern software tool for pavement thickness design. It was produced by the Finnish Road Administration together with NESTE Bitumen in Finland. In addition to being able to calculate the layer thicknesses of new structures, APAS can also be used when designing rehabilitation of an existing pavement structure based on Falling Weight Deflectometer (FWD) measurements.

BISAR

The current version of BISAR runs under Windows 95/98 and is contained within SPDM3.0. This model is a linear elastic, multi-layer programme which can accept to 10 loads defined in the vertical direction and also in unidirectional horizontal shear. Interface slip between each layer can be defined.

CIRCLY

CIRCLY is a software package based on multi-layered, elastic theory that allows the analysis of a comprehensive range of load types. It originates from software developed at CSIRO (Harrison, Wardle and Gerrard, 1972) and has been under continuous development since its release in 1977. The current version of CIRCLY includes the addition of multiple loads and polynomial type radial variation in contact stresses to enable a more realistic representation of actual loading conditions (Wardle, 1977).

MMOPP

The Mathematical Model Of Pavement Performance (MMOPP) simulates the deterioration of a length of road under the influence of dynamic loading, climatic effects and time. It is based around a conventional multi-layered elastic model which accepts single and dual loads by superposition. Damage is calculated using an incremental-recursive procedure for sections of pavement that have varying material properties and layer thicknesses as would be expected in reality. MMOPP takes into account seasonal temperature variations and dynamic loads.

NOAH

The NOAH model contains a conventional, linear-elastic, multi-layer response model. It is set-up to enable the user to derive the maximum benefit from this simple model. The software includes databases of load conditions, material properties which can be defined by the user. User defined variations in temperature, stiffness and layer thicknesses can be set and then all the cases calculated at once. An output processor is provided to easily view the effect of the defined variations. NOAH is applicable to sensitivity studies in which one investigates the sensitivity of pavement performance to variations of any of the involved input parameters.

VÄGDIM95

VÄGDIM95 was developed as a user-friendly and flexible system for structural design of pavements. Design can be performed with regard to both bearing capacity and frost heave. The frost design procedure follows an earlier established Swedish method. For the bearing capacity design, the CHEVRON programme is used which is a conventional multi-layer, linear elastic programme.

VESYS-3PC-RD

VESYS was originally developed by the FHWA in the USA. This version of VESYS adapted at the University of Wuppertal (Germany), concentrates on the calculation of rut depths. Considerable modifications were made to include such features such as estimation of material parameters from laboratory test results, load spectra and the lateral distribution of loads. Output from this model is the predicted permanent surface deformation at 150mm transverse intervals across a 2400mm width.

3.3 Selection and distribution of the models

The models included in AMADEUS were selected in the following way. The 15 partners were asked to mention, among the pavement models identified in the first inquiry (see 2.3), those which were of potential interest to the project. Others were submitted voluntarily by interested parties. The Project Co-ordinator, BRRC, then contacted those responsible for the models to ask for their co-operation and permission to use the models in AMADEUS and, where necessary, special license agreements were set up with the partners. Several candidate models could not be used either because they were still research tools and not sufficiently developed for general use, or because ownership problems needed to be resolved, or because the license agreement would severely restrict their use within the framework of AMADEUS. The final list of models for evaluation in AMADEUS is as follows:

APAS
CIRCLY
MMOPP
VAGDIM95
AXIDIN
ELSYM5
NOAH
VEROAD
BISAR
KENLAYER
VESYS-3H
CAPA3D
MICHPAVE
SYSTUS
WESLEA

This collection of models covers a wide range of modelling methods and issues including: non-linear behaviour, visco-elastic behaviour, anisotropy, dual wheel load and non-uniform wheel loading, dynamic response, stochastic variations of parameters and temperature effects.

The models were grouped in three categories according to their complexity.

Simple models : ROADENT and ELSYM5.

Moderately complex programmes: AXIDIN, MICH-PAVE, VAGDIM95, KENLAYER, BISAR-SPDM and APAS.

Complex models : VESYS, MMOPP, CAPA-3D, SYSTUS, VEROAD, NOAH and CIRCLY.

3.4 Selection of the cases

The cases to be treated in the three successive phases of the evaluation were chosen in accordance to the purpose of each phase and to the level of complexity of the software packages to be tested.

- Phase 1 was carried out on a simple three-layer structure with two interface conditions and two types of loads.

- Phase 2 consisted in evaluating the response on three different structures corresponding to three accelerated loading test sites owned by partners DTU, CEDEX and LAVOC. Predicted response had to be compared to the measurements carried out at different locations in tests.

- Phase 3 concerned the prediction of the long term pavement behaviour of four monitored test sites located in Germany.

The detailed description of the structures and the corresponding input data are given in Deliverable D3 of the project. A summary of these conditions will be presented in the introductory part of the sections reporting the three evaluation phases in Chapter 4.

3.5 Material properties

Each of the accelerated test facilities and full scale test sections has its particular features and testing variables. Hence the implementation of the different programmes required a very detailed description of the structures materials and environmental conditions to be modelled. Although the detailed description of these test sections was given in Deliverable D3, it appeared in some cases and for some models that input data was not available. In such cases, the users had to base the evaluation on default values derived from the design elements 3 (Traffic and loads), 4 (Material properties), 5 (Climate and environment) and 8 (Performance model) of the flowchart, when they existed in the models.

Otherwise these data had to be derived from outside the programmes either by the use of other prediction methods such as BANDS or PAMINA programmes (mentioned in Deliverable D3) or by taking realistic assumptions to be corrected by trial and error.

BANDS : BANDS 2.0 is a programme developed by Shell, as one of the packages in the series of Shell Pavement Design software packages, together with BISAR 3.0 and SPDM 3.0 (the Shell Pavement Design Method).

BANDS contains tools to assist the pavement designer in estimating relevant material properties of the bituminous binder and the asphaltic mix for use in thickness design related calculations. BANDS provides calculated material properties for a large range of conditions and compositions.

PAMINA : As an outcome of the COST 333 action, this programme has been developed at BRRC for the specific needs of the AMADEUS project and more generally for supporting modelling and design exercises. Properties such as the modulus, fatigue laws and permanent deformation law can be derived from the knowledge of the mix composition and binder properties.

4. EVALUATION

4.1 Phase 1 : Comparison of the response models

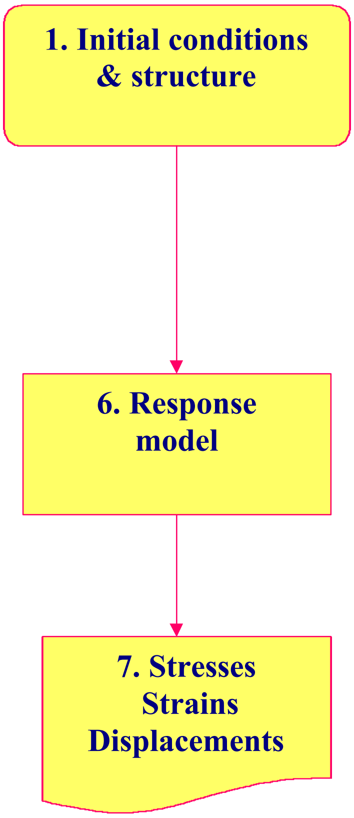


Figure 5 : Design elements involved in evaluation phase 1.

4.1.1 Approach

A desk study was carried out to compare the predictions of response models using simple pavement structures and identical loading conditions. The purpose of phase 1 was to :

- become familiar with the new models in preparation for the later more complex evaluation phases,
- compare the results of the different models in terms of stresses, strains and displacements,
- compare the results obtained by the different users with the same model.

In this first phase of the evaluation, the 15 partners were asked to test 14 software packages and models. The exercise, consisting in the calculation of the response of theoretical pavement structures, was performed on a three-layer flexible structure with two interface conditions combined with two assumed loading conditions (single and dual wheels) as described below.

4.1.2 Phase 1 evaluation teams

Initial planning proposed by WP3

In the initial planning proposed in the WP3 specification work package, the partners were distributed over six evaluation teams to perform phase 1 of the evaluation. Evaluation teams C1-C6 are shown in table 6, together with the programmes assigned to each team. Each team was placed under the leadership of one of the main contractors**.** All 14 selected programmes were supposed to be used at this stage. Two simple programmes (ROADENT/WESLEA and ELSYM5) were assigned to all partners, moderate (type 2) programmes were assigned to two teams and one complex programme was assigned to each team.

Table 6 : AMADEUS Evaluation teams in phase 1.

Team	C1	C2	C3	C4	C5	C6
Leader	TUD	TUD	BRRC	BRRC	BUGH	DTU
Partners	VTT	PRA	BUGH	VTT	TRL	LNEC
	DTU	NTUA	KTI	KTI	ISTU	PRA
	LNEC	LNEC	DDC	DDC	VTI	VTI
	TRL	TRL	LAVOC	LAVOC	CEDEX	CEDEX
	NTUA			ISTU	DTU	
Complex	CAPA	VEROAD	SYSTUS	NOAH	VESYS	MMOPP
Moderate	AXIDIN BISAR-SPDM		KENLAYER APAS		MICH-PAVE VAGDIM95	
Simple	ROADENT-WESLEA ELSYM5					

Actual distribution of models in phase 1

In practice it appeared that some programmes were not fully operational yet at the time phase 1 started. Other programmes of types 2 and 3 were not able to output the information and data required in this phase. These were primarily performance models in which the internal response model could not be easily separated from design calculations.

This resulted in a smaller number of models tested than initially planned. The models evaluated in phase 1 were distributed across the partners of AMADEUS.

4.1.3 Selection of the cases

Structures

The calculations in phase 1 were performed using one structure (ST1 in table 7). The structure used was derived from information on the RILEM 152PBM Long term performance tests sections in Villach, Austria and Mindelo, Portugal (Francken et al 1997). The constructions at these sites, which are on heavily trafficked primary roads and motorways, are similar and can be considered identical for this task.

Table 7 : Structure ST1 used in phase 1.

Layer	Thickness (mm)	Modulus	Poisson s ratio	Interface
Asphalt	260	5000	0.35	
				Smooth/Friction
Granular	500	200	0.4	
				Friction
Soil	∞	50	0.45	

For the same type of structure, two interface conditions (FR or SM) and two loading conditions (a single (LC1) and dual (LC2) wheel load) were considered. As shown in table 9, up to four sets of calculations were carried out using each model.

Table 8 : Different interface and loading conditions used in the four cases proposed to test response models in phase 1.

	Loading condition	
Interface condition	Single wheel	Dual wheel
Friction	ST1-FR-LC1	ST1-FR-LC2
Smooth	ST1-SM-LC1	ST1-SM-LC2

Output requirements

Each calculation involved predicting the pavement response at various points in the pavement structure. At each location one or more of the following parameters had to be computed:

σ_{z1} = Vertical stress at the surface.
ε_{t1} = Horizontal strain at the bottom of the asphalt layer.
ε_{z2} = Vertical strain at the top of the subbase.
ε_{z3} = Vertical strain at the top of the subgrade.

In the comments made further in this chapter on the results, the response parameters will be referred to by the labels assigned here above.

Location of the output

The output was requested at a number of depths in the pavement structure and two horizontal locations.

For the case of the single wheel, the horizontal locations were under the centre of the loaded area and under the edge of the tyre. For the case of dual wheel load, the locations were under the centre of one of the wheel loads (position A) and mid-way between the two wheel loads (position B).

It should be stated that the results presented in this report are based on a limited number of calculated values located at three depths; $z_1 = 0$ at the surface, $z_2 = 260$ mm at the bottom of the asphalt layer and $z_3 = 760$ mm at the top of the subgrade.

These depths are critical locations close to or at the interfaces between layers. Calculated responses can change abruptly in these areas so that large errors are possible from very small changes in the depth introduced as input.

4.1.4 Results of the evaluation

Table 9 presents the list of programmes actually evaluated in phase 1 with their respective possibilities with regards to the cases proposed. As mentioned in chapter 3.1, some of the models, selected for the AMADEUS project, could not be tested in phase 1 and 2. Some because they were primarily performance models, where the internal response model could not be easily separated from the calculations or others because they were considered too complex to justify its use for these simple constructions.

Table 9 : Cases studied with the different software packages in phase 1.

	ST1-FR		ST1-SM	
	LC1	LC2	LC1	LC2
APAS	⊗	⊗	–	–
AXIDIN	⊗	–	–	–
BISAR	⊗	⊗	⊗	⊗
CIRCLY	⊗	⊗	x	x
ELSYM5	⊗	⊗	–	–
KENLAYER	⊗	⊗	⊗	⊗
MICHPAVE	⊗	–	–	–
NOAH	⊗	⊗	⊗	⊗
VAGDIM	⊗	–	–	–
VEROAD	⊗	–	–	–
VESYS	⊗	–	–	–
WESLEA	⊗	⊗	⊗	⊗

⊗ Possible and tested
x Possible but not tested
- Impossible with this software

Output from the response models evaluated in phase 1 was compiled in two ways. The first was to group the output from each user by model. Thus enabling the comparison of the results from the different users. A variance was calculated for each set of responses to give a numeric measure of the differences between the users. The second compilation of results was to group the results of all the models together. Here, the results chosen to represent the model table were modal values rather than mean average values. This was because inevitable user error will distort the results and make reliable comparison impossible. Some judgement was necessary in compiling the results of different users in a single representative value.

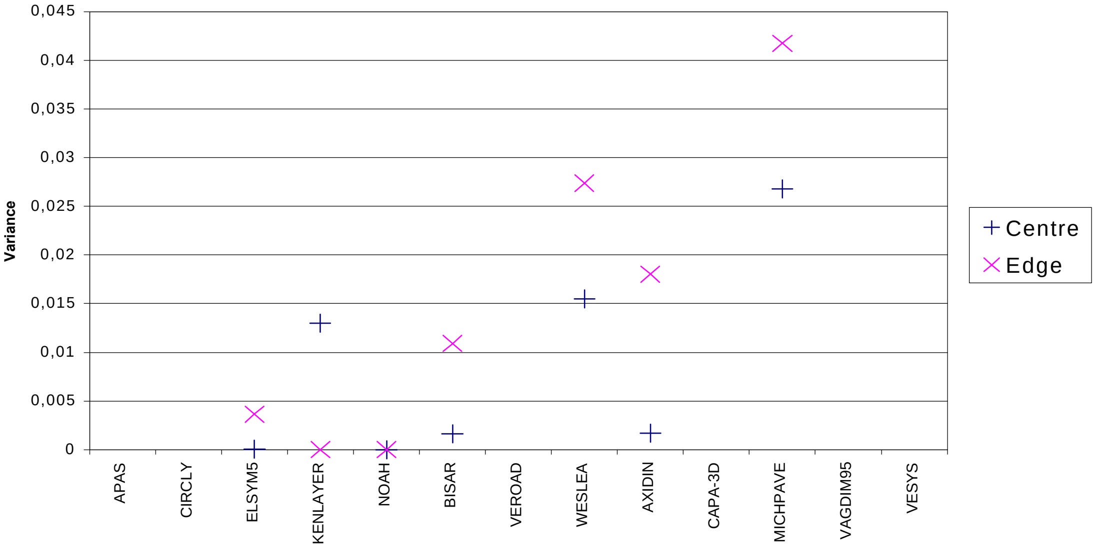


Figure 6 : Variances of different models at the centre and edge of the single loaded area [Include only programmes tested in phase 1].

Summary of the variability between different users

In general there is variability in the results given by the users which in theory at least should not occur if each user is using precisely the same input data. For consistent results in later performance predictions and pavement design, this variability should be small or negligible.

From the work it has been found that in many cases users gave erroneous results through confusion at in both the input stage of the model and also when presenting the output. Smaller errors or variances were seen due to rounding of the data.

To give an overall numerical comparison between the model a variance has been calculated for each analysis case. An overall figure for all the cases for each model is not given because not all models can compute all the cases with significant difference in the variances of each case, this will distort the results unnecessarily. The base case for comparison in which the maximum number of models was able to compute an answer was for a single wheel with full friction between the layer interfaces.

For the cases with smooth interfaces between layers, the variability in the results markedly increases over the fully bonded cases. This is largely due to the manner in which the interface condition is defined.

The variance of the results from finite element models was not necessarily higher than those from analytical type models.

Summary of the variability between different models

One objective of phase 1 of AMADEUS was to obtain an impression of the variability of the results between the models. Given the same input data, the models should provide similar answers, indeed analytical models should ideally give the same answers. On the other hand, finite element models should provide similar but not identical solutions given the inherent variations due to particular approximate solution methods employed.

The base case in which these models can be compared is that of a single wheel load and friction at the interfaces of all layers. This case can be computed by all the AMADEUS response models whereas some models, particularly those based on the finite element method, do not have the extra facilities of multiple wheel load and slip between layers. A smaller number of models can deal with dual wheel loading and smooth interfaces between layers. These were assessed later.

The results summarised in the preceding section showed considerable variation in predicted responses of the partners using the same model and input data. These differences are often the result of user error that is not the fault of the model. It would be unfair to judge the model incorporating such error therefore a method of neglecting errors must be used.

In this work some models have been used by a considerable number of partners. In this case a consensus of opinion about the “true” result should be evident. If a number of partners have used a model erroneously, they are unlikely to register results similar to each other. This consensus of opinion about the true value is harder to obtain for models where a small number of partners have used them. If no consensus on the true answer is evident, i.e. all values are different, then the most adequate method of presenting the response is to use the mean value and forsaking any obvious outliers.

Results

Using this approach, the phase 1 results are presented in the table 10.

Table 10 : Results from different models for single wheel load.

	Centre of load				Edge of load			
Software	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}
	MPa	µS	µS	µS	MPa	µS	µS	µS
APAS	0.700	-100.4	251.8	185.1	0.000	-61.8	192.0	177.5
AXIDIN	0.723	-116.0	212.0	163.0	0.386	-68.1	167.0	156.0
MICHPAVE	0.700	-91.6	238.9	129.0	0.000	-38.0	177.0	119.0
BISAR	0.700	-100.5	251.7	185.0	0.350	-61.9	192.2	177.5
CIRCLY	0.700	-93.96	246.7	185.1	0.350	-62.9	193.1	177.5
ELSYM5	0.700	-99.7	250.1	176.0	0.342	-61.1	190.7	168.3
KENLAYER	0.817	-100.5	251.6	185.3	0.319	-61.95	192.2	177.0
NOAH	0.700	-100.5	251.6	185.0	0.000	-61.9	192.1	177.4
VAGDIM	0.700	-100.5	251.6	185.1	0.327	-61.9	192.0	177.4
VESYS	0.700	-99.4			0.372	-61.5		
WESLEA	0.700	-100.4	251.5	185.0	0.000	-61.9	192.0	177.4

σ_{z1}=vertical stress on the road surface, ε_{t1}= horizontal strain at the bottom of the asphalt layer, ε_{z2}= vertical strain on the surface of the granular material and ε_{z3}=vertical strain on the surface of the soil.

Under the centre of the load, six models give almost identical answers: APAS, BISAR, KENLAYER, NOAH, VÄGDIM (CHEVRON) and WESLEA. KENLAYER appears to give different results at the surface but reasonable results elsewhere. These models are all multi-layer. Of the other models, ELSYM5 consistently gave slightly different values. It is suggested that the difference between ELSYM5 results and the majority of results from analytical models is due to error created on conversion from SI to Imperial units for computation, and then back to SI units again for presenting the results. CIRCLY also gave slightly different answers to the majority of analytical models. A possible reason for this could be the inability of this model to give results exactly at the interface as required.

Differences are seen between the finite element model results and the analytical results. AXIDIN gives an incorrect result for stresses at the surface, higher values of horizontal strains at the base of the asphalt layer and lower values for vertical stresses. MICHPAVE give the correct value of stresses at the surface but underestimates all of the other responses. The proximity of the FE results to the analytical results is largely dependent on the element size. Both these models have intrinsic limits on element sizes that can be the cause for differences between their output and the multi-layer.

Under the edge of the wheel load there is more scatter in the result. At the surface the predicted response is entirely dependent on how the software regards the output point. If the software regards the output as outside the loaded area, zero stress is given. Otherwise the models give values which are between zero and the contact pressure. In the case of BISAR and CIRCLY, this value is simply 50% of the contact pressure. Observations about the calculated responses at other depths are similar to those made directly under the wheel load.

Dual wheel load

For the case of dual wheels, just 7 of the original 14 models can compute these cases. The results from these models are presented in table 11 for two positions. Position A (x=0;y=0) is directly underneath the centre of one of the wheel loads. Position B (x=170mm;y=0) is located exactly in the middle of the two wheel loads.

Table 11 : Results from different models for dual wheel load.

	Position A (under the centre of one load)				**Position B (in the middle of the two loads)**			
Software	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}
	MPa	**µS**	**µS**	**µS**	**MPa**	**µS**	**µS**	**µS**
APAS	0.7000	-60	186	170	0.0000	-51	183	177
BISAR	0.7000	N/A	186	170	0.0000	N/A	182	177
CIRCLY	0.7000	N/A	181	170	0.0000	N/A	186	177
ELSYM5	0.7013	N/A	185	168	0.0000	N/A	184	170
KENLAYER	1.4660	-85	186	170	0.0045	-89	183	177
NOAH	0.7000	N/A	186	170	0.0000	N/A	183	177
WESLEA	0.7000	N/A	186	170	0.0000	N/A	182	177

σ_{z1}= vertical stress at the road surface, ε_{t1}= horizontal strain at the bottom of the asphalt layer, ε_{z2}= vertical strain at the surface of the granular material and ε_{z3}=vertical strain on the surface of the soil, N/A = Not Available.

Table 11 exposes a large error between what KENLAYER states for the stress at the surface and the prescribed pressure. Other models conform to this natural condition. Most analytical models produce similar answers away from the surface of the pavement for both position A and position B. The only model to produce significantly different results is CIRCLY, but this is only for the vertical strain at the top of the unbound layers.

Slip at the interface

Just four models were able to compute the cases in which there was slip at the layer interface but all four were able to handle single and dual wheels. The results for the single and dual wheel loads are given in tables 12 and 13.

Table 12 : Single wheel load with slip at layer interface.

	Centre of load				**Edge of load**			
Software	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}
	MPa	**μS**	**μS**	**μS**	**MPa**	**μS**	**μS**	**μS**
BISAR	0.7000	-120	1	217	0.3500	-78	-10	205
KENLAYER	0.7000	-120	1	216	0.0000	-78	-10	205
NOAH	0.7000	-110	111	204	0.7000	-69	91	194
WESLEA	0.7000	-122	1	43	0.0000	-81	-8	41

σ_{z1}= vertical stress on the road surface, ε_{t1}= horizontal strain at the bottom of the asphalt layer, ε_{z2}= vertical strain on the surface of the granular material and ε_{z3}=vertical strain on the surface of the soil.

Table 13 : Dual wheel load with slip at layer interface.

	Position A				**Position B**			
Software	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}	σ_{z1}	ε_{t1}	ε_{z2}	ε_{z3}
	MPa	**μS**	**μS**	**μS**	**MPa**	**μS**	**μS**	**μS**
BISAR	0.7000	N/A	-9	193	0.0000	N/A	-12	204
KENLAYER	0.5885	-103	-9	194	-0.0444	-107	-12	204
NOAH	0.7000	-93	85	184	0.0000	N/A	87	195
WESLEA	0.7000	N/A	-8	40	0.0000	N/A	-11	41

σ_{z1}= vertical stress on the road surface, ε_{t1}= horizontal strain at the bottom of the asphalt layer, ε_{z2}= vertical strain on the surface of the granular material and ε_{z3}=vertical strain on the surface of the soil. N/A = Not Available.

The results for the smooth case depend as much on the method of dealing with the interface condition of each particular model as the consistency or accuracy of the input data.

Considering the results alone, KENLAYER and BISAR are shown to produce very similar results for most of the results under both types of loading whereas. NOAH produces different results. By comparing these results to the earlier results with friction at the interfaces, NOAH's results are closer to the cases of interface friction than either KENLAYER or BISAR suggesting that the maximum amount of slip available in NOAH is lower than the other models. This difference is probably due to the type of interface model employed.

In NOAH interface slip is defined linearly using the relative displacement on either side of the interface using the following model (Van Cauwelaert, 1995).

$$I = \frac{U_i}{U_{i+1}}$$

U_i and U_{i+1} are the displacements of the upper and lower layer. It is clear that full slip cannot be defined but approached using high values of i. In NOAH numerical limitations limit the value of i to 10E+10.

BISAR uses a different interface model based on shear spring compliance, AK (BISAR-PC User's Manual, 1995). The parameter α is used to define the amount of slip in the model; a is the radius of the wheel load; E and ν is the modulus and Poisson's ratio of the upper layer respectively.

$$\mathrm{AK} = \frac{\text{the relative horizontal displacement of the two layers}}{\text{stresses acting at the interface}}$$

$$a = \frac{\mathrm{AK}}{\mathrm{AK} + \frac{1+n}{E} \cdot a}$$

In KENLAYER only two cases can be considered: full friction and full slip. Depending on the option chosen by the user the software uses a different method of solution. When full slip is chosen, it is assumed that there is zero shear stress at the interface and the appropriate modified layered solution selected (Huang, 1993). No information on the interface models of WESLEA has been offered.

It is clear that each model deals with slip in a different manner, it is therefore unsurprising that the results are different.

Users opinions on the models

During the execution of phase 1 evaluation, it was also estimated useful to gain a subjective opinion of the performance of the models rather than only to rely on the objective comparison of results. A user's questionnaire was prepared for that purpose.

It must be stressed that these opinions were formed purely within the frame of AMADEUS where the users had a short period to learn how to use the model effectively and then the model was used for a specific purpose, in pavement analysis. Some models fare badly in this particular part of the evaluation because of their complexity and also because they are designed to be applied to problems other than pavement analysis. A low opinion is not a necessarily criticism of the model as a whole.

Filling this questionnaire allowed completing the evaluation regarding the following items:

- General (type and purpose).
- Installation of the software.
- Learning the software.
- User's opinion.
- Input.
- Running the model.
- Output.
- Parametric studies.

The following section summarises in a general manner, the remarks made through the user's questionnaire concentrating of particular strengths or difficulties encountered. A more detailed description is provided for each model in Chapter 5.

APAS	The users found APAS easy to use however some limitations in the use of the formula generator were encountered.
AXIDIN	No input interface is supplied with AXIDIN hence some inexperienced users have found this hard to use. File storage and retrieval did not receive a high rating primary because the software used just one filename for input and one for output.
BISAR	The users found BISAR easy to use and was highly rated in all areas. No major problems were reported.
CIRCLY	The use of CIRCLY was viewed as fairly easy. Problems with version 3.0 of the software mostly stemmed from an inflexible system of defining the output positions and also the file management. This has been improved in version 4.0, which was supplied in the course of the project.
ELSYM5	This model operates in imperial rather than SI units. Other aspects of the software were highly rated except for the file storage and retrieval system.
KENLAYER	An average rating was given by the users in most areas with mixed views of the input interface and the output files. The only major problem encountered was in the file storage and retrieval system, only one input and one output file name can be used which can cause problems.
MICHPAVE	Mixed opinions were expressed about MICHPAVE namely related with the use of imperial units rather than SI units which is awkward for European users. Major problems encountered were the limited control allowed over the definition of the finite element mesh and its subsequent restrictions on the output positions.
NOAH	This software was rated as easy to use and particularly suited to performing parametric studies. Although computation is swift, when multiple variations of parameters are analysed, long run times can occur.
SYSTUS	SYSTUS is not typical of the software in the AMADEUS project because it is a general, high-powered finite element code and not a specifically pavement model. This caused a number of problems for inexperienced users.
VÄGDIM	The response model in this software is CHEVRON. This programme was only used by the owner (VTI) and consequently no user questionnaires were completed.
WESLEA	The users found WESLEA easy to use and did not report any major problems. The users noted that possibly not all the required responses could be calculated and that when similar runs were performed the input data had to be entirely re-entered each time.

4.1.5 Overall conclusions of phase 1

User Variability

- Variability was found in all models when users were using the same input data and the same model.
- The variability was smaller for the cases when full friction is assumed at the interface and under the load than either at the edge of the load or between the loads for dual wheels.
- The results at the surface were most variable particularly away from the centre of the load.
- The variability of the finite element models was not necessarily higher than multi-layer models.

Users Views

- Large differences have been exposed in the ease of use of each model. Also, it showed that some models require parameters which are not easily available.
- Common problems were found in the areas of file handling and where Imperial units were used.
- Some models were harder to use than others simply because of their type. For instance, the users encountered more problems with finite element codes because they are not designed specifically for use in pavements.

Results from different models

- The multi-layer models generally give similar answers to each other.
- Finite element models do not correspond entirely with the results of the multi-layer models. While this is accepted because of issues such as mesh geometry and approximation methods, it does pose the problem as to how to handle the finite element results.
- Slip between layers is handled differently by a number of methods consequently the results of each model are different.
- The features of the models are significant. All 11 models computed the single wheel load case, 7 models were able to accept dual wheel loads, 4 of these provided slip at the interface.

Final remarks about phase 1

The analysis of the results showed that most of the models based on multi-layer elastic approaches are in close agreement.

The most important differences in the models were found in :

- loading conditions (different contact areas),
- interface conditions (full friction or slip),
- ease of use.

4.2 Phase 2 : Verification based on accelerated loading tests

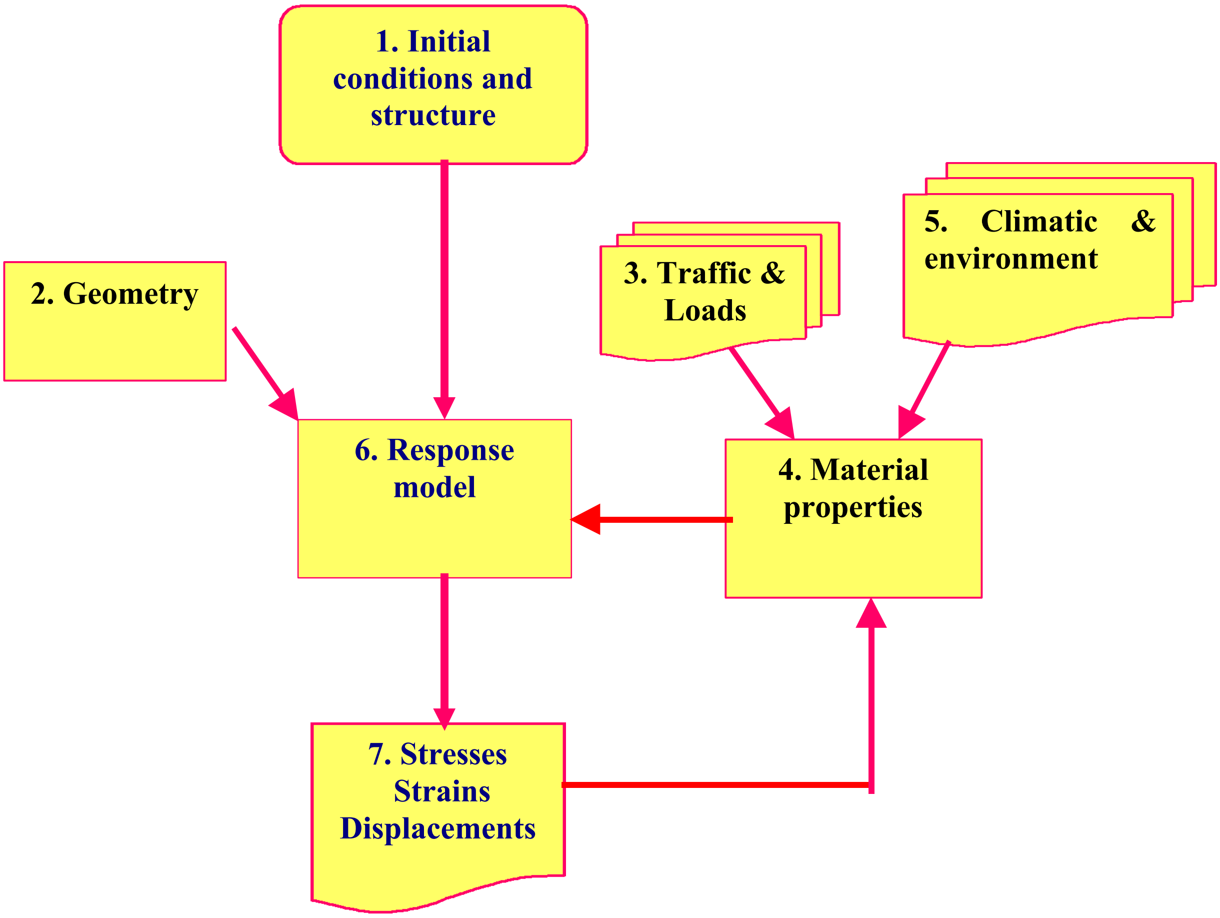


Figure 7 : Design elements involved in evaluation phase 2.

4.2.1 Approach

As previously stated, phase 2 consisted in the evaluation of selected response models, through the comparison of the calculated response (stresses, strains and displacements) with the responses measured under controlled conditions in three accelerated load test facilities situated in Spain, Switzerland and Denmark.

As the temperature and loading conditions were in general variable or, at least, more complex than in the simplified situations considered in phase 1, the applications made in the frame of phase 2 must use four additional design elements shown on figure 7 :

- Geometry (in some cases).
- Traffic.
- Climate (temperature).
- Material properties (depending on climate and traffic).

When some of the models did not have these design elements included, the relevant information had to be taken from assumptions or external prediction programmes. For the case of bituminous material properties for example, the mechanical properties could be derived (in function of mix composition, temperature and traffic speed) from external programmes such as BANDS and PAMINA.

Each model was evaluated primarily for the simpler linear elastic case, and then it was verified whether the use of special features from the model (non linearity, viscosity, anisotropy, etc.) would lead to a better prediction of the measured response.

Remark : The reader should be aware of the fact that measured features will be taken as references to which estimated values will be compared. Such measurements are also subject to errors.

4.2.2 Phase 2 evaluation teams

As shown on table 14, four evaluation teams dealing with eight programmes carried out the evaluation. In addition to the initial programme described in Deliverable D3 special applications were also made by LAVOC with SYSTUS, and computations were also made by BRRC using VEROAD.

Owing to the amount of effort involved in the evaluation of medium and complex models, it was decided in phase 2 to organise four evaluation teams as shown on table 14 out of the six teams initially formed for phase 1.

These teams were arranged to perform the work of phase 2 with each team being assigned between two and three models. Not all the models evaluated in phase 1 were carried on to phase 2. In most cases this was because the evaluation in phase 1 included a number of models with essentially the same features, and providing similar results, making it redundant to use them all in phase 2.

Table 14 : Structure of the evaluation teams in phase 2.

Team	**1** C1/C2	**2** C3/C4	**3** C5	**4** C6
Leader	TUD	BRRC*	BUGH	DTU
Members	TRL	LAVOC	ISTU**	PRA
	NTUA	KTI	VTI	LNEC
	VTT	DDC	CEDEX	
Models	CAPA 3D	SYSTUS		
	BISAR	NOAH	MICH-PAVE	CIRCLY
	CIRCLY	KENLAYER	KENLAYER	KENLAYER

* BRRC also computed the DTU case with VEROAD.
** ISTU was also using NOAH.

4.2.3 Selection of the case studies : accelerated load test sections

Three accelerated load tests were employed, located in Spain at CEDEX, in Switzerland at LAVOC, and in Denmark at DTU.

These tests provided a broad base of information (i.e. variations in temperature, load and position and tyre configuration) on which to assess the ability of the models to predict the measured responses in an actual pavement structure.

A summary of the main features and characteristics of these three test sites is given here after. More detailed information can be found in Deliverable D3 of the AMADEUS project and in the relevant references given.

CEDEX accelerated loading facility

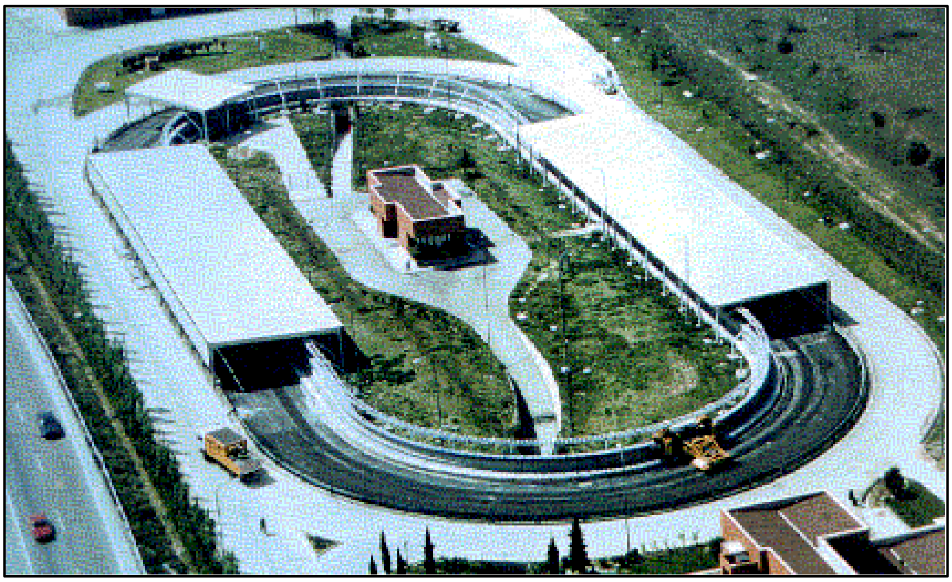


Figure 8 : CEDEX accelerated test facility (North of Madrid, Spain).

General description

The CEDEX test was carried out in open air, so that the temperature was varying daily and seasonally during testing. However, the six instrumented test sections, located in the straight lines of the test ring were shaded as can be seen on figure 8. Measured data were given for four selected temperatures. The main features of the CEDEX test and the relevant output results required in phase 2 are summarised in the tables 15 and 16. More details can also be found in papers published by Romero (1994) and Rubio (1999).

Table 15 : Loading conditions for CEDEX test section.

Type	Position		Load (kN)	Contact Pressure (MPa)	Load radius (mm)	Speed (km/h)
	X	y				
Dual	-175	0	32.5	0.78	115.2	40
	175	0	32.5	0.78	115.2	40

Table 16 : Properties and structure of CEDEX test section.

	E (MPa)	**μ**	**Thickness (mm)**
Asphalt	22600 (0°C) 16000 (10°C) 8700 (20°C) 3150 (30°C)	0.35	180
Soil cement	20000	0.25	220
Subgrade	105	0.4	1600
Concrete	40000	0.15	250
Native soil	200	0.3	∞

Output

Displacement of the surface.
Horizontal strains at the bottom of the asphalt and at (x, y) = (0, 120), (0, 400), (260, 120), (260, 400). Vertical stresses and strains at 450mm depth.

DTU accelerated loading facility

Figure 9 : Accelerated facility at DTU (Denmark).

General description

The DTU test was performed at a single temperature (25°C) under single and dual wheel loads. Extensive information was obtained from this test through the large number of gauges placed at many different positions in the pavement. Single or dual wheels are allowed to run back and forth over the sections. Additional details on these test facilities are given by Mcdonald et al (1997) and Zhang et al (1998).

Table 17 : Loading conditions for DTU test section.

Load case	Type	Position		Load (kN)	Contact Pressure (MPa)	Load radius (mm)	Speed (km/h)
		x	y				
1	Single	0	0	25	0.7	106.6	20
2	Dual	-170	0	25	0.7	106.6	20
		170	0	25	0.7	106.6	20

Table 18 : Properties and structure of DTU test section.

	E (MPa)	**μ**	**Thickness (mm)**
Asphalt	5200	0.35	84
Basecourse	200	0.45	140
Subgrade	50	0.45	1376
Filter Gravel	250	0.35	181
Concrete	27500	0.15	250
Native soil	200	0.45	∞

Output

Horizontal strain at base of the asphalt layer.
Vertical stresses at 244mm, 374mm, 504mm depth.
Vertical strains at 304mm, 434mm, 574mm depth.

LAVOC accelerated loading facility

Figure 10 : LAVOC accelerated test facility (Switzerland).

General description

The experimental structure described by Perret et al (1999) is situated in a large shed ("Halle-Fosse"). A constant temperature is maintained by an air conditioning system. The axle is running back and forth over the sections. The structure to be investigated is a flexible pavement of conventional construction comprising two layers of bituminous materials differing in composition. Data from the LAVOC test was supplied under both single and dual wheel loading, and at four temperatures (0, 10, 20 and 30°C).

Table 19 : Loading conditions for LAVOC test section.

Load case	Type	Position		Load (kN)	Contact Pressure (MPa)	Load radius (mm)	Speed (km/h)
		X	y				
1	Single	0	0	57.5	0.90	141	12
2	Dual	-170	0	28.2	0.75	109	12
		170	0	28.2	0.75	109	12

Table 20 : Properties and structure of LAVOC test section.

	E (MPa)	**μ**	**Thickness (mm)**
Asphalt 1	17500 (0^oC) 12000 (10^oC)	0.35	30
Asphalt 2	18000 (0^oC) 11650 (10^oC)	0.35	50
Unbound Granular	250	0.40	400
Silt	90	0.45	1520
Concrete	40000	0.15	∞

Output

Displacement of the surface.
Horizontal strain at the base of the asphalt layer (80 mm).
Vertical strain at 480 mm depth.
All the above outputs were to be collected at a number of horizontal positions.

To allow a comparison of the main characteristics of the three selected test sites, these are summarised on table 21.

Table 21 : Main features of the accelerated loading tests.

	Location	**DTU (DK)**	**CEDEX (SP)**	**LAVOC (CH)**
	Structure	**Flexible**	**Composite**	**Flexible**
Thickness (mm)	Asphalt	84	180	80
	Soil-cement		220	
	Granular Base	140		400
	Subgrade soil	1500	1600	1500
Conditions	Single axle (t)	5		11.5
	Dual axle (t)	10	13	11.5
	Speed (Km/h)	20	40	12
	Temperature (°C)	One temperature Fixed at 25	Variable from -3 to 35	Four fixed at 0, 10, 20, 30

4.2.4 *Results of the evaluation*

The details of the evaluation carried out in phase 2 are given in AMADEUS Deliverable D4-2 and a detailed analysis of the results is also given in the Guidelines for users (Deliverable D5). Some of the main statements and conclusions of this phase of the study are given in the rest of this section.

- **BISAR**

BISAR was evaluated by Team 1 (C1/C2) using data from all 3 test sections.

No problems were reported by the users during phase 2 of AMADEUS. The team noted the similarity in the results of BISAR and those of CIRCLY, in particular the deflection and horizontal strain predictions. Closer agreement was found for the DTU data for one side of the response rather than the other, this was attributable to the visco-elastic properties of the asphalt layers.

Conclusion

BISAR gave good results for the LAVOC data, vertical responses excepted. For the CEDEX data, predictions were not too close to the measured values, particularly for vertical responses. Modifications to the CEDEX data did not produce any real improvement in the match of the results.

- **CAPA-3D**

CAPA-3D was evaluated by Team 1 using data from all 3 test sections.

Issues

CAPA-3D is a complex and general finite element programme. This means that the use of CAPA is necessarily more involved than a simple multi-layered model. Some team members reported difficulties with running CAPA-3D which were attributable to a lack of experience. Moreover the results from these team members were different to those of the expert users in the group. This more importantly stresses the value of competency when using FE models.

Conclusion

CAPA is a powerful finite element package that can be used to predict responses of pavement structures with complicated geometry. The experience of Team 1 is that good knowledge is vital for CAPA-3D to be used effectively.

- **KENLAYER**

KENLAYER was evaluated by Team 2 (C3/C4), and it was also assessed by Team 3 (C5) using data from all three test sections.

Team 2 acknowledged that this model does not give horizontal strains in either the X or Y direction, instead it just gives horizontal principal strains. For this work where such strains are needed for comparison, the horizontal strain was not considered and the comparison for this model concentrated on the vertical response. Team 2 also tested the visco-elastic possibilities in order to compare this model with VEROAD (see figure 14). The assumptions made in this model only account for static loads, which results in symmetric distributions that are not more realistic than the linear elastic solutions.

Issues

Team 2 found that the programme assisting in the setting up of the KENLAYER input file is inflexible in that if say 1300mm is entered instead of 1.3m the programme does not warn of an error until the programme is started. The file is then unusable and has to be re-entered.

For some parameters KENLAYER require imperial units only. It can slow up the running of the model but moreover inexperience could lead to confusion with these units and therefore error.

Conclusion

Using KENLAYER, vertical stresses and strains were under estimated but modifications to the input parameters could not improve the results without adversely affecting other calculated responses. However, satisfactory predictions of deflection and horizontal responses were obtained. A conclusion of Team 3 was that “the users experience with the non-linear features and the use of the non-linear input data, including visco-elastic calculations should be improved before using the model”.

Team 4 remarked that ‘It seems that KENLAYER cannot properly predict the surface deflections on a semi-rigid pavement (with the CEDEX data) or under a dual wheel load on a flexible pavement (with the LAVOC data)’. The team concluded that KENLAYER could be used for predicting horizontal strain at the base of the asphalt layer but not for predicting vertical strain on the subgrade as is required in most design methods.

- **NOAH**

NOAH was evaluated by Team 2.

NOAH was considered as a user-friendly programme, which allows for easy statistical analysis and parametric studies. There also is a very useful formula generator which allows considering behaviour laws.

Issues

The software only allows for loads to be defined in terms of load and contact pressure. The team came across minor problems with NOAH that were communicated to the producers for improving the next version of the software.

Team Conclusion

Vertical stresses and strains for unbound materials are underestimated by up to 50% directly under the load. At far distance from the centre of the load, the predictions of response improve. Neglecting any visco-elastic phenomena, predictions of horizontal response are good. Deflections and their dependence on temperature are also predicted with fair accuracy as can be seen for the CEDEX case on figures 11 and 12.

Team 2 found NOAH to be a user friendly tool which is easy to learn. The team notes that while NOAH is powerful and applicable to a wide range of problems, the user may quickly find that its use becomes complex when all NOAH’s facilities are employed.

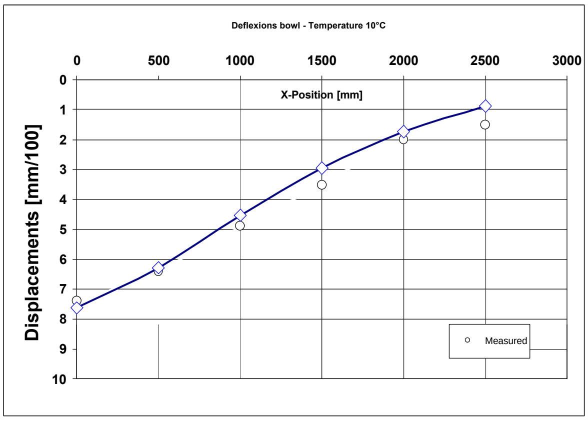


Figure 11 : NOAH calculated and measured deflections on CEDEX composite test section.

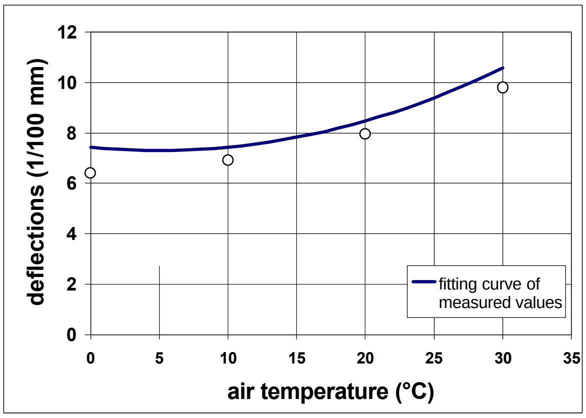


Figure 12 : Measured deflections (solid line) and values calculated with NOAH at four temperatures for the CEDEX composite structure.

- **SYSTUS**

SYSTUS was used by Team 2 for modelling special situations.

The team used the major advantage of the SYSTUS finite element programme in that it can be used to model irregular geometries. This was applied to modelling the LAVOC trial including the strain gauge. This is a more accurate representation of the real system than can be achieved with models requiring homogeneous layers.

Conclusion

Team 2 acknowledged that SYSTUS is a powerful tool which can be applied to a far wider range of problems, more realistically, than the majority of specific pavement models. However its major short comings, apart from those mentioned about the user interface, originate from the fact that SYSTUS is not specifically a pavement model and for this evaluation the team found the input and output of results difficult compared with the specialist pavement models in AMADEUS.

Most of the problems were encountered while defining the geometry of the structure (loads and meshing). Once the definition of the structure was made, it was much easier to make new calculation by changing parameters, such as layer modulus, Poisson’s ratio and magnitude of the load, which don’t depend on the model geometry.

Candidate users should be aware that learning how to use this software requires additional training to understand both finite element analysis and the operation of the programme itself.

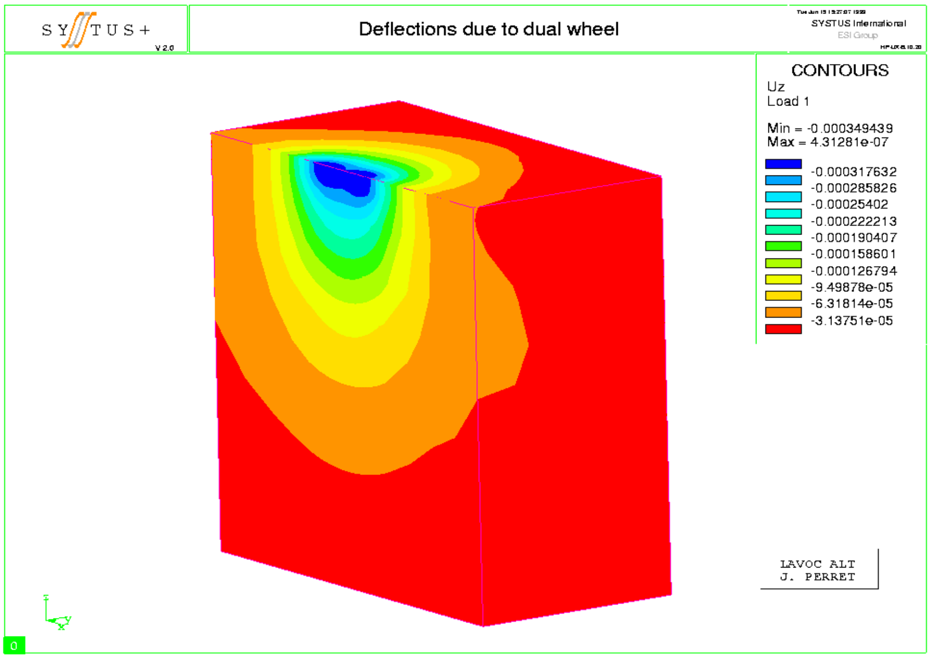


Figure 13 : 3D representation of the deflections under a dual wheel load in the LAVOC test site using the new version of the SYSTUS software.

- **VEROAD**

VEROAD was evaluated by Team 2.

In order to test the possibilities of a more realistic visco-elastic approach, VEROAD was evaluated in phase 2 in a different manner to the other packages. The team suspected that the profile of measured responses at the DTU test track was influenced by the visco-elastic nature of the bituminous layer. VEROAD was used to see if it could reproduce this profile using the four visco-elastic parameters of a Burger's model.

VEROAD was first tested with phase 1 test conditions and with purely elastic assumptions (giving very large values to the dashpot elements of Burgers model) in order to verify the consistency of the response with other linear elastic response models. This being achieved successfully VEROAD was used with BURGERS parameters derived from correlations suggested by Gerritsen and further used by Hopman. The results obtained for the DTU test site are shown on figure 14. KENLAYER visco-elastic options were also used for the same case, but the agreement with the measured data is worth. The probable reason is that KENLAYER assumes a static load while VEROAD considers a moving load (accounting for the speed and the direction).

Issues

The team noted that in VEROAD the user can define a grid over the x-y plane for calculation but when this feature was used, the calculation time was very long. The team also found the DOS version laborious to work with.

Conclusion

In conclusion, VEROAD was thought to be a promising tool. It would also be wise to learn more about the role of visco-elastic parameters used in this model.

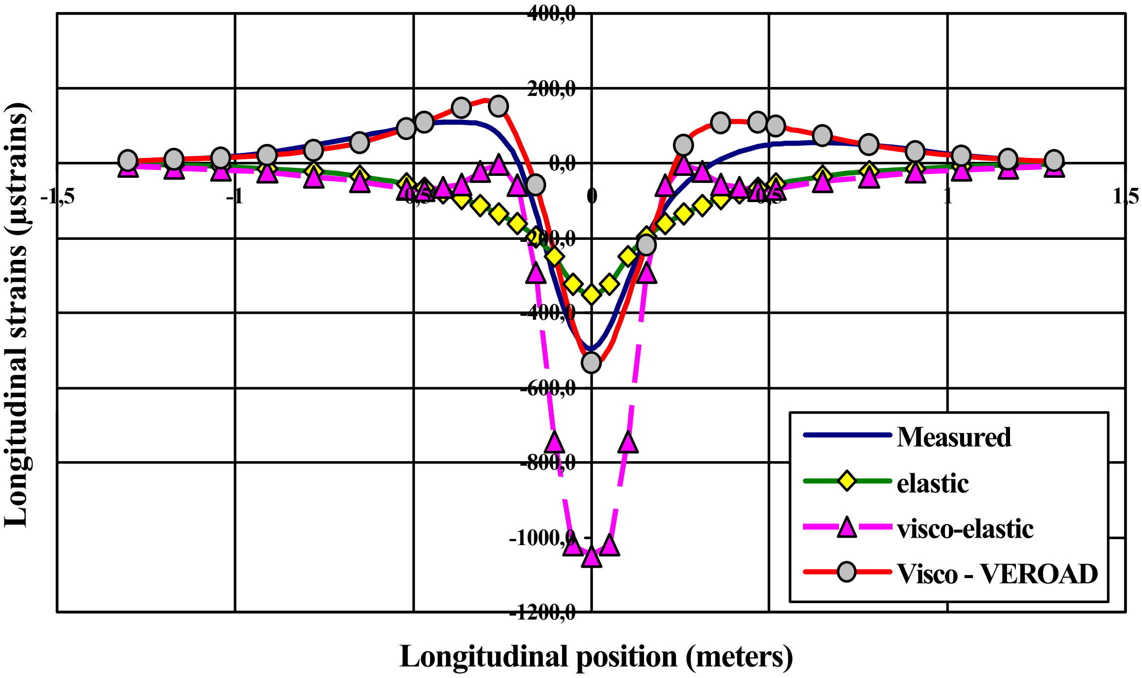


Figure 14: Longitudinal strains measured at the bottom of the asphalt layer (solid line) and calculated with 4 models (elastic case was from BISAR and visco-elastic from KENLAYER and VEROAD).

- **MICHPAVE**

MICHPAVE was assessed by Team 3 using information from LAVOC only.

The Team decided that since MICHPAVE only offers the possibility of analysis with single wheel loads, the DTU and CEDEX test could not be considered because they used solely dual wheel loading. The LAVOC test was performed using both single and dual wheel loading.

Three responses (deflection at the surface, horizontal strains at the base of the asphalt and vertical strains at the subgrade) at two temperatures (0 and 10°C) were considered. Using unmodified actual parameters at 0°C, MICHPAVE gave good predictions of the deflection and horizontal strain. At 10°C, the deflection prediction was poorer than at 0°C, but again the horizontal strain prediction was close. The measured vertical strain on the subgrade for both temperatures exceeded by far the predicted strain.

A number of modifications to the input data were attempted by Team 3 to improve the prediction including:

- reducing the moduli of the asphalt layers together with an increase in the modulus of the granular layer,
- calculating the modulus of the asphalt layers using both the PAMINA and BANDS mix design packages,
- including the non-linear behaviour of the soil layer.

None of these modifications consistently improved the results with improvements being made in one response at the detriment to others.

- **CIRCLY**

CIRCLY was used by Teams 1 and 4.

In all three test sections Team 4 performed two primary analyses with CIRCLY. The first using the actual parameters supplied in Deliverable D3 and then a further modification to take into account the possible anisotropic behaviour of the subgrade.

Figures 15 and 16 show examples of results obtained with CIRCLY, for strains at the bottom of the asphalt layer and vertical strains below the top of the subgrade, respectively. These figures refer to the case of the longitudinal strains at the bottom of the asphalt layer and vertical strains at 0.8m test trial performed at DTU, and to the consideration of anisotropy in the unbound granular layer and subgrade.

Other Issues

Team 4 reported no practical problem in running CIRCLY. The team noted the large number of features in CIRCLY, such as multiple wheel loads and wheel spectra, isotropic and anisotropic material. CIRCLY also has the unique feature of being able to define complex forms of wheel load. The original version of CIRCLY supplied to the AMADEUS members allowed output only at the top and the bottom of each layer and at one depth per run. This was a restriction created by the Windows user interface and was overcome by external editing of the underlying DOS files. Team 4 noted that when unbound layers are defined to be cross-anisotropic, an additional parameter is needed which is not easily determined by in-situ nor laboratory testing.

On the other hand, Team 1 regarded CIRCLY as more laborious to use in phase 2 in comparison to BISAR. Consequently with the knowledge that the results were similar to BISAR in most cases it was more efficient to concentrate on the use of BISAR in terms of time.

Conclusion

Both teams feel that CIRCLY can be used to obtain reliable horizontal strains however it tends to consistently underestimate the vertical strains in the subgrade. The use of CIRCLY's additional features of slip between layers nor cross-anisotropic materials behaviour did not improve the results.

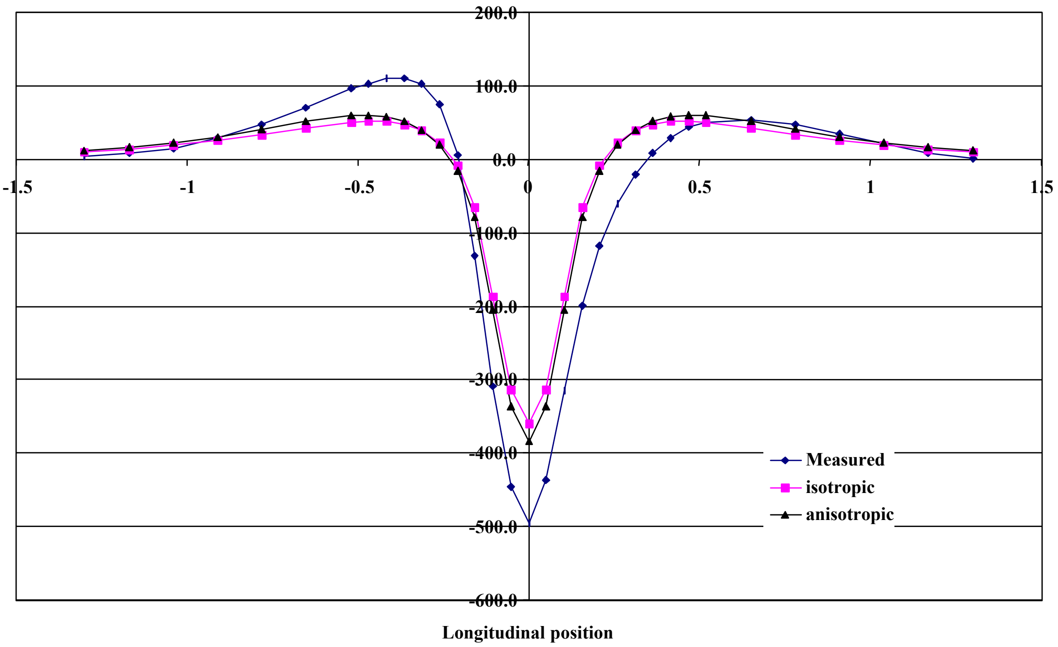


Figure 15: Comparison between calculated and measured longitudinal strains at the bottom of the asphalt layer at DTU test trial, using the computer programme CIRCLY.

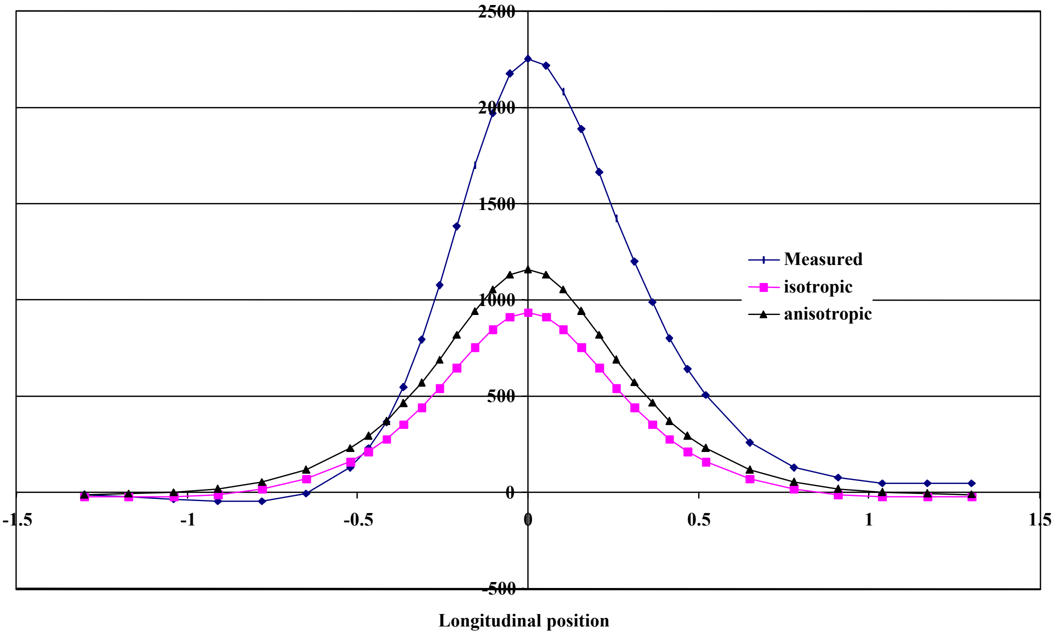


Figure 16: Comparison between calculated and measured vertical strains 0.8m below the top of the subgrade at DTU test trial, using the computer programme CIRCLY.

- **MET Method of Equivalent Thickness**

  Owing to the fact that none of the advanced methods seemed to predict correct values in the subgrade layer a trial was made within team 4 to use the Method of Equivalent Thickness suggested by Odemark (Ullidtz 1998). Odemark's method is based on the assumption that the stresses and strains below a layer depend on the stiffness of that layer only. This depends on the thickness and on the mechanical properties (modulus and Poisson's ratio) of its component material. In the MET this approach is used to calculate thickness of a layer that is equivalent to several different layers. This very simple method can be used iteratively to simulate a multi-layer system.

  Deflections recorded under a FWD load were back-calculated in team 6 with MET assuming the test pavement to be a 3-layered system. This allowed to derive moduli that were used in a forward calculation to obtain strains and stresses in the pavement layers.

  The results obtained, by introducing equivalent thickness factors, are presented in Deliverable D4-2, they are fitting very well with the measured values

4.2.5 Overall conclusions of phase 2

The following table summarises the findings of phase 2 with regard to whether in general the prediction of measured response were good, overestimated, underestimated etc. In most cases these were obtained for the "actual parameters" given in Deliverable D3.

Table 22 : Summary of phase 2 findings.

Model	**Team**	**CEDEX**				**DTU**			**LAVOC**		
		ε_x	ε_z	σ_z	d	ε_x	ε_z	σ_z	ε_x	ε_z	d
BISAR	1	⇩	•	⬇	⇳	⇩	⬇	⬇	⇔	⬇	⇧
CAPA3D	1	⇩	•	⬇	⇧	⇩	⬇	⬇	⇔	⬇	⇔
CIRCLY	1	⇩	•	⬇	⇳	⇩	⬇	⬇	⇔	⬇	⇧
	4	⇔	•	⬇	⇔	⇩	⬇	⬇	⇔	⬇	⇧
KENLAYER	2	•	•	⬇	⇔	•	⬇	⬇	•	⬇	⇳
	3	•	•	•	⇔	•	⬇	⬇	•	⬇	⇩
	4	⇔(1)	•	⬇	⇔	⇔	⬇	⇔	⇔	⬇	⇔(2)
MICHPAVE	3	•	•	•	•	•	•	•	⇔	⬇	⇔
NOAH	2	⇳	•	⬇	⇔	⇔	-	-	⇔	⬇	⇧
SYSTUS	2	•	•	•	•	•	•	•	•	•	•
VEROAD	2	•	•	•	•	•	•	•	•	•	•

Key:

εx	horizontal strain at bottom of the asphalt.
εz	vertical strain in the sub-grade.
σz	vertical stresses in the subgrade.
d	deflection at the surface.
⇩	Underestimate of response.
⇧	Overestimate of response.
⬇⬆	Large under or overestimate of response.
⇔	Predicted response close to measured response.
⇳	Predicted responses span the measured response.

- Response not compared.

\- Response yet to be included in Team report.

(1) Elastic analysis with full friction between layers.

(2) Smooth interface used between asphalt and granular layer.

This table clearly demonstrates that vertical stress and strains are underestimated when compared to measured values with all models tested in AMADEUS. Predictions of deflection and horizontal strain are better with many teams reporting good or close agreement with their models.

Remarks :	The systematic under estimation of vertical stress that was pointed out in phase 2 is an important finding that must be considered in further developments. This stress component is indeed used in most pavement design methods as a criterium to avoid deformations and settlements of the subgrade. It’s under estimation can thus result in early deterioration of the road structure.

The following points outline the findings of phase 2.

One of the conclusions of the study is that elastic multi-layer theory can be used to obtain horizontal strains at the bottom of the asphalt layer. However they are unable to model the asymmetry of the response (visible on figures 14 and 15) due to visco-elastic effects or the vertical strains and stresses in the subgrade. Additional features existing in some models (anisotropy, non-linearity and visco-elasticity) were tested as well. The main issue in such cases is that the additional parameters that are then required are difficult to obtain (neither from in-situ nor laboratory tests).

Specific findings

- Asymmetric responses due to a moving wheel load and visco-elastic effects were reproduced using VEROAD. However, the input parameters need to be known for reliable analysis.

- The anisotropic behaviour provided with CIRCLY gave no relevant improvement in the modelling of the pavement in AMADEUS phase 2. However, this can be attributed to lack of knowledge on the parameters that describe anisotropic behaviour of materials.

- SYSTUS and CAPA-3D finite element models gave comparable results to the multi-layer models.

- The interface slip feature tested in BISAR and NOAH gave no overall improvement in the results.

- Although MET (Method of Equivalent Thickness) is not a precise method from a mathematical point of view, it can predict the strains and stresses in pavement layers reasonably well. This should be considered as a simple and efficient method for practical purposes.

General findings

- Most models gave similar results using the actual or standard data. This was expected considering the results and conclusions of evaluation phase 1.
- Finite Element models require experienced users to be effectively applied. Hence, considerable training is required for novice users.
- Some of the additional features of the models, such as interface slip, did not provide any real improvement in the results over the actual data in phase 2.
- When complex material behaviour is used, reliable input data should be used or at least the user should have experience in using the behavioural models.
- Vertical stresses and strains in the sub-grade tended to be underestimated by up to 50% by all models.
- Predictions of deflection and horizontal strains were much closer than the vertical responses.

4.3 Phase 3: Long term pavement performance (LTPP) prediction and verification

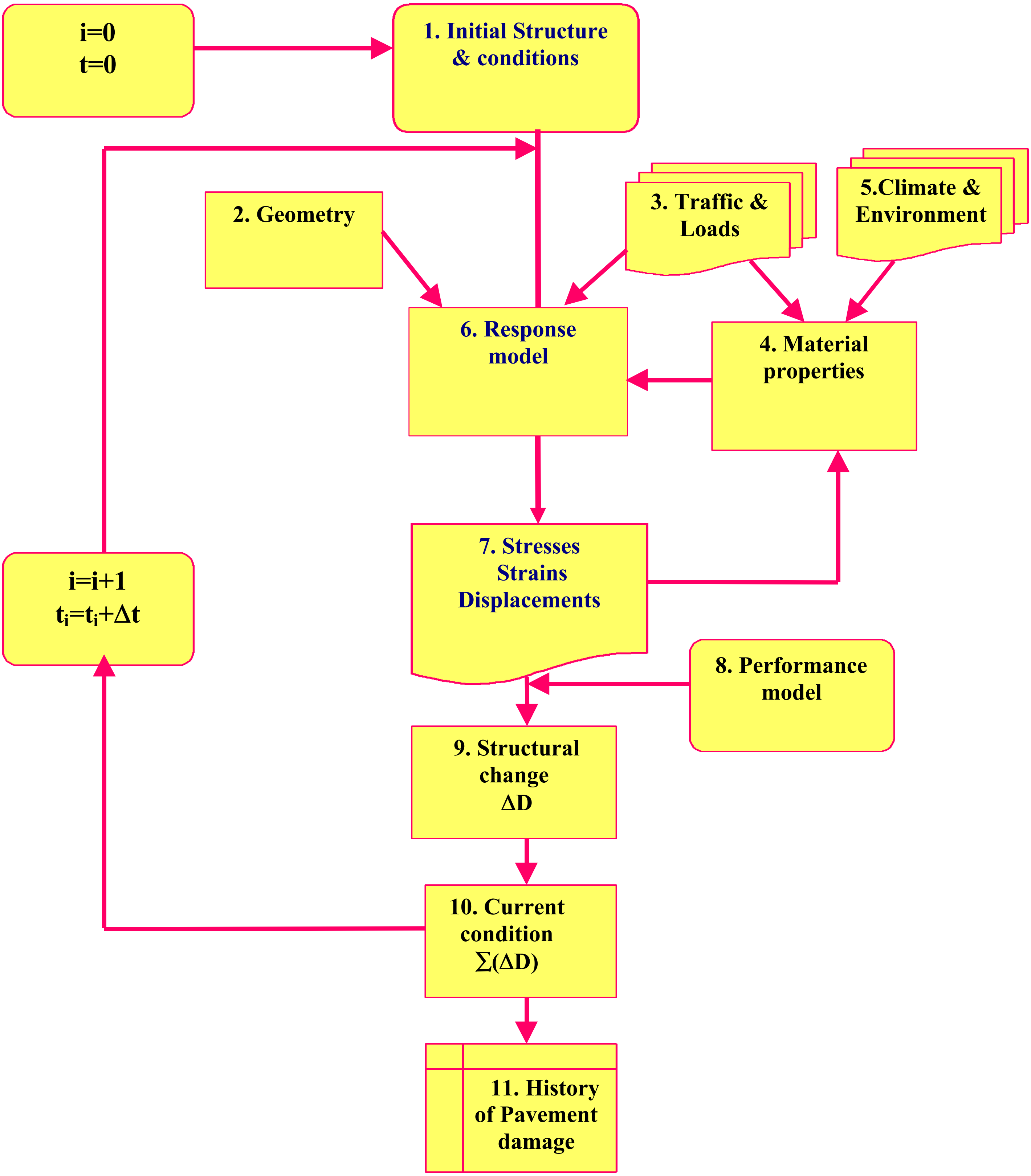


Figure 17 : Design elements involved in the incremental procedure for evaluation phase 3.

4.3.1 Approach

It is a well-known fact that the structural design of a pavement and the actual performance of the pavement structure are in a close connection. That is why one of the tasks of the AMADEUS project was to evaluate several advanced pavement design models by comparing their outputs with measurements and long term monitoring made on several sections selected of the public highway network.

The models allowing such long-term predictions should take into account the evolution of material properties and structural characteristics during the whole service life. Ideally full incremental design procedures such as the one proposed by COST 333 should be used at this stage. This type of procedure shown on the flowchart of figure 17 includes the eleven design elements identified in 1.3.

Eight programmes, mentioned in table 23, were chosen to perform this evaluation in the third phase of AMADEUS WP4 evaluation task.

In most cases, either the 11 required elements were not available or the possibility to close the incremental loops by re-entering modified data did not exist. To overcome such situations partners involved in the study had to perform these operations by using, when necessary, external programmes or additional features that could replace the lacking elements and features.

The details of this study are reported in Deliverable D4-3 of the AMADEUS project and the overview of this action is also given in Deliverable D5 “User guidelines”. The main lines of the study and related conclusions are given in the next sections.

Warning : It must be recalled here that not all measurements are 100 % reliable, however they will be used as a reference in all the statements made below.

4.3.2 Phase 3 evaluation teams

The evaluation method was similar to phase 2 with models allocated to four teams except that some of the phase 2 models were not suitable for use in phase 3. The arrangement for phase 3 is shown in table 23.

Table 23 : Structure of the evaluation teams in phase 3.

Team	**1 C1/C2**	**2 C3/C4**	**3 C5**	**4 C6**
Leader	TUD	BRRC	BUGH	DTU
Members	TRL	LAVOC	ISTU	PRA
	NTUA	KTI	CEDEX*	LNEC
	VTT	DDC		VTI
Models	BISAR	NOAH	VESYS	MMOPP
	CIRCLY	APAS	CIRCLY	VÄGDIM

* CEDEX evaluated MMOPP instead of CIRCLY.

4.3.3 Phase 3 : Choice of the test sections

From the very beginning of this kind of investigation (comparison), it has been evident that the following main features of the test section type evaluation can have a significant influence on the results:

- monitoring of test sections chosen from the public highway network can supply the most realistic performance information since they reflect the ”actual conditions”,
- long-term performance of these sections can be determined in a quite long period (a whole pavement life of 10-15 years or more is needed),
- due to the high number of variables (pavement structure, traffic volume, subsoil characteristics, climatic variables, etc.), many test section types should be selected when ”homogeneous” highway performance models are to be aimed at,
- every test section type has to be represented by several (at least 3) ”parallel” sections in order to reveal the eventual extreme behaviour (e.g. because of construction failure),
- the monitoring can comprise only the ”surface” condition evaluation or also stress-strain-displacement type information using built-in gauges and transducers,
- the traffic and the weather data - as important influencing parameters - should also be carefully monitored during the investigation,
- special investigations can be added to the main goal, e.g. actual condition improving effect of various rehabilitation actions, seasonal variations of condition parameters, regionally typical deterioration (failure) types.

Reliable data sets on the detailed performance of a pavement data over many years are difficult to obtain. However, the Bundesanstalt für Straβenwesen (BASt) have a database of over 170 sections of pavement that have been monitored for over 20 years (Horz and Kalisch, 1992). Four test sections were selected from this database: two fully flexible structures and two composite structures.

Structures

Table 24 summarises the main features and characteristics of the selected pavement sections.

Table 24 : Characteristics of the full scale test sections considered in phase 3.

	Section N°	145	400	370	395
	Structure	Flexible		Composite	
Thickness (mm)	Asphalt (total)	217	195	224	258
	Cement SBC	0	0	147	145
	Frost blanket	580	356	580	800
Conditions	Climatic zone	1	1	2	1
	Open M/Y	12/66	10/67	01/67	07/67
	Rehabilitation M/Y	No	No	07/79	10/75 10/87
	Period(Month)	277	276	276	276
	Total Traffic (Millions of axles)	30.8	25.5	44.7	(44.7)
	Traffic (Millions of 100 kN ESALs)	1.81	0.56	0.61	(0.61)

SBC : Stabilised base course.

Information given on the test sections

Input data suggested for these sections was detailed but not comprehensive. In some cases data was supplied for some years and not others, also some measurements were given on some sections but not others. Table 25 lists the types of data supplied to give and indication of what was available to the partners. It is clear that considerable conversion of such data was needed by the partners for input into most of the models in AMADEUS. Exact details of the extensive input information is given in Deliverable D3.

Table 25 : Types of input data supplied to the Partners for phase 3 evaluation.

	Description
Structural data	Layer thicknesses and variation of thickness throughout the section
Binder properties	Penetration, T_{R+B}
Mix properties	Binder content , specific gravity, density, void content Grading curves
Bound material properties	Compressive strength, resilient modulus
Loading	Number of vehicles in 7 load classes per month
Environment	Mean air temperatures by month and year Frequencies of temperature with depth
Performance	Benkelmann beam deflections

Traffic

Figure 18 shows the evolution of total traffic distribution and growth and figure 19 presents the same information in terms of equivalent 100kN standard axle loads (100 kN ESAL's), the conversion being based on the fourth power law.

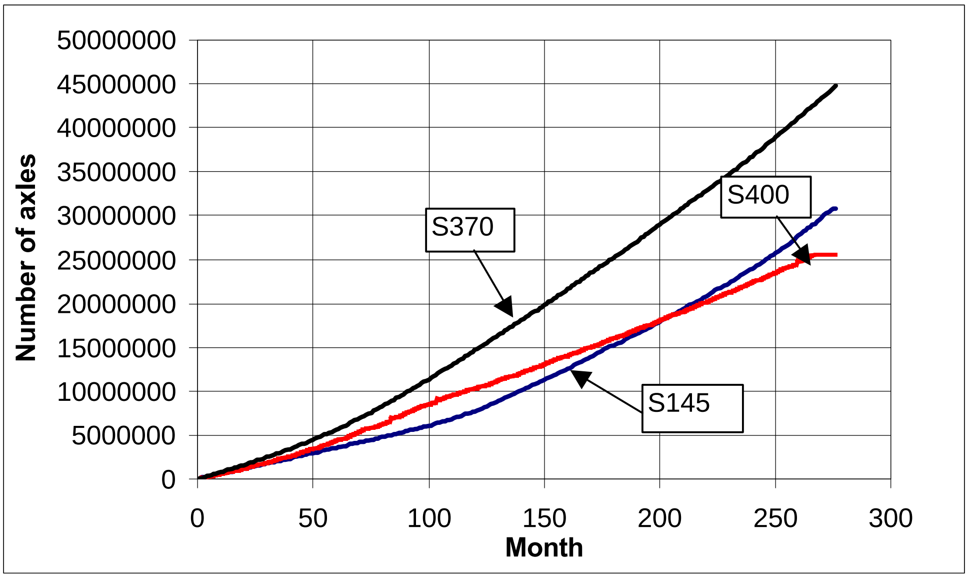


Figure 18 : Evolution of total traffic on three sections.

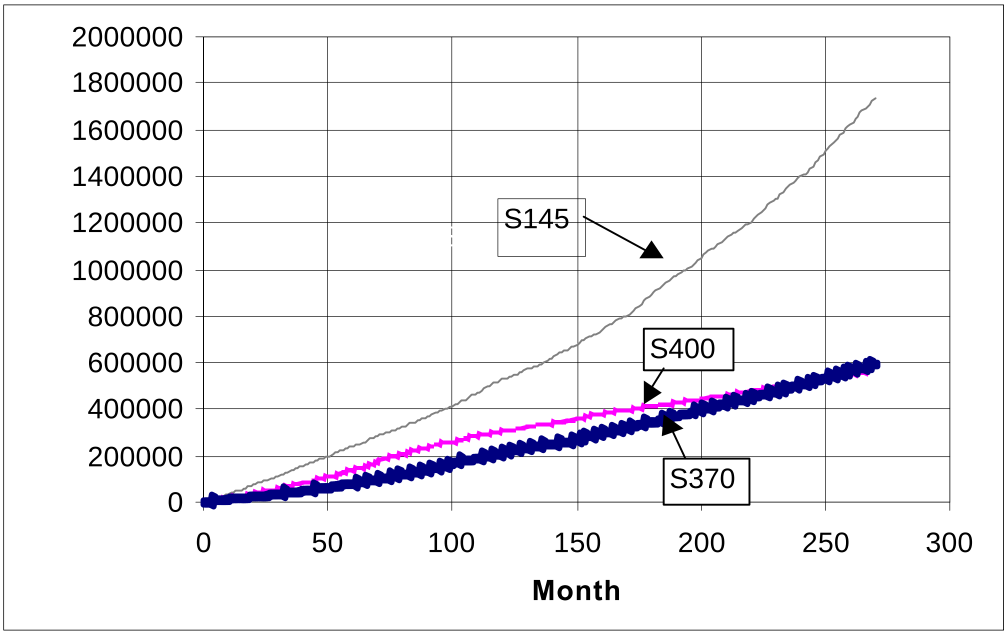


Figure 19 : Evolution of total traffic expressed in 100kN Equivalent standard axle loads (ESAL's).

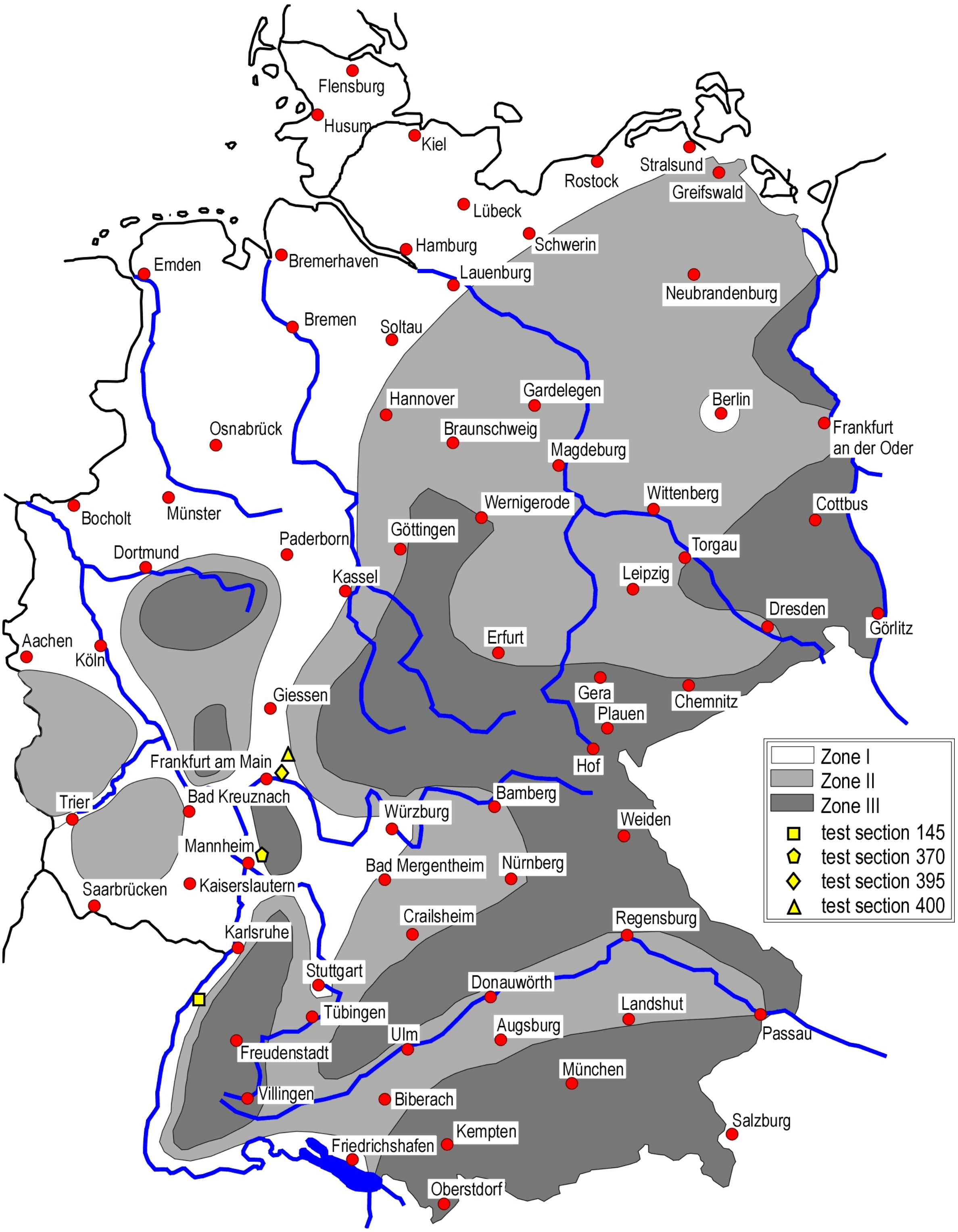


Figure 20 : Distribution of climatic zones in Germany and location of the test sections.

Climate

Climatic information was supplied for the climatic zones 1 and 2 geographically distributed over Germany as indicated on the map presented on figure 20. The locations of the four test sections considered in this phase of the project are also given.

This map was originally made by calculating the frost-index (map of frost zones) but later on the information about the monthly average temperature and their probabilistic distribution at different depths as shown on figures 21 and 22 were included.

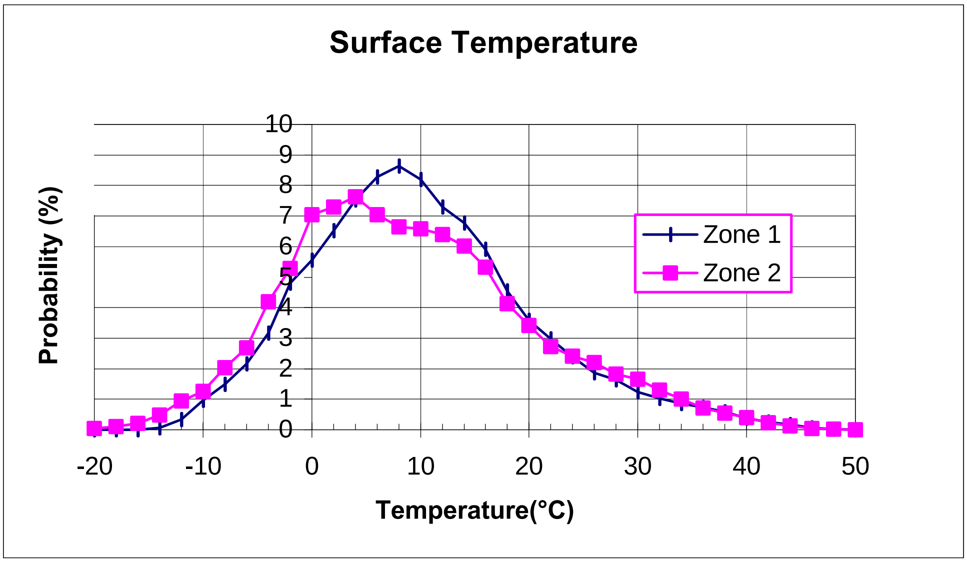


Figure 21 : Statistical distribution of surface temperature.

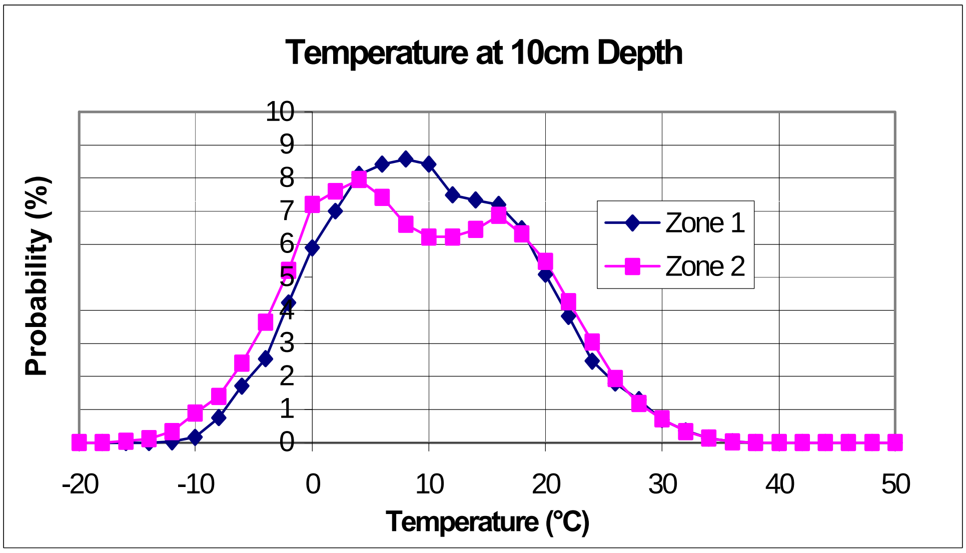


Figure 22 : Statistical distribution of temperatures at 10 cm depth.

The models selected for AMADEUS evaluation phase 3 were used to predict performance in terms of fatigue life, rut depth and other features (roughness, PSI when possible) during the 23-year investigation period of the test sections. The input applied were those available in the German Database.

The comparison of the ”parallel” information was partly hindered by the fact that one of the sections did not show any cracking during the whole investigation period, so its actual ”fatigue life” was not known.

The evaluation method for this phase of the work was less prescriptive than the previous phases, with each user using the available data as they saw best and where there was missing information, engineering judgement was used. This process conforms to a practical situation, where full site information is rarely available.

4.3.4 *Results of the evaluation*

Team 1

Team 1 used BISAR (SPDM) and CIRCLY for analysis of phase 3. It was decided to concentrate the analysis on the types of performance for which these models are most applicable. Since these models are based on layer elastic theory, the most suitable behaviour and performance to predict is structural rutting of the subgrade, fatigue at the underside of the asphalt layer and deflection on fully flexible pavements. Layered elastic models cannot describe the important behaviour of semi-rigid pavements where the joints can dominate the performance of the pavement.

SPDM includes a routine to calculate permanent deformation in the asphalt layer itself. This programme has been used and can give an indicative of the relative rutting performance of each section.

Using the information supplied in the German Database, PAMINA was used to calculate the stiffness modulus for each asphalt layer in each section at four temperatures : 0, 10, 20 and 30^{o}C. Average monthly air temperatures were used to determine the average monthly stiffness modulus by interpolating the moduli calculated at the four temperatures.

The data from the German Database indicated that these pavements incurred ageing, seen as a reduction in penetration over the nominal Pen and a reduction in the measured deflections. This was taken into account in the fatigue life and structural rutting calculations by computing the responses at early life and in the present and assuming a linear transition between them in time.

Fatigue life

The design life was assumed to be 20 years. Using BISAR, the evolution of permissible and actual pavement damage was calculated on the basis of the monthly evolution of traffic.

Similar fatigue behaviour was seen for both sections 145 and 400. The overall result was that these structures should not be failing by fatigue. This was confirmed with the observed behaviour.

Structural rutting

Using three equations for the rutting criteria based on vertical strain on top of the subgrade and assuming a 10mm level of failure, the maximum calculated ruts were found to 1.1mm for section 145 and 0.6mm for section 400. These magnitudes of deformation are negligible.

Therefore it was concluded that these sections were not failing by structural rutting.

Non-structural rutting

An analysis for deformation in the asphalt layer was performed using the rut calculation module of SPDM. Rather than using the material characteristics predicted from PAMINA as used in other work, Team 1 decided to work with the Shell BANDS programme which works seamlessly with SPDM.

Deformation of the asphalt layer can occur on semi-rigid structures, therefore Team 1 extended the range of pavements to include one composite structure, section 370.

Damage

A cumulative damage calculation was performed using CIRCLY because this model can calculate automatically the effect of wheel load spectra. An average modulus based on the annual average temperature for each section was used. Cumulative damage results calculated with different assumptions and performance laws derived from BANDS, PAMINA or other relationships reviewed during the COST 333 report are given in table 26.

Table 26 : Cumulative damage calculated using CIRCLY.

Section	Performance Law	Calculated Miner s Value
145	PAMINA fatigue	0.31
145	TRL rutting	0.0155
145	SHELL rutting	0.00101
145	AI rutting	0.00606
400	PAMINA fatigue	0.625
400	TRL rutting	0.0134
400	SHELL rutting	0.000875
400	AI rutting	0.00585

AI = Asphalt Institute.

None of these values exceeds 1, therefore none of the sections should have failed. This was in fact in accordance with the observed performance of the pavement's sections behaviour. The team noted that it is easy to use traffic spectra with CIRCLY to produce such values.

Deflection

Team 1 calculated moduli using PAMINA from data in early life and after 20 years. The responses were simply calculated for each section and the deflection of the surface noted. These values of deflection reduced with age were consistent with the observed behaviour.

Team 1 conclusions

- The calculation of damage using the conventional deterioration mechanisms, together with Layered Elastic theory, led to the conclusion that none of the flexible sections reached failure.
- The rutting module of SPDM may be able to provide relative rutting performance, however the actual magnitudes of the predictions are unrealistic.
- The test sections stiffen with age, indicated by the reducing deflection.
- Although BISAR was used extensively in phase 3, it is a response model and as such requires a further work to predict performance.
- CIRCLY provides similar answers to BISAR but can also easily accept traffic spectra.

Team 2

Using NOAH, Team 2 investigated the damage related to cracking and rutting in the asphalt layer on one fully flexible section 145 and one flexible composite section 370.

Rutting (non structural)

The team was able to investigate rutting due to the deformation of the asphalt layer by means of the BRRC deformation law (Francken, 1977).

$$\varepsilon_p = \frac{\sigma_v - \sigma_h}{2.E_p(V,T)} . \left[\frac{N}{450.V} \right]^{0,25}$$

V and T are the speed (km/h) and the temperature (°C) respectively. N is the number of load applications. E_p is the permanent deformation modulus that depends on the temperature and the speed. σ_v and σ_h are the principal stresses at a particular location in the structure.

Values of E_p were determined using PAMINA and assuming a vehicle speed of 60km/h. The pavement was split into several sub-layers according to a procedure described by J. Romain (1972) for predicting rutting. The full history was obtained from year per year time steps. In each sub layer stress components were calculated for different combinations of traffic and yearly temperature classes. An elementary (increment of) deformation was derived from the BRRC law for each sublayer and each traffic temperature combination. The total increment for one year was obtained by summing all the elementary deformations of each layer.

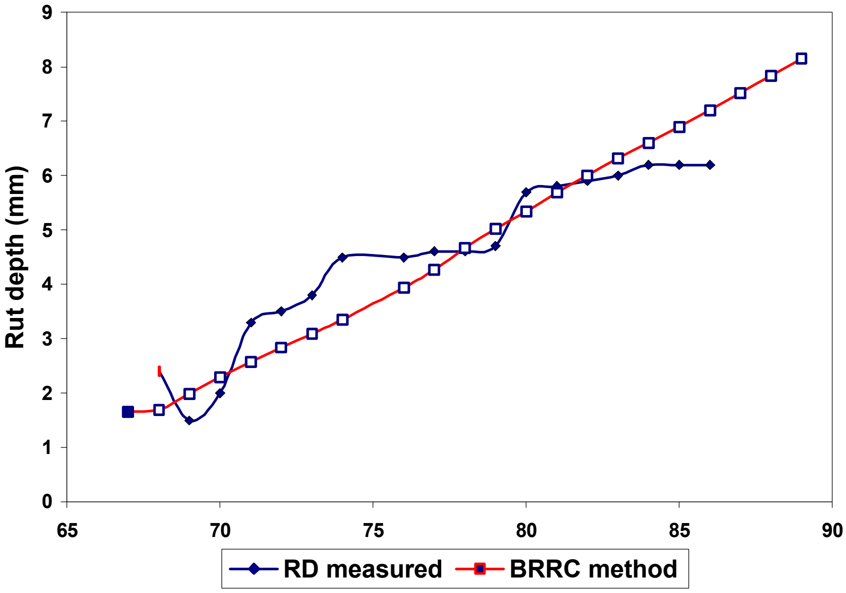


Figure 23 : Comparison of the calculated and measured development of rutting in section 145.

The total calculated deformation of section 145 after 22 years was 8.15 mm. The developed of the rutting is shown in figure 23.

In this application, NOAH was mainly used as a response model. Material properties and performance laws were derived from PAMINA programme and the incremental step procedure to calculate cumulated deformation was developed in a spreadsheet.

Fatigue cracking

Team 2 dealt with cracking in terms of fatigue cracking. NOAH was used not only as a simple response model, because in this application some of the useful features of NOAH could be exploited and the different contributions of temperature: traffic classes could be dealt under the form of a parametric study.

The SHELL fatigue model was chosen for the analysis in order to take into account changes in temperature.

$$N(\mathrm{e}) = 10^6 \cdot \left(\frac{\mathrm{e}_6}{\mathrm{e}}\right)^{\frac{1}{b}}$$

ε_6 and b are constants dependent on the material and temperature and PAMINA was used to calculate them. An arbitrary shift factor of 10 was used in order to relate this laboratory measurement to behaviour in the field. The team also assumed that the calculated figure with the shift factor corresponds to a cracked area of 50%. Total damage was assessed piecewise using Miner’s Hypothesis.

$$\mathrm{D} = \sum_i \frac{\mathrm{ni}}{\mathrm{N_i}}$$

Results

The team calculated a total fatigue life in excess of 30 years. Therefore after 25 years, it was concluded that the cracked area of the wearing course is less than 50%. This concurs with the measured data, in which after a 20 year period indicates that section 145 had developed a very low rate of cracked area.

Team 2 conclusions

- Fatigue :

  - In all cases, based on fatigue of the bituminous layers, the predicted fatigue life extends far beyond the actual monitoring period of 23 years.
  - For semi-rigid structures the predictions of cracking seemed too pessimistic, but no real evidence exists that cracks did not initiate in the base layer.
  - In the case of semi-rigid structure it might be necessary to complete the prediction of fatigue initiation by an analysis of the propagation phase of the cracks.
  - The extent of cracking could be evaluated by assuming the fatigue life to follow a log-normal distribution.
  - The results obtained by using three different fatigue laws are widely different but they all predict very low amounts of the damage, which is in accordance with the observations.
  - It is clear that the structures considered in this study were over-designed with regard to fatigue and therefore it is difficult to derive any quantitative comparison on this basis.

- Permanent deformation :

  - The feasibility of calculating permanent deformation by means of an incremental procedure was demonstrated.
  - The programmes evaluated by Team 2 are not able to implement such a procedure and specific tools had to be developed to do this.
  - The results that were obtained are encouraging in the sense that they were close to the observed rut depth without any fitting.
  - The permanent deformation law that was used gives realistic results and may be proposed as a reasonable basis for the development of a more comprehensive model.

Team 3

Team 3 investigated the test sections for deformation in the asphalt layer using VESYS and cracking using CIRCLY.

Permanent Deformation

VESYS-3PC-RD was used to calculate the permanent deformation in the asphalt layer.

The software uses a phenomenological model based on the following formula:

$$w_{permanent} = w_{total} \cdot \mu \cdot n^{\alpha}$$

where the total deformation w_{total} is the result of the multi-layer programme for each season or temperature, each layer, each load and each transverse position of calculation (each spaced 150 mm from each other) and is to be called as the layer compression (+) or layer dilatation (-) with respect to the multiple dependent conditions, mentioned above. ***n*** in the above equation is the number of repetitions of each load during the period of interest, μ and α are input data to describe material behaviour.

Remark : The main steps of the VESYS procedure are rather similar to the approach adopted by Team 2. The main difference is to be found in the basic deformation law although it has been shown in COST 333 report that these two relationships are almost equivalent and that the parameters of one relation can be converted to those of the other one.

Parameters commonly taken by Team T3 for μ and α are given in the table 27.

Table 27 : Parameters adopted for the VESYS model.

	μ	α
Asphalt layers	4.00	0.40
Frost blanket course	2.31	0.13
Subgrade	2.14	0.10

Moduli of each layer was determined for each month using a procedure included in VESYS after Francken and Verstraeten (1974). Although the moduli were determined in the same manner by all team members, there were differences in the results.

The application made by the team were based on :

- seasonal traffic coefficients,
- average daily traffic in each year,
- lateral distribution of traffic.

The following figures 24, 25 and 26 show the rut development calculated for sections 145, 400 and 370 together with the measured rut depths. Discussion of the results is given in Deliverable D5.

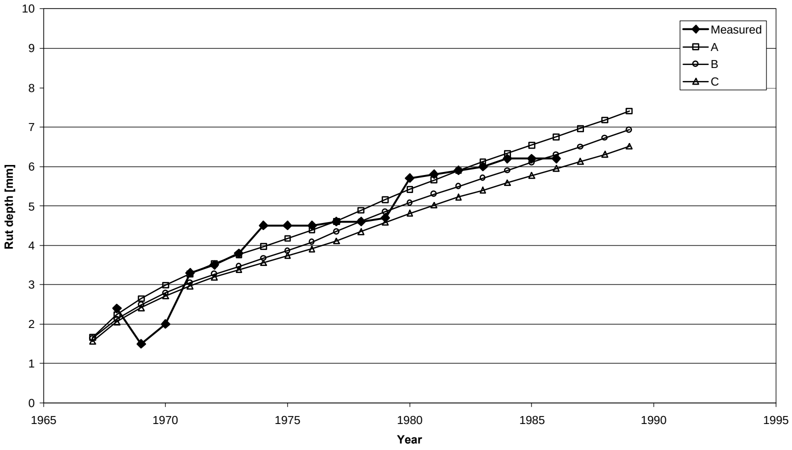


Figure 24 : Calculated and measured rut development of LTPP section 145.

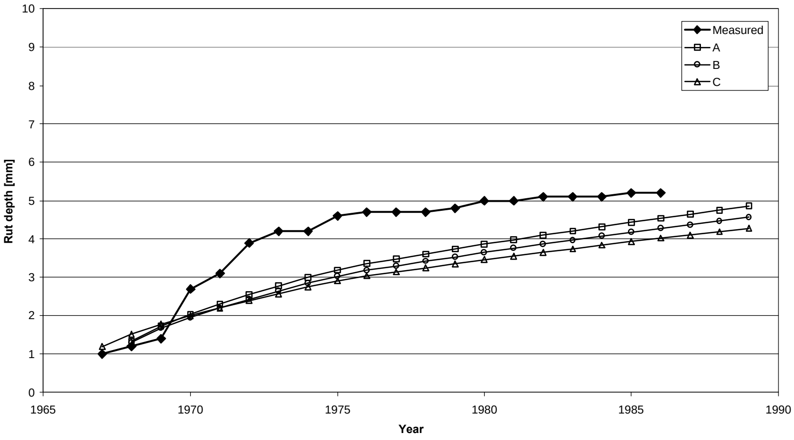


Figure 25 : Calculated and measured rut development of LTPP section 400.

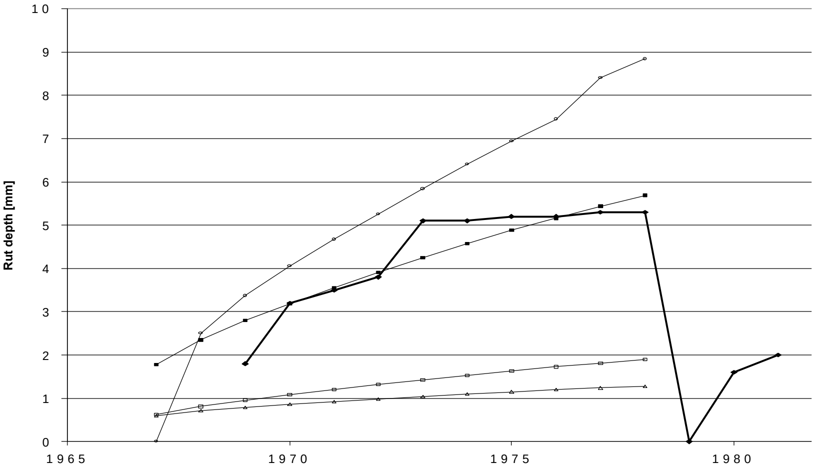


Figure 26 : Calculated and measured rut development of LTPP section 370.

Cracking results

CIRCLY can only be used to estimate fatigue cracking of the selected pavements. Small differences between the results, arised from consideration of taking the loading into account in two different ways. Both the section 145 and 400 were calculated using exactly the same damage function but using, in the case of BUGH, the loads axles converted to a 10 t standard axle, and in the other case, using an axle load spectrum as measured.

During the whole time period of the AMADEUS project, different versions of the CIRCLY software were made available to the partners. Although the last version 4.0 has been equipped with a numbered of new features and possibilities for the calculations, there are still some problems when using the programme in an intensive way. From the users point of view, it seems that these problems arise from the interface, which has been developed for making CIRCLY more user friendly, and not from the underlying DOS- programme CIRCLY itself.

The main advantages of CIRCLY are the possibilities to handle the loads and the material characteristics in an advanced way. To define a loading spectrum, which is based on the different wheel-and axle loads, instead of using the ESAL concept is an important improvement.

It is well known that unbound materials are not isotropic. The introduction of cross-anisotropy shows a way for further developments. The determination of the relationship between E_v and E_h as well as the shear modulus remains as a more or less unsolved problem. A major disadvantage is the impossibility to take different temperature distributions over the whole pavement lifetime into consideration, therefore it is always a difficult question which E modulus of the asphalt layers should be taken into account. Also it is not possible to consider a variation in the bearing capacity during the year within one calculation run.

Team 3 conclusions

- VESYS 3PC-RD provided good predictions of rut development in fully flexible sections using the standard data. Using the standard data, the results for the semi-rigid section 370 were not as good. However modifications to the data provided a better fit.
- Some of the differences in the rut depth results between the team members originated in the values used for material composition.
- Section 395 should not be used in this assessment.
- VESYS 3PC-RD should be improved to allow more layers to be defined.
- Although there are differences in the prediction of fatigue cracking, the actual values are small and so, the agreement with the observations can be considered satisfactory.
- The ability to define cross-anisotropic material behaviour in unbound materials using CIRCLY demonstrates a possible further development in the area of pavement design.
- Although the latest version of CIRCLY, version 4.0, is equipped with many new features and possibilities for the calculations, there are still some problems when using the programme in an intensive way.

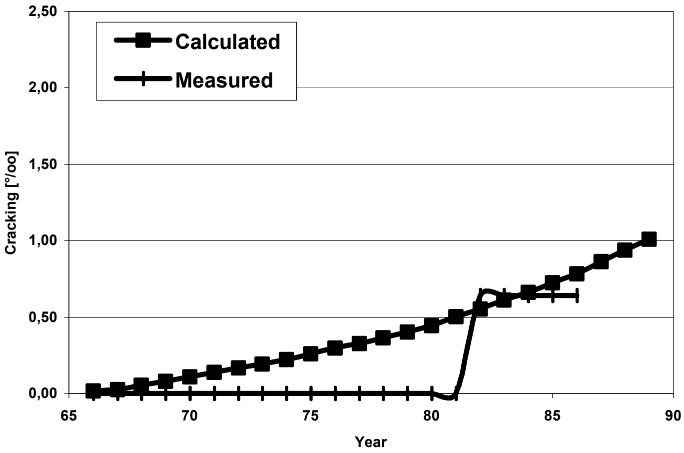


Figure 27 : Calculated and measured cracking in section 145.

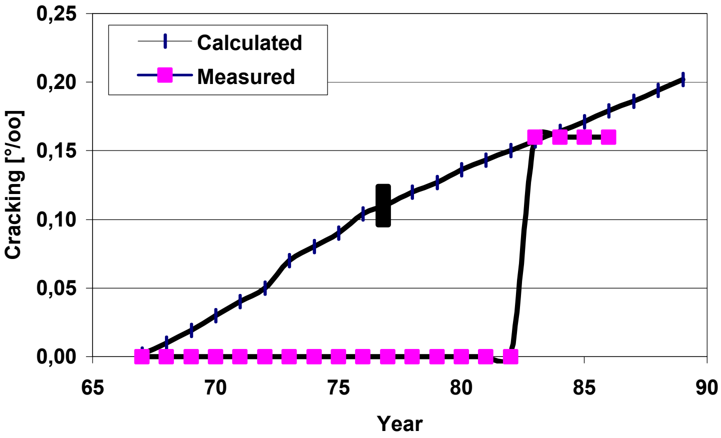


Figure 28 : Calculated and measured development of cracking in section 400.

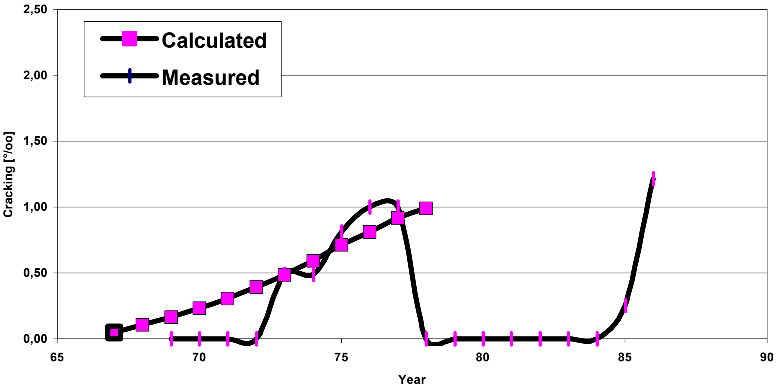


Figure 29 : Calculated and measured development of cracking in section 370.

Team 4

Team 4 used two models in phase 3 of AMADEUS, MMOPP and VÄGDIM95. All four sections were analysed by the team.

MMOPP

MMOPP can be used to evaluate pavement performance. The model can include a variation on layer thickness, stiffness, plastic and strength parameters along a length of road, as well as the variation of load caused by dynamic effects.

- Method

  Additional inputs in excess of those given in the German Database were required. These included traffic volume and growth, mass of the wheel and suspension, and some plastic parameters to calculate permanent deformation.

  The modulus of the unbound foundation layers was varied according to season. Four seasons were employed; Winter, Spring Thaw, Summer and Autumn with related assumed moduli of the unbound layers in the flexible sections. The cemented layers are assumed to have a constant modulus of 7000MPa in each season.

- Results

  Each team member (A, B, C, D) interpreted the data available in the German Database separately, consequently there are differences in the input data used.

  The predictions of the rutting do not follow the actually observed development however it can be stated that the values at the end of the analysis period can be close depending on the parameters used as input. Also the predicted PSI value is close to the measured and does not drop significantly. To illustrate the results, typical results from section 400 are given in figures 30 and 31. Full results are available in the evaluation report.

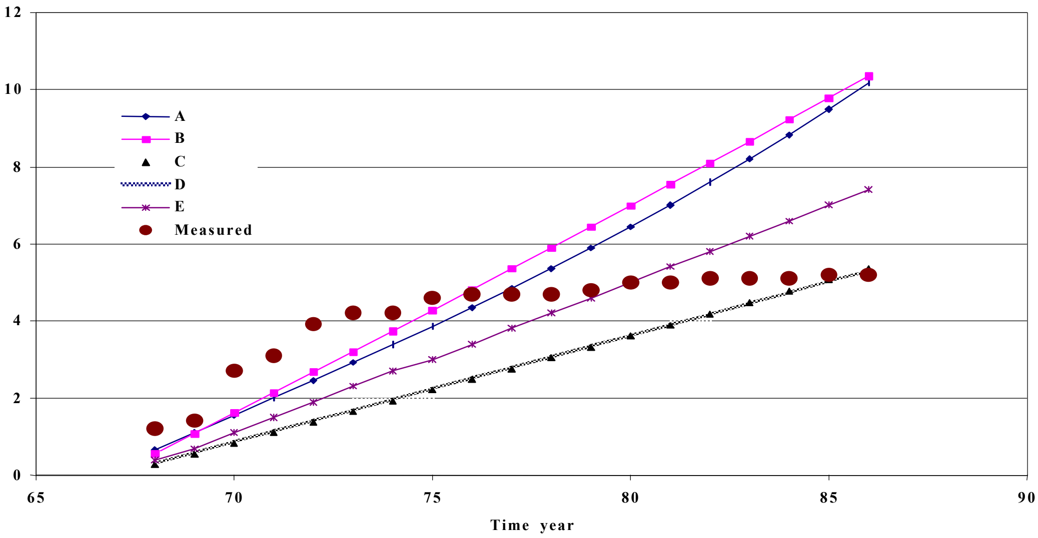


Figure 30 : Rutting in section 400 (***Note : A, B, C, D-team members).***

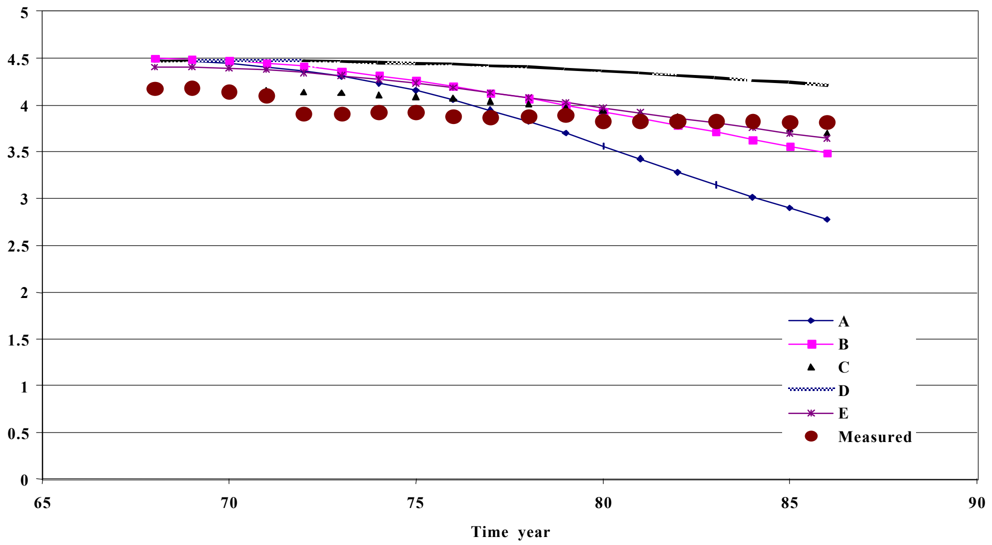


Figure 31 : PSI in section 400.

The team also applied MMOPP to the semi-rigid structures of section 370 and 395. Here difficulties arose since their sections had received rehabilitation.

VÄGDIM95

- Method

VÄGDIM95 is a tool for the design of flexible pavement structures. Team 4 used the information supplied in phase 3 in order to design a new pavement for traffic and climatic conditions comparable to those of the four BASt test sections considered. The design period was set as 20 years.

Designs were produced as shown in figures 32 and 33. In these figures, the dark colour indicates bituminous layers and the light colour granular layers.

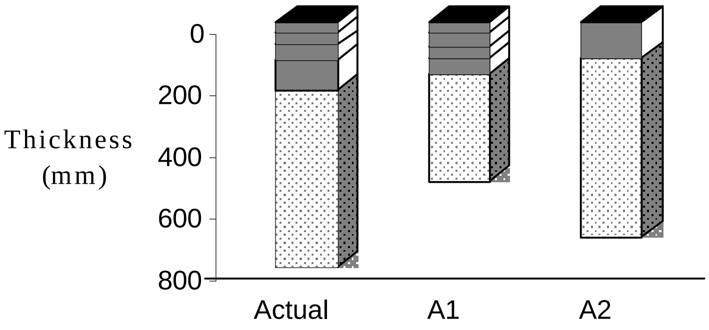


Figure 32 : Actual and calculated thicknesses of section 145.

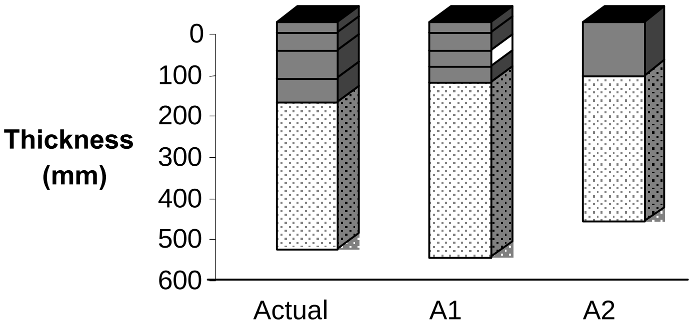


Figure 33 : Actual and calculated design thicnesses of section 400.

Figures 32 and 33 show that the calculated thickness of the test sections are less than the construction or "actual" thicknesses of the pavement. This concurs with the fact that each flexible test section was showing very little deterioration after 20 years. Section 145 and 400 had only 6mm and 5mm of rutting respectively after 20 years.

Team 4 conclusions

- With the default values of the parameters used in the fatigue law for asphalt layers and in the calculation of vertical plastic strains in the pavement layers, MMOPP can produce a reasonable estimation of pavement performance. The rut depth are well predicted for both flexible sections.
- Although MMOPP is mainly intended for flexible pavements, it can also be used to estimate performance of semi-rigid pavements.
- Regarding rut depth, it seams that MMOPP does not produce an initial rut depth, and that rut depth increases almost linearly with time. While observed rut depth does not start from zero and increases sharply in the first a few years and then remain in a stable level, as show in the following figure 34.

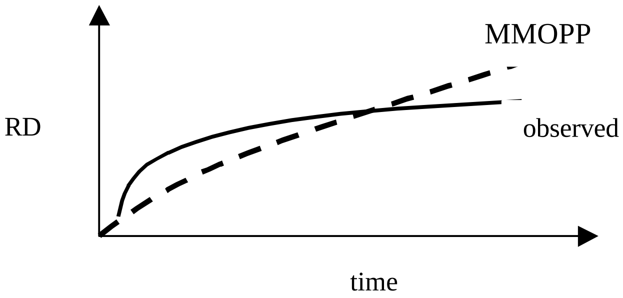


Figure 34 : MMOPP rut depth curve compared to the typical observed evolution.

- With the current version of MMOPP, rehabilitation of a pavement cannot be taken into simulations.
- For the two flexible sections, VÄGDIM95 produces reasonable design thicknesses with the default parameters for the fatigue law and frost heave.
- For the two flexible sections, VAGDIM95 produces a thinner designed thickness of the pavement layer with the default parameters for the fatigue law compared to the actual thickness of the sections.
- VÄGDIM95 should not be used for semi-rigid pavements.

4.3.5 Overall conclusions of phase 3

Scope of phase 3 evaluation

The main purpose of this phase of the evaluation task was the implementation of models and software packages on real situations over long periods of usage.

The limited time and manpower resources of the project combined with the limited availability of case studies of pavements with detailed performance data over an extended period meant that it was only possible to examine a small number (four) of actual field situations.

Due to this limitation, the exercise performed in phase 3 cannot be considered as a validation of any of the products that were tested.

In phase 2 of the evaluation, described in Deliverable D4-2, we have shown to what extend the outcome of a model may depend on the input data defining traffic, climate and material properties.

In long term prediction of performances the additional data needed to define performance and the evolution of damage will result in more variable predictions.

With the current state of modelling, it cannot be expected that accurate predictions supported by field observation can be made. Any agreement is likely to be fortuitous and should be viewed in a critical manner

Phase 3 of the evaluation is best considered to be a feasibility study in which the models were assessed to see whether they broadly complied with the requirements for the various design elements of an incremental procedure set up by COST 333.

Conclusions about the models

Eight models were selected for their wide coverage of the eleven design elements identified in an incremental procedure.

The type of performance (damage) considered in this phase of evaluation were :

- Fatigue cracking.
- Deflection.
- Roughness (IRI).
- Present serviceability index (PSI).

Quantitative information on these features were available for the four test sections over a period of 23 years :

- All of the features listed above could be treated by at least one model. The degree of compliance of the results with the corresponding field situation was however depending on the type of model and (as already stated above) on the assumed input data and performance laws.

- Models like VESYS and MMOPP are full incremental procedures allowing recursive calculations accounting for an evolution of geometry and material properties. The version of VESYS used in AMADEUS was however limited to rut depth prediction.

- Other models like NOAH or BISAR are comprehensive and open to external assumptions but they do not work yet in an incremental way. They were completed by external programmes that could treat their output data (response) and re-enter modified properties and data repeatedly.

- A third category of models (APAS, VÄGDIM) are programmes intended for structural design rather than for performance prediction. Although they contain large possibilities for the design of layer thickness and strengthening layers they do not comply, in their present form, with the required prospective for an incremental procedure. Their structure and layout of large databases can be used as good examples for the development of a final product.

- Their results could be used to calculate expected service lives but not to determine complete history.

- The APAS and VAGDIM Design programmes lead to the conclusions that the four structures considered do not present any type of critical damage.

Conclusions about the damage types

- The predictions made for permanent deformation in the asphalt layers were generally in reasonable accordance with the observations. The predictions made using the BRRC law in NOAH, take into account the stress components together with the influence of mix compositions and temperatures, they seem to give the best results. The approach used in VESYS is very similar to the BRRC-NOAH model and realistic results are also obtained by this model.

- Overall rut depth predictions made by MMOPP are also reasonable over long term but the initial phase of deformation is not well reflected by this programme.

- The distribution of the deformation among the different layers appears to differ from one programme to another.

- The type of structure (flexible or semi-rigid) also leads to different conclusions. For semi-rigid structures fatigue cracking based on the fatigue of cement bound layers leads to pessimistic results. The model used by Team 2 predicts early crack initiation at the bottom of the cement stabilised base. It is likely that the thick asphalt layer above will prevent cracks to propagate to the surface. This indicates the need to incorporate crack propagation in the models.

- Deflection calculations were made with BISAR including ageing reducing faster over time than actually observed.

- Other properties like IRI, and PSI are well predicted by MMOPP.

- The most important issue remaining in long term performance is the prediction of fatigue cracking. Large quantitative differences are observed when different fatigue laws are used.

- All the programmes indicate that fatigue is not likely to occur in any of the flexible structures considered. Estimated life times are widely different between the programmes and some analyses predict that it will not affect pavement performance significantly.

- Although fatigue damage is a main criterion in structural pavement design, there is no clear agreement on :

  - How to quantify field observation.
  - How to discriminate fatigue cracking from other cracking phenomenon.
  - What critical level determines the end of the service life.

- On the other hand, the data used as input for the performance law depend on the experimental method used to test the materials and the way the shift factor was calibrated so that these experimental laws could be applied to actual pavements (see COST 333 report Ch.9).

- The evaluation made in AMADEUS phase 3 clearly points out the danger of mixing data from different sources in this type of evaluation. For example, pavement design based on fatigue must exclusively be made on the basis of a consistent set of data that have been calibrated and validated as a whole. Also, in the present process where the user is required to complete loops required for the incremental calculations, there are invariably several ways in which an analysis can be performed even using the same model and data set. This introduces a subjective element.

5. GUIDANCE ON THE USE OF MODELS

The information given in this chapter has been used to formulate guidelines for the use of the advanced pavement design models under some typical European conditions (climate, materials, type of structure and traffic). It is based on the consensus view of the AMADEUS Consortium. The overall objective was to examine the suitability of existing models to predict the response or performance of existing roads. This will enable serious modelling deficiencies to be identified and for these to be taken into account in the development of the next generation of models required for an advanced pavement design method. Although desirable, it was not possible to perform a comprehensive study in AMADEUS so the models were assessed for a limited number of relevant cases. Nevertheless, the evaluation conditions ranged from a simple paper study to the prediction of the long-term performance of actual pavements.

Remark :	The information given in this report represents the position at the completion of AMADEUS (June 1999). Software and computing capabilities are progressing at a fast pace and consequently the versions of the software assessed in this report may not be the latest versions.

These guidelines are intended to give the reader advice on the situations in which the individual models may help to give insight into the response or behaviour of the pavement based on the experience gained from the AMADEUS project. With this in mind, each of the models considered is dealt with in turn, grouped by the following classifications.

- Models assessed in Phase 1 only.
- Models assessed in Phase 2.
- Models assessed in Phase 3 and other phases.

The models assessed in these three groups could also be classified into three types of model; Multi-layer response models, finite element response models and performance/design models. It is of value to consider the following classifications in respect of common limitations and features which apply to each type of model. Also guidance on the use of each type of model is given in Chapter 5.

- **Multi-Layer response models** are generally based on the work of Burminster (1945). They are often referred to as exact “closed form” solutions. These models give the response, induced by a wheel load, in a multi-layered, linear elastic pavement in which the layers are treated as being horizontally infinite and resting on a semi-infinite subgrade. Originally, multi-layer models of this type only considered linear elastic isotropic layers, uniform circular loading and full bond at the layer interfaces, but now some models can consider complex interactions between the road and tyre, multiple wheel loads and complex material behaviour.
- **Finite Element response models** are those based on the method of finite elements. This method assumes that a continuum can be divided into smaller more manageable elements. These elements are finite in size and together form a finite element mesh. Each element has its material behaviour defined. The behaviour local to each element can be solved within a global system of equations and the cumulative deformations of the elements brought together to give a resultant deformation for the whole structure. These models can deal with complex material behaviour, complex tyre contact stresses and virtually any geometric condition, such as pavement discontinuities.

- **Performance and design models** are more sophisticated models that may be based on multi-layer or finite element response models, but the manner of how the user interface is designed can prevent access to the response model and its output. In the case of a design model, the inputs are used in the response model and the pavement response is automatically checked to see whether it satisfies specific design criteria. Often these models include software routines to automatically refine the structure to produce more optimum pavement design solutions. Pavement performance models use output from the response model to predict some performance indicator using pavement performance transfer functions. The development of cracking, longitudinal unevenness and rutting can be predicted.

As far as possible, each model is dealt with in section 5.1 to 5.3 in a standardised manner under the headings:

- General information

  - Description of the model
  - Main features
  - Conditions of use
  - Supplier

- Summary of assessment

- Objective overview

  - Range of application
  - Relevance to incremental procedure
  - Comparison with similar models
  - User friendliness

- References

Under general information, the origins and development of the model are covered. Its major features are listed with some information about how the model can be applied. Information is given on the computing requirements, details of its availability and contact information for the model.

The summary of the assessment gives an overview of the result of the three phases that were followed in the AMADEUS evaluation.

Finally an objective overview of the model is given based on the assessment. This deals with the range of conditions over which the model can be usefully applied, comparison with the output of similar models, any strengths and weaknesses and special features. The user-friendliness of the model as perceived by the members of the AMADEUS Consortium and the experience required for operating the model.

Section 5.4 is a summary of all the main information contained within this chapter.

5.1 Models used in phase 1 only

5.1.1 AXIDIN

General information

Description

AXIDIN is an axi-symmetric finite element response model for analysis of pavement under dynamic loading. This model was primarily produced as a research tool for interpretation of dynamic non-destructive FWD (Falling Weight Deflectometer) test results on pavements, however it may also be applied to the problem of dynamic loads induced by moving heavy goods vehicles.

Main features

The finite element mesh is a system of horizontal layers of linear elastic materials of constant thickness. These layers are assumed to be homogeneous and isotropic. Control over the definition of the mesh is limited to specification of the vertical and horizontal extents of the mesh and also the number of vertical element division in each layer. This limitation aids the use of the model by more novice users and also reduces the time for the construction phase of the model.

Due to the use of axi-symmetric mesh the load is necessarily assumed to be circular. The load is also assumed to be uniformly distributed over this area. The load can be applied statically and also dynamically using a continuous function describing the load variation with time. The dynamic response of the structure is controlled by the mass of the material and a damping parameter.

There is no user interface with AXIDIN. Input of the model is achieved through a formatted text file, *.dad. Output from the model is also in the form of a formatted text file, *.dat, with calculated responses clearly labelled for easy identification.

Operating requirements

The current version of AXIDIN runs under Windows 95.

Supplier

AXIDIN was developed at Laboratório Nacional de Engenharia Civil and it can be made available free of charge provided that the user specifies the purpose for which the program will be used.

Laboratório Nacional de Engenharia Civil
Departamento de Vias de Comunicação
Av. de Brasil, 101
PT-1700-066
Lisboa Codex
Portugal

Summary of assessment

AXIDIN was only considered in Phase 1 of the AMADEUS evaluation.

Since AXIDIN is an axi-symmetric finite element model only a single loaded area can be defined. Therefore results for the cases of dual wheel loads could not be calculated. 6 Partners used AXIDIN for the case of a single wheel load with full friction assumed between all layers. Slip between layers is not an option in AXIDIN therefore the smooth interface cases could not be calculated.

The natural condition of stress under the centre of the loaded area equal to the applied pressure is not satisfied by any of the results. This is expected because AXIDIN is a finite element model and thus the solution is obtained using approximations. A finite element solution is not an exact solution.

Under the edge of the wheel the results showed more scattered than expected. The two partners who obtained irregular results on the axis of the wheel load repeat also obtained irregular results below the edge of the tyre. Of the four Partners who obtained similar results under the centre of the wheel load, two Partners obtained identical results below the edge of the wheel load. The other two Partners obtained similar results but different to those of the other Partners.

It is likely that this error originates in the geometry of the finite element mesh used. AXIDIN allows the user to specify how many elements to use in both vertical and horizontal directions within the limits of the software. Also, the absolute extent of the mesh can be controlled by choosing the width of the mesh and a large, but finite, depth of the subgrade layer and this will affect the results. No Finite Element geometry issues were dealt with in the Phase 1 input data so this is a ready source of variance in the AXIDIN results.

Variances of AXIDIN results from different users

Load	**Interface**	**Centre load**	**Off axis**
Single	Friction	1.70E-3	1.80E-2

Overview

Range of application

AXIDIN is a pure response model with which stresses, strains and displacements can be calculated at any point in the pavement structure. It is also an axi-symmetric finite element model allowing only a single wheel load.

The dynamic features of the model were originally included to analyse loading due to a FWD. However should knowledge about the dynamic behaviour of the layer be available this model can be used to look at moving wheel loads through a transient application of load and the inertial effects of the layer.

Users of AXIDIN should have an appreciation of Finite Element Analysis due to decisions which may be required concerning finite element mesh and the output positions which can affect the results.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by AXIDIN.

1	▨ 2	▨ 3	▨ 4	▨ 5	6	7	▨ 8	▨ 9	▨ 10	▨ 11

Comparison with similar models

The results in Phase 1 results were different to the majority of the other models, figure 6. This can be expected as AXIDIN is based upon approximate finite element techniques whereas the majority of the other models arrive at a solution using a similar analytical method. Relative to other these models, AXIDIN tends to overestimate the radial strain but underestimate the measured vertical strains. Consequently, using this model for conventional pavement design will give a misleading balance between fatigue and deformation lives.

User friendliness

The users reported no problems when installing AXIDIN.

All users received basic information on how to run AXIDIN. It was agreed by all users that this information was necessary, however most users did not see the need for training.

No user interface is supplied with AXIDIN with input achieved through a formatted text file. Furthermore, the layout of the text file did not receive a high rating. Also the rating of the ease of data entry ranged from adequate to poor, only an experienced user of the model viewed the data entry as simple. The terminology used received a higher rating than the data entry ranging from easily understood to adequate.

The users thought that the definition of the pavement structure was simple and that all the required input variables were readily available. Two users rated the definition of loading as poor. This is probably because AXIDIN is designed to accept dynamic, time-dependent loads and only one single load can be defined.

The users found the computation time of AXIDIN to be less than 10 seconds, this reflects the low hardware requirements of the model.

Output from AXIDIN is in the form of a text file. Most users had the opinion that the output file was clearly labelled but there were differing views on whether it was easy to import the text file into spreadsheets and whether the file was suitable for printing without modification.

Most users thought that AXIDIN gave the users adequate control over the output positions for the responses and that all required responses were available. AXIDIN uses a single file name for input and a single file name for output. Therefore where multiple runs are needed, these files must be renamed accordingly to avoid them being destroyed. Consequently the majority of users gave the file storage and retrieval features of AXIDIN an adequate to poor rating.

Where errors occurred in AXIDIN, it is generally considered by the users that help to solve these problems is not given.

References

Antunes M. L. : Avaliação da capacidade de carga de pavimentos utilizando ensaios dinâmicos (Pavement bearing capacity evaluation using dynamic tests) PhD thesis, LNEC/Technical University of Lisbon, October 1993.

5.1.2 ELSYM5

General information

Description

ELSYM5 is an axi-symmetric response model based on a idealised multi-layered, linear elastic, analysis. ELSYM5 was adapted to run on personal computers and is a modification of the LAYER5 model, which was developed at the University of California.

ELSYM5 follows other multi-layer models in that the layers are assumed homogenous and extend infinitely in horizontal directions and into the subgrade. Loading is also conventional and can be defined in terms of single, dual or more than two circular loaded areas of uniform, vertical contact stress.

The input interface of ELSYM5 was modified by BRRC for the purposes of the AMADEUS project. This modified interface allows the use of SI units but some output results remained labelled in imperial units.

Special features

This particular version has a limit of 5 defined layers with the possibility of defining slip between the subgrade and the layer immediately above.

User input to the model is aided by a simple DOS based user interface. This user interface sets up a formatted text input file for the ELSYM5 processor. Proficient users of ELSYM5 can edit this text input file directly if desired. Output from the model is a formatted text file containing normal, principal and shear stresses together with strains and displacements at each output point specified.

Operating requirements

ELSYM5 is designed to run under MS-DOS, and it is recommended that the PC should have a 386 Processor or better.

Supplier

Details about how to obtain ELSYM5 can be found on the following web address :

www-mctrans.ce.ufl.edu

Or by contacting:

McTrans Center
Department of Civil Engineering
University of Florida
Gainsville
Florida, USA

Summary of assessment

ELSYM5 was only considered in Phase 1 of the evaluation with 13 partners performing the analysis.

In the centre of the loaded area, all but one partner achieved consistent results. The natural condition of equality of pressure at the surface was achieved for the single wheel load case, however for the dual wheel load a small but consistent error in this pressure was seen. This small error may originate in the imperial units used in the model whereas the problem is specified in SI units.

At the edge of the single wheel load, the results were less consistent than at the centre of the loaded area. The increased variability is likely to result from the location of the output positions relative to the loaded area being extremely sensitive to small errors in position. Numerical rounding will produce small positioning errors and in this region, close to the edge of the tyre, the results are highly sensitive to small changes in location.
Between the dual wheels, generally consistent results were produced, with the exception of two partners who obtained slightly different results.

The variability of the results is greatest at the surface and negligible for almost all partners results at depth.

Variances of ELSYM5 results from different users

Load	Interface	Centre load	Off axis
Single	Friction	6.25E-5	3.74E-5
Dual	Friction	1.54E-5	7.38E-5

Overview

Range of application

ELSYM5 is purely a response model. The facility of single and dual wheel loads gives some flexibility with regards to axle configuration. Also the facility of slip at the interface between subbase and subgrade is an added feature. However, caution needs to be exercised in calculations involving slip as the slip condition is very hard to define in practice.

The model is limited to just 4 layers resting on a semi-infinite half-space. In the frame of pavement design and pavement assessment this is a significant limitation since a basic asphalt pavement will have at least three layers with many design methods for new constructions specifying more. The picture is further complicated when considering composite pavements and the rehabilitation of simple structures or sub-layering a pavement to deal with temperature gradients.

ELSYM5 is thus best suited to simple applications in pavement modelling where it can provide consistent results and be easy to use.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by ELSYM5.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

For Phase 1 tasks, ELSYM5 compares well with other pavement models. Results provided are similar to other Multi-layered models although there are some deviations (see figure 6 in chapter 6). It appears that ELSYM5 underestimates the measured pavement response compared to other Multi-layered programmes. It is probable that the source of this error lies primarily in the conversion of the units from SI to imperial for computation then back to SI units for output.

User friendliness

With the exception of one user, ELSYM5 was considered to be easy to install. In some cases it was necessary to alter the configuration of the PC to make ELSYM5 run, which can prove difficult or inconvenient.

Most of the users did not receive documentation to run ELSYM5, however the number of results obtained with this model confirms that this model does not require documentation to run and that a training course is not necessary.

A basic user interface is supplied with ELSYM5 that provides assistance with the input of data. Most users rated the layout of this interface as adequate or more than adequate with similar comments applied to the ease of data entry. The users generally thought that the terminology used was easy to understand. ELSYM5’s user interface allows the use of SI units.

Note: The version working in SI units was translated to this system by BRRC. Results are consistent with this system but the units labels mentioned in the output data were not translated at some places. This is a possible source of confusion.

The definition of the pavement structure was viewed as easy with all required input data readily available. It was noted that since the number of layers is limited to 5, this may cause problems in dealing with more complex structures. All but one of the users, thought that the definition of loads in ELSYM5 was easy.

Computation times stated by the users demonstrate that results can be obtained almost instantaneously. The maximum reported computation time was three seconds. This reflects on the hardware requirements for ELSYM5 which are considered undemanding by the users in AMADEUS.

Output from the model is in text files only, although these are clearly labelled. It was viewed that the users had adequate control over the position of the output responses and that ELSYM5 calculates all required responses.
The file storage and retrieval system was not rated highly by the users. Comments were made about the need to modify the results file;

- when the responses were labelled in imperial units even if SI units were used,
- when data were to be exported to spreadsheet programmes for further applications.

An even split of opinion was given on the subject of help with errors. 2 users thought help was always given when an error occurred, 3 said help was sometimes offered while 2 stated that help was never given.

References

Monismith CL., Finn F.N., Ahlborn G. and Markevich N. : A general analytically based approach to the design of asphalt concrete pavements. *6th International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan*. 1987.

5.1.3 WESLEA

General information

Description

WESLEA is a conventional multi-layered, linear elastic pavement response model developed at the U.S. Army Waterways Experiment Station. WESLEA is based upon continuum mechanics therefore it is suggested for use only with flexible pavements. The programme was later adapted to run in a Windows environment at the University of Minnesota by David Timm and Bjorn Birgisson.

Main features

WESLEA includes a five-layer isotropic system programme written by F. Van Cauwelaert at l'Institut Supérieur Industriel Catholique du Hainaut in Belgium. A separate programme, INLEA, is required to create the input files then these files can be run in batch mode. Normal and shear stresses, normal strains and displacements can then be calculated at the specified evaluation points. Up to 50 evaluation points may be entered in terms of layer number and x,y,z co-ordinates.

WESLEA can analyse up to 4 pavement layers, all extending infinitely in the horizontal directions resting on a semi-infinite half-space. The user specifies Poisson's ratio, modulus, thickness and interface friction for each layer. Layer interface conditions can be set to full adhesion, full slip or at any degree of partial slip. The user must specify loading conditions for one to 20 uniform circular loads. The load is specified in terms of magnitude, radius and x,y co-ordinates.

The Windows version of WESLEA includes predefined transfer functions to estimate the amount of damage to the pavement using Miner's hypothesis.

Operating requirements

The MS-DOS version of WESLEA should run on any PC with the DOS® operating system, but it is highly recommended that a math co-processor be installed. The Windows 95/98 version requires either Windows® 95 or 98 and a minimum 486 33 MHz processor.

Supplier

The DOS version of WESLEA is available in the public domain from:
U.S. Army Corps of Engineers Waterways Experiment Station
Engineer Research and Development Center
3909 Halls Ferry Rd.
Vicksburg MS 39180-6199 USA

The Windows version is available at the following internet site:

www.ce.umn.edu/fns/newcomb/

Summary of assessment

10 Partners used WESLEA which was used only in Phase 1 of AMADEUS. All of these partners performed all sections of the analysis for both single and dual wheel loading, with full friction and slip at the layer interfaces.

Directly underneath the wheel load the predicted stress was equal to the applied loading in all cases.

General agreement over all the responses is good for the case of full friction between all layers. Only two partners, who worked closely together, provided answers that were significantly different to the majority. It is probable that this difference was the result of a common systematic error by the two partners.

One Partner provided different answers for horizontal strains, but this appears to be a minor mistake due to confusion over the orientation of the strain component since other responses provided by the Partner are concordant with the majority.

For the case of dual wheels with full friction between layers there is almost unanimous agreement on the results with just one partner supplying different values. No reason has been offered for this discrepancy.

For the case of slip between layers, the findings from the case of full friction between layers are repeated.

Variances of WESLEA results from different users

Load	Interface	Centre load	Off axis
Single	Friction	1.55E-2	2.74E-2
Dual	Friction	5.53E-4	1.48E-2
Single	Smooth	9.63E-1	2.11E-0
Dual	Smooth	5.75E-1	3.93E-1

Overview

Range of application

WESLEA is a response model completed by some additional design and prediction features. The facility of single and dual wheel loads gives some flexibility with regards to axle configuration. Also the facility of slip at the interface between layers is an added feature. However, caution needs to be exercised in calculations involving slip as the slip condition is very hard to define in practice.

The model is limited to just 4 layers resting on a semi-infinite half-space. In the frame of pavement design and pavement assessment this is a significant limitation since a basic asphalt pavement will have at least three layers with many design methods for new constructions specifying more. The picture is further complicated when considering composite pavements and the rehabilitation of simple structures or sub-layering a pavement to deal with temperature gradients.

WESLEA is thus best suited to simple applications in flexible pavement modelling where it can provide consistent results and be easy to use.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by WESLEA.

1	**2**	3	4	**5**	6	7	8	9	**10**	**11**

Comparison with similar models

For Phase 1 tasks, WESLEA compares well with other pavement models. Results provided are almost identical to other Multi-layered models (see figure 6). There is a small deviation in calculated strain but this is not significant and it may be due to rounding errors by the software.

User friendliness

The installation of WESLEA was simple with no problems reported by the users.

The majority of the users did not receive any documentation. This did not create a problem with all users agreeing that documentation was not needed to run WESLEA successfully, furthermore a training course was not considered essential.

WESLEA contains a fully interactive user interface which was well received by the users. Opinions regarding the layout of the interface were that is was easy to follow and familiar. The data entry was viewed as easy to perform with the terminology easy to understand.

The definition of the structure and the loading was considered an easy task with all required parameters readily available.

Computation of results was achieved almost instantaneously by all users, the maximum computation time quoted was 2 seconds. This is a result of the low hardware requirements that WESLEA was designed to run on. Although WESLEA computes the results using imperial units, a feature of the interface is that it can convert SI units to imperial units for computation and then convert the output back. A comment was made that this is a possible source of precision error which could affect the results slightly.

Output from WESLEA is in the form of text files. These files are thought to be easily imported into spreadsheets for further analysis but opinions were split as to whether the labelling within the text file is clear and whether the file is suitable for printing in its original state. The users reported adequate control over the positions of the output responses but not all the required responses were calculated.

To perform a parametric study using WESLEA, repeated single runs are necessary. Unfortunately WESLEA requires that all parameters are re-input for every single run. This makes the prospect of using WESLEA for parametric studies, where many runs are needed, unappealing.

There were different opinions expressed about the occurrence of errors in WESLEA. Some users reported that help with errors was always given, others state that help with errors was obtained in some circumstances while one user obtained no help from WESLEA when errors occurred.

References

Van Cauwelaert F.J., Alexander D. R., White T.D. and Barker W.R. : Non-destructive testing of pavements and back-calculation of moduli. *ASTM special technical publication stp 1026*. American Society for Testing and Materials, 1989.

5.2 Models assessed in phase 2

5.2.1 CAPA-3D

General information

Description

CAPA-3D is a linear or non-linear, static or dynamic finite element system for the analysis of problems in 3-dimensional continuum solid models as those typically encountered in pavement engineering. As such it can simulate a very broad range of soil and pavement engineering materials under various loading conditions.

It has been developed at the Section of Structural Mechanics of TU Delft in close co-operation with the laboratory of Road & Railroad Engineering with partial financial support from the Dutch Foundation of Technical Sciences.

The system is under continuing development as a research tool for various research groups at TU Delft and overseas.

Main features

The complete system consists of a mesh generation facility with pre- and post data processing capability, the main finite element code and an analysis data post-processing facility. All these facilities are integrated in a Windows based user interface.

Spatial discretisation

A specially developed mesh generation facility can be utilised for the description of the spatial discretisation of the structure to be analysed only the basic geometric characteristics of the structure are necessary to be input by means of the so called super-elements. Once the general shape of the structure has been described, finite element mesh generation is automatically performed on the basis of user specified instructions.

Element types

20-noded hexahedral elements: This type of element is typically utilised for the simulation of continua. It has been known to be one of the best performing 3-D finite element types enabling large element side aspect ratios without significant loss in accuracy.

The following types of element loads are available:

- face pressures,
- nodal forces,
- gravity forces,
- temperature loads.

The following material types are currently available:

- linear elastic isotropic,
- linear elastic anisotropic,
- plasticity based von-Mises,
- visco-plasticity based Desai with cracking,
- dynamic plasticity based including cracking (ACRe model).

Embedded layers of distributed reinforcement, spanning along arbitrary directions, can also be specified. These can be linear or von-Mises based.

A 15 points reduced integration and a full 3*3*3 integration schemes are available. Output of stresses and strains is currently available at these locations only.

The elements can be collapsed for simulation of sharp crack tips.

16-noded interface elements: These are specially developed elements for the simulation of discontinuities like cracks and/or layer interfaces in the body of the pavement. Their thickness can be specified arbitrary small.

The following types of element loads are available:

- face pressures,
- nodal forces.

The following material types are currently available:

- linear elastic anisotropic,
- visco-plasticity based Desai.

Embedded layers of distributed reinforcement, spanning along arbitrary directions, can also be specified. These can be linear or von-Mises based.

A 3*3 integration scheme is available. Output of stresses and strains is currently available at these locations only.

Key Algorithms

Combinations of linear/non-linear and static/dynamic analyses can be specified. Incremental analysis is possible via user specified load incrementation functions.

Various Newton iteration schemes can be specified for non-linear analyses.

For dynamic analyses, time history integration is via Newmark's beta method.

During all iterative processes force tolerance and number of iterations limits can be specified.

All analysis combinations allow for large-displacements and large-strains.

For typical pavement engineering analyses, a sparse-matrix direct solver with multi-front minimum degree reordering can be chosen. For extraordinary large finite element meshes, which would normally require extremely large virtual memory capacity, a linear preconditioned conjugate gradient solver implemented in an element-by-element architecture is available.

Successive analyses can be run in a batch mode.

Output features

Element output consists of :

- stresses, strains, principal strains and their directional cosines
  Currently, element output is available only at the locations of the numerical integration points.

Nodal output consists of :

- displacements and accelerations
  All output quantities are included in an ASCI based output file and in individual ASCI files for easy plotting and post processing via the CAPA-3D graphics facility or otherwise.

Operating requirements

The user-system interaction facility runs on Intel based Windows NT systems. Finite element related computations can be performed on local or network accessible:

- Intel based single/multi processor Windows NT systems.
- Dec Alpha Windows NT systems.
- Dec Alpha Unix systems.
- CRAY multi parallel.

The system is supplied on a CD disk. An automatic installation procedure installs all system components on hard disk. The system is hardware protected via a locking chip that docks at the parallel printer port.

Supplier

For information about CAPA-3D contact:

Tom Scarpas
Structural Mechanics Section
TU Delft
P.O. Box 3095
Delft
The Netherlands

Summary of assessment

CAPA-3D was only considered in Phase 2 of the evaluation by Team 1.

Horizontal strains were slightly under estimated for the DTU data but were close for the other sites. Vertical responses were under-estimated at all sites by between 45 and 60% of the measured values. For the LAVOC and CEDEX trials, CAPA-3D predicted the deflection well though in some cases it tended to slightly over estimate the measure values.

No modifications to the standard data were performed with CAPA-3D.

Some team members recorded results which were different to the expert users in the Team. These differences were attributed to a lack of experience, also these users reported difficulties with the CAPA-3D software. This emphasises the need for a high level of competence with CAPA-3D and also other general FE codes.

The conclusion was that CAPA-3D can be used for the prediction of the responses as effectively as other models such as the multi-layer type models.

Overview

Range of application

CAPA-3D has been primarily developed as a research platform for the solution of very large scale three dimensional pavement engineering models across a very broad range of hardware platforms. As such it is currently utilised by various international research groups for the study of damage development and propagation in several types of pavement structures, the development of new material models, the study of pavement-vehicle interaction etc.

Over the years, techniques have been developed at TU Delft for the experimental determination of the parameters necessary for the effective utilisation of the aforementioned material libraries. Nevertheless, the experimental determination of material parameters constitutes an expensive, time consuming undertaking which was clearly outside the scope and the objectives of the AMADEUS project. As a result, only the linear elastic, static/dynamic features of the system were considered in AMADEUS. Also, since the great majority of the codes that were to be evaluated addressed static analysis, only the TU Athens team in co-operation with the TU Delft team undertook, outside the scope of AMADEUS, some studies involving the dynamic analysis features of the system.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by CAPA-3D.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

The ability of imposing loads of any type, combination and geometry anywhere in the structure provides an advantage to the finite element method especially in comparison with axi-symmetric formulations. However, as with any other finite element system, in CAPA-3D, appropriate mesh discretization in both, the horizontal and the vertical directions, is important if accurate solutions are to be obtained. Because the finite elements mesh does not represent a semi-infinite continuum, meshes of appropriate extents are required. This necessitates utilisation of several hundreds to several thousands elements. CAPA-3D was specifically designed for the solution of such large meshes even on Intel based processors, however, for the solution to be possible, large disk space and fast disk IO are necessary. These are not untypical characteristics of modern Pentium based PCs.

For linear elastic analyses, like the ones performed within the scope of the AMADEUS project, CAPA-3D is a purely response model. Nevertheless, the non-linear features of the system enable the simulation of the development and propagation within the body of the pavement of various damage phenomena like cracking, visco-plastic deformation etc.

User friendliness

CAPA-3D was not used in Phase 1 hence no questionnaires were returned.

References

Scarpas A. : CAPA-3D Finite element system User’s manual. Department of Structural Mechanics. Faculty of Civil Engineering TU-Delft, The Netherlands, 1992.

5.2.2 KENLAYER

General information

Description

KENLAYER is a pavement response and performance model, which incorporates non-linear and visco-elastic behaviour. It is recommended that this software be exclusively applied to flexible pavements.

The basis of KENLAYER is a conventional multi-layered, elastic model under a single, circular load area. Multiple loads can be defined in terms of groups of 6 loads with a possible maximum up to 24 groups. Non-linear and visco-elastic behaviour is approximated using an iterative process. Non linear behaviour is restricted to unbound layers while visco-elasticity in the bound layers is characterised by the creep compliance curve.

Special features

The software includes the possibility of evaluating damage during different periods of the year. Up to 24 periods can be defined with the damage due to fatigue cracking and permanent deformation in each period summed to evaluate the design life. Permanent deformation is estimated based on the compressive strain at the top of the subgrade. Fatigue damage calculations are based on those of the Asphalt Institute design method.

Operating requirements

The model runs within MS-DOS with a recommended minimum specification of 486 33Mhz processor.

Supplier

The software is supplied with the publication ‘Pavement Analysis and Design’ by Huang (1993).

Summary of assessment

Phase 1

Six Partners have used this model in Phase 1 of AMADEUS. All 6 partners have used the model using fixed interfaces between layers only with a smaller number extending the use of the KENLAYER to include the interface slip feature.

Underneath the single wheel load, the natural condition that the pressure at the surface is equal to the requested contact pressure is violated in all partners results with a modal average of 817kPa compared to the requested 700kPa. At the edge of the wheel load, the amount of variation in the predicted responses is similar to within the loaded area. Although the stress at the surface is consistently calculated by four of the partners, the response at this output position is expected to be extremely sensitive.

In the dual wheel load case similar inconsistencies occur between the partners. The predicted stress under loaded area varies by a massive amount from commonly predicted 1470kPa to 83kPa, this compares to the requested contact pressure of 700kPa.

The number of Partners who attempted the smooth interface cases was small making the analysis difficult. Half the partners predicted the required contact pressure at the surface with large differences predicted by the other two. The partners whose results at the surface differ predict similar results to each other further down in the pavement structure for the single wheel load case, but this is not so for the dual wheel load case. It was discovered that these two partners had incorrectly set up the problem by assuming an extra frictionless interface between the subgrade and the overlying granular material so these results will be neglected.

For the case of friction between the layers, two partners provided inconsistent results to the others and also to each other. At depth, all partners results are generally regular. For the smooth interface case, half the partners provide consistent results whereas largely varying results were predicted by the other half, which were later rejected. Little can be drawn from the results of the smooth case due to small sample size.

Variance of KENLAYER results from different users

Load	Interface	Centre load	Off axis
Single	Friction	0.013	0.03913
Dual	Friction	0.0659	0.269
Single	Smooth	0.1315	0.4978
Dual	Smooth	0.00207	5.84E-5

Phase 2

Three teams evaluated KENLAYER in Phase 2.

All teams acknowledged that KENLAYER does not output horizontal responses, instead it calculates principal stresses and strains. One team however, has assumed that the principal stresses and strains can be considered close to the horizontal strain when directly underneath the wheel load.

Where the predicted principal strains were compared to the measured horizontal strains, reasonably close agreement was found. This agreement improved with depth and it was suggested that this was an indication of the error between horizontal and principal strains. Predictions of vertical responses did not match the measured values, and were always under-estimated. Non-linear behaviour, slip at interface and visco-elastic behaviour were all tried in an attempt to improve the results. with the exception of minor improvements found in the responses of the LAVOC trial when introducing visco-elastic or smooth interface, this was not achieved. One team experienced vastly different results using non-linear parameters from two sources, and this was said to demonstrate the need for accurate parameters when using non-linear models.

Overall KENLAYER was viewed as easy to use and, with care, is suitable for predicting the horizontal response even that it calculates principal rather than horizontal responses. It does not accurately predict vertical strain as is required in most bituminous pavement design methods.

Overview

Range of application

In addition to the single wheel load, KENLAYER offers a large number of multiple loads to be defined. These are through specification of load groups defining axle type and position; up to 24 groups can be defined in one analysis. This method enables load spectra to be defined.

The software includes facilities to predict damage during different periods of the year. Climate has been identified by the COST 333 Action as an important aspect of pavement design, particularly in extreme climates, so these facilities could prove very useful.

KENLAYER is primarily a response model but it also can predict damage through the use of the above load and climatic facilities. KENLAYER is as suited for use in Pavement Design as any other multi-layer response model.

The model is multi-layer type and is therefore difficult to apply to rigid or composite pavements where joints in the layers are involved.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by KENLAYER.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

With the exception of the calculation of stress immediately beneath the wheel load, the Phase 1 results from KENLAYER are almost identical to other Multi-layered models. Where interface slip was specified, KENLAYER matched the results of BISAR while other models provided differing answers.

User friendliness

The users of KENLAYER report that the software is easy to install with no major difficulties encountered.

Documentation was supplied to just over half of the users. The feelings about documentation were mixed; those without documentation coped adequately, while those with documentation thought that it was important to have. The documentation supplied included the theory behind the model, explained all the features and how to run KENLAYER. Just under half the users thought some form of training course would benefit their use of KENLAYER.

The input data is coded in such a way that additional information not contained in the software is mandatory to carry out a structural analysis. The user input interface does not provide enough explanation to avoid fundamental errors.

A simple user interface is supplied with KENLAYER, that assists in the setting up of an input text file. The model is then run outside of this interface and a text output file produced. Opinions about the user interface are mixed with no clear views about the terminology used in the interface, the general ease of data entry or the layout of the interface itself. Generally, the responses on these points were average with neither excellent nor poor ratings supplied.

The users thought that the process of defining the pavement structure was simple with all required data for this process available to them. The opinions were widely split about the ease of defining loads in KENLAYER. The low marks probably originate from the case of dual wheel where the orientation of these loads is fixed, and this may cause confusion where the orientation of a specific problem is different. This was the case in the Phase 1 evaluation.

Running the model proved a very quick process with users reporting run times of a few seconds.

Opinions were mixed about the output file. Approximately half the users thought that the output text file was clearly labelled, with another different group consisting of half the users replying that the output file is easily imported into spreadsheets, and another of similar size replying that the output is formatted for easy printing.

There was more agreement in that adequate control over the output positions of the responses is available but not all users felt that a comprehensive set of response is included in the output. One major problem which resulted in the rating of the file storage and retrieval system as low was the fact that KENLAYER can only accept one input file name and write to just one output filename. This arrangement risks the loss of information when performing multiple runs as well as making this procedure more laborious.

Almost all users replied that where a problem occurs, helpful suggestions as to the cause of the problem were offered by the software, but not always.

References

Huang Y. H. : Pavement Design and Analysis. Prentice-Hall, Englewood Cliffs, New Jersey. ISBN 0-13-655275-7. 1993.

5.2.3 MICHPAVE

General information

Description

MICHPAVE is a non-linear, axi-symmetric finite element response model. Produced in 1989 at the Department of Civil and Environmental Engineering of Michigan State University, it is a development of the ILLI-PAVE model (Thompson, 1986). The primary use of this software is for modelling the response of flexible pavements where it is intended to be an improvement over conventional multi-layered elastic programmes.

ILLI-PAVE is also a non-linear finite element code but while this code takes into account the behaviour of unbound materials it suffers from the consequence of using only finite elements. When solely finite elements are used the boundaries are, by definition, finite and will have an effect. The position of these boundaries must be chosen so that they are at a distance where their effect is small. Hence in ILLI-PAVE, the boundaries at the base of the model had to be placed at great distance from the load. The penalty for this is that the now large ILLI-PAVE model takes a considerable amount of memory and computation time to reach a solution.

Main features

MICH-PAVE avoids the major drawback of ILLI-PAVE by considering the boundary at the base of the model as a ‘flexible boundary’ which accounts for displacements at depth. The flexible boundary is not a finite element boundary, but is a simple layered elastic solution. The speed and efficiency of the solution achieved by making this assumption is far greater than the purely finite element solution and can give results which are closer to ‘exact’ MLE solutions (Harichandran et al., 1989). Figure 35 shows a representation of the MICH-PAVE finite element with flexible boundaries.

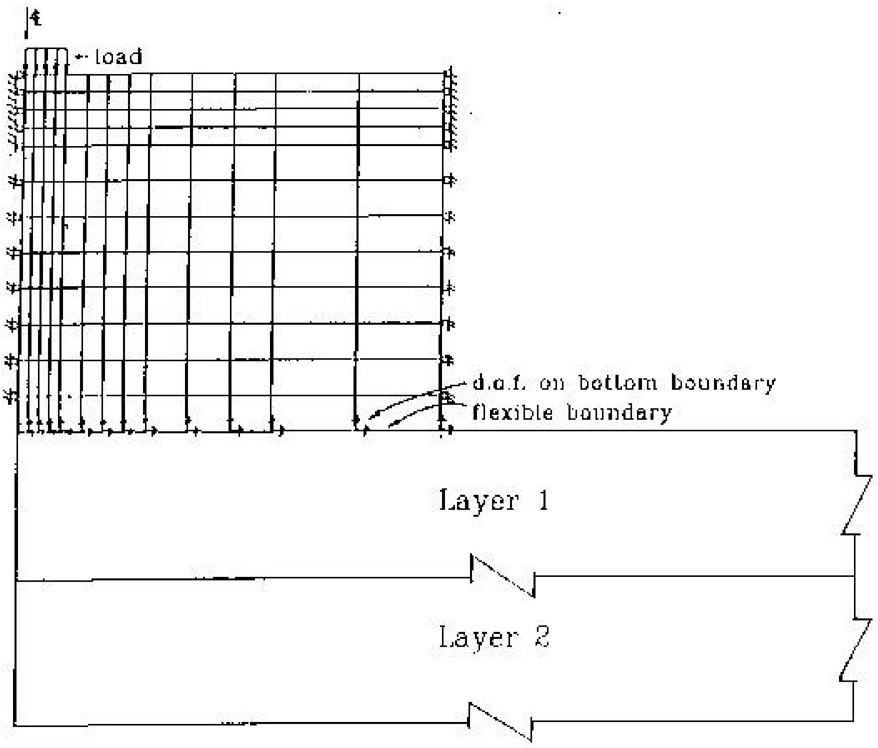


Figure 35 : Schematic of MICH-PAVE model.

The axi-symmetric formulation of the MICHPAVE model implies that the loading is circular. In addition it is assumed that the load is distributed evenly across the loaded area in the vertical direction only. Non-linear material behaviour is included by calculating the resilient modulus for granular materials using the K-θ model, Equation 1, and for cohesive soils a bi-linear model is used, Equation 2. The effect of gravity and confining pressure on the stresses at depth is incorporated by specification of material densities and a coefficient of lateral earth pressure, K_0, respectively.

$$M_R = K_1 \theta^{K_2} \qquad 1$$

$$\begin{array}{ll} K_1 > (\sigma_1 - \sigma_3) & M_R = K_2 + K_3\left[K_1 - (\sigma_1 - \sigma_3)\right] \\ K_1 < (\sigma_1 - \sigma_3) & M_R = K_2 + K_4\left[(\sigma_1 - \sigma_3) - K_1\right] \end{array} \qquad 2$$

The software also includes two transfer functions to predict fatigue life and rut depth. These empirical formulae were constructed using fatigue data from 10 test sections and rut depth data from 7 test sections and are given in Equations 3 and 4.

$$\begin{aligned} \log(ESAL) = &-2.416 - 2.799\log(SD) + 0.00694TBEQ + 0.917\log(MR_B) \\ &+ 0.154TAC - 0.261AV + 0.0000269MR_s - 1.096\log(TS) \\ &+ 1.173\log(CS) - 0.001KV \end{aligned} \qquad 3$$

$$\begin{aligned} \log(RD) = &-1.6 + .067AV - 1.4\log(TAC) + 0.07AAT - 0.000434KV \\ &+ 0.15\log(ESAL) - 0.4\log(MR_B) - 0.50\log(MR_{RB}) + 0.1\log(SD) \\ &+ 0.01\log(CS) - 0.7\log(TB_{EQ}) + 0.09\log(50 - [TAC + TB_{EQ}]) \end{aligned} \qquad 4$$

Where ESAL = Equivalent standard axles to failure.
SD = surface deflection (inches).
TB_{EQ} = base thickness + equivalent subbase thickness (inches).
MR_B = Resilient modulus of base material (psi).
TAC = Thickness of AC layer (inches).
AV = % Air voids in AC layer.
MR_S = Effective resilient modulus of subgrade (psi).
TS = Tensile strain at the bottom of the asphalt layer.
CS = Average compressive strain in the AC layer.
KV = Kinematic viscosity of AC binder (centistokes).
RD = Rut depth (inches).
AAT = Average annual air temperature (^oF).

An MS-DOS®-based user interface is supplied which performs all necessary functions: mesh generation, material definition, load definition, running the model and displaying the output. The interface is designed for imperial units which can cause some problems for users experienced in SI units. Although no on-line help is available, the interface is intuitive and familiar, and advice is offered to the user in the form of on-screen captions. The computation of the solution takes seconds using a modern PC allowing fast, efficient answers for the pavement modeller. The user interface includes facilities for outputting stresses, strains and displacements to a printer in the form of formatted tables and also in a graphical form using preformatted graphs.

Operating requirements

MICHPAVE runs on most PC operating systems and requires minimal computer hardware: 640kB RAM with 515kB of free memory, 500kb free hard disk space, CGA display adapter and compatible monitor. A 386 with math co-processor is recommended.

Supplier

MICHPAVE is freely available in the public domain from the following address or

www.egr.msu.edu/~harichan/software/mpmb.html.

Instructional Media Center
Marketing Division
Michigan State University
P.O. Box 710
East Lansing
MI 48826-0710
Phone (517) 353-9229

Summary of assessment

Phase 1

Since MICHPAVE is an axi-symmetric finite element model only a single loaded area can be defined. Therefore results for the cases of dual wheel loads could not be calculated. 5 partners used MICHPAVE for the case of a single wheel load with full friction assumed between all layers. Slip between layers is not an option in the MICHPAVE model therefore the smooth interface cases could not be calculated.

Under the loaded area the predicted stress is equal to the applied contact stress. This is an achievement considering that the finite element technique requires that all loads whether specified as distributed pressures or point loads are converted to point loads at nodes and the stress distributions are calculated using approximate methods rather than exact method employed by Multi-layered models.

At the edge of the loaded area either the contact pressure or zero pressure is predicted. This indicates the sudden change in stress which has been defined in the model.

Deeper in the structure the responses are less consistent. Three partners offer similar results under the wheel load, although this similarity is not maintained at the edge of the wheel load. There are three primary reasons for the discrepancy between the results at depth.

Firstly, one of the major features of MICHPAVE is the non-linear behaviour of soils. The User Interface is constructed to guide the user into using this non-linearity when specifying layer type. The options given are ‘asphalt or linear’, ‘granular’ and ‘cohesive soils’. The user can easily presume the sub-base and the subgrade layers to be better defined as unbound and cohesive soil respectively. Also the user interface suggests appropriate parameters for the non-linear behaviour of these material. The inexperienced user of MICHPAVE is likely to use this non-linear behaviour in preference to the linear option as this is implied to be applicable to just asphalt.

Secondly, MICHPAVE allows the user to specify the number of elements to be used in both the horizontal and vertical direction subject to the limits of the programme. Also the depth at which the flexible boundary is placed can be controlled. These conditions were not defined in the AMADEUS Phase 1 input data and left to the individual user to specify. These details will affect the calculated finite element results.

Thirdly, MICHPAVE does not allow the user to precisely define the output positions. Instead the user interface relies upon the specification of vertical and horizontal output sections and the definition of the elements in the finite element mesh to define the output positions. Along a specified vertical section, output is computed at all layer interfaces and the middle of elements. Along a specified horizontal section, output is computed at the middle of elements. In response, some users may tailor the finite element geometry so that the output is obtained as close as possible. Others may interpolate the results from the two closest output points.

These primary reasons offer more than enough explanation for the variability of the MICHPAVE results. Given more control over the use of MICHPAVE more consistent results would easily be obtained. This variability is not entirely bad. It demonstrates, in the case of non-linearity, the versatility of MICHPAVE with respect to the potential definition of materials which may be necessary to adapt the model to actual conditions.

Variance of MICHPAVE results from different users

Load	Interface	Centre load	Off axis
Single	Friction	2.68E-2	4.97E-2

Phase 2

The evaluation of MICHPAVE was performed by Team 3 only. Team 3 decided that since the CEDEX and the DTU trials involved only dual wheel loading and that MICHPAVE only allows for analysis of single wheel loads, these trials would be neglected. Therefore only measurements taken at the LAVOC trial were used.

In all cases the horizontal strain predictions with MICHPAVE were close to the measurements. Deflection was predicted well with the standard data at 0^{o}C, however, at 10^{o}C the predictions were poorer. At both temperatures the predicted vertical strain greatly underestimated the measured value.

Modifications attempted to improve the results included modifying the stiffnesses of the layers and the inclusion of non-linear behaviour. None of the modifications attempted consistently improved the results.

Apart from the severe limitation of the single wheel load, the team found it difficult to control the output positions and suggest that this problem be addressed. While the facility of non-linear granular material behaviour was seen as an asset, the Team had reservations about the availability of good input data to make it work well.

Overview

Range of application

MICHPAVE is a response model but while it contains performance transfer functions, it may be unwise to apply these. This is because they are purely empirical relationships which are probably not applicable to conditions in Europe.

In a non-linear model, principles of superposition do not apply. It is therefore more complex to compute multiple loads using an axi-symmetric formulation. Consequently MICHPAVE only allows for single wheel loads.

The restrictions in the style of loading combined with the non-linear material models used in the granular layers make MICHPAVE more suited to looking at stresses in the foundation material than closer to the surface.

The user interface is clear with the model easy to run and the computational requirements low. This makes MICHPAVE an ideal tool for routine investigation. However, to make best use of the model, the user must be aware of error which can occur due to conversion from SI to imperial units and should ideally have a knowledge on the non-linear behaviour of the soils and unbound materials under consideration.

Although it is not necessary, the user should have an appreciation of the concept of Finite Element Analysis because the decisions which can be made with regard to the finite element mesh will affect the output.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by MICHPAVE.

1	2	3	4	5	6	7	8	9	10	11
	▨	▨	▨	▨			▨	▨	▨	▨

Comparison with other models

The Phase I results show that the MICHPAVE results are different to the majority of the other models (see figure 6). This is expected since MICHPAVE is based upon approximate finite element techniques whereas the majority of the model are based on similar analytical solutions. The size of the difference between results obtained with MICHPAVE and Multi-layer models is significant and increases with depth.

It is suspected that although linear material behaviour was requested in Phase I, non-linear unbound material behaviour was actually used in the computation of these results. The user interface does not request either linear or non-linear analysis instead the user selects a material type for each layer such as asphalt, granular or soil. Correctly selecting the material type will automatically invoke the non-linear routines.

User friendliness

Views about the installation of MICHPAVE were shared equally between easy and not easy.

Documentation was supplied to all users of MICHPAVE in the form of a users guide explaining the features of MICHPAVE and how to run the model but it was agreed that this documentation was not vital to be able to run the model. It was also agreed that the user's did not require a training course.

A user interface is supplied with MICHPAVE, the layout of which was rated as adequate to good. Similar opinions were shared regarding the ease of entering the data into the user interface and the terminology used.

The views on defining the structure was widely split from easy to difficult, with the same users stating that all input data was or was not available for this task respectively. The negative response on this point maybe due to the non-linear parameters which are requested. Values for these parameters are suggested by the interface however for a particular pavement, precise input data may be hard to obtain. Also all inputs to the model must be in imperial units which may cause confusion to users more used to SI type units. No facility is offered to enter the input data as SI units.

Even though this is a non-linear finite element model, computation times reported by the users were impressively low and generally a few seconds. These low computation times are a reflection on the relative low hardware requirements of the software.

MICHPAVE provides output in the form of formatted text files which may be viewed from within the user interface and also graphical output. The output is clearly labelled but only one user responded that it was suitable for importing into spreadsheet for further analysis. Graphical output is easy to produce with predefined graphs of the major responses available.

The majority of the users report that inadequate control over the output positions is offered by MICHPAVE. While all types of required responses are calculated, the output positions are defined by the geometry of the finite element mesh and specified vertical and horizontal output sections. Since the user has a very limited control over the finite element mesh to reduce the complexity of the model, this limitation is extended to the output. Also, the users commented that the imperial units used must be converted into SI units which is awkward.

Help was obtained with many errors but not all. Errors in which help were given were mainly encountered while constructing the input data file.

References

Harichadran R.S., Baladi G.Y. and Yeh M.S. : Development of a computer programme for design of pavement systems consisting on bound and unbound materials. *FHWA-MI-RD-89-02*. Michigan State University, Department of Civil Engineering, East Lansing, Michigan 48824, 1989.

Harichadran R.S., Baladi G.Y. and Yeh M.S. : MICH-PAVE User's Manual. *FHWA-MI-RD-89-03*. Michigan State University, Department of Civil Engineering, East Lansing, Michigan 48824, 1989.

5.2.4 SYSTUS

General information

Description

The SYSTUS software uses the Finite Element method to calculate the response of a structure subjected to any set of loads. SYSTUS does not include tools especially dedicated to pavement analysis and design because it is a general Finite Element package.

Main features

The fields of application of this programme are very broad. The calculation method based on finite elements makes it possible to tackle numerous issues such as:

- static 3D analysis of linear or non-linear structures,
- dynamic analysis with determination of eigenmodes and eigenfrequencies,
- analysis of large displacements and large strains,
- analysis of second-order problems: stability and buckling; both linear and non-linear,
- definition of numerous interfaces of different natures: sliding, perfect sticking, variable friction.

Furthermore, SYSTUS also gives the user the opportunity to define his own material behaviour laws, the geometrical shape of the load distribution, interface properties.

Besides these numerous options, the software also allows the application of fracture mechanics both in a linear elastic approach and in a plasticity domain, by offering the user finite elements which are especially dedicated for this type of analysis. This opportunity is very interesting for studying reflective cracking as well as for assessing the behaviour of crack retarding interface products in pavement rehabilitation.

Finally, SYSTUS is essentially used as a very advanced response model which calculates the stress and strain tensor at selected points of the structure.

Operating requirements

SYSTUS requires a high-performance working station with at least a 1 Gigabyte hard disk. The use of SYSTUS for 3D modelling of cracked pavements requires at least a 160 Mb RAM.

Supplier

For Belgium:

FEM-Consult
Mechelsevest 12/6
3000 Leuven
Belgium

The FRAMATOME company that developed SYSTUS has now put the SYSTUS+ software on the market in windows form, which is more user friendly than the version used in this evaluation.

Summary of assessment

SYSTUS was only evaluated in Phase 2 of AMADEUS by Team 2.

The team used the major advantage of the SYSTUS finite element programme in that it allows for the structure to be modelled with the strain gauges in-situ.

Comparing the results of SYSTUS with the measured values, the team reported that the differences between the predicted and the measured values vary widely with temperature. A further comparison was made between the SYSTUS results and results obtain with the NOAH multi-layered model. The findings were that SYSTUS generally under-estimates the strains produced by NOAH by between 1 and 10%.

The team encountered considerable difficulties with SYSTUS which seem to stem from the fact that it is a general finite element code rather than a dedicated pavement model. A period of training was necessary and later the team found problems with the interface at both the input and output stage of the work.

Overview

Range of application

SYSTUS is a general finite element code which can be applied to wide range of problems including pavement analysis. Most pavement models assume homogeneous layers and this ideally restricts the use of these models to fully-flexible pavement constructions. SYSTUS allows for the analysis of structure with inhomogeneous layers extending the applicability of the model to such problems as concrete layers with joints and also structures with strain gauges as performed in evaluation phase 2 the AMADEUS project.

SYSTUS should not be considered as a swift solution to general pavement modelling problems. The user interface is not developed for such a specific purpose and also Finite Element skills are required to make an adequate use of the software.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 could be satisfied by SYSTUS.

1	2	**3**	**4**	**5**	6	7	8	9	**10**	**11**

Comparison with other models

No results for SYSTUS were supplied in Phase 1 of AMADEUS however in Phase 2, a comparison with the NOAH model was made. It was noted that SYSTUS tended to under-estimate the strains obtained from NOAH by up to 10%. 3D finite element models tend to under estimate responses predicted using multi-layer models (Merrill et al., 1998).

User friendliness

Three Partners have used SYSTUS.

No users thought that the installation process of SYSTUS was easy because it requires detailed configuration on high powered computer hardware.

All users were supplied with documentation about the software and it was commented that without it this software would be impossible to run successfully. Furthermore it was considered by all users that training in SYSTUS is vital and the documentation alone is not sufficient. Experience of the finite element method would be a major advantage when using SYSTUS.

SYSTUS has a fully interactive user interface however all users of this software thought that the layout of the interface was unclear, the data entry slow and complicated and the terminology used in the interface unclear.

Consequently it was difficult to define the structure with many problems encountered by the users. More problems were met while defining the loading.

Running times for SYSTUS were longer than most models in the AMADEUS evaluation due to it being a general FE package. No consensus on run times were given, largely due to this being dependent on the type of model constructed and the hardware on which it is run. Run times of between 10 seconds and 30 minutes were reported for the models constructed within AMADEUS.

SYSTUS output is in the form of text files and graphics. While users found the text files clearly labelled and easy to print, the users do not agree on the graphical output. There was inadequate control over the output positions although no reasons are offered as to how this conclusion was arrived at and the file storage and retrieval system was considered difficult.

The users report that help with errors in SYSTUS are not always given.

Most of the problems were encountered while defining the geometry of the structure (loads and meshing). Once the definition of the structure was made, it was much easier to make new calculation by changing parameters, such as layer modulus, Poisson's ratio and magnitude of the load, which don't depend on the model geometry.

References

SYSWORLD+2.0 User's manual, ESI Group-Systus International.

5.2.5 VEROAD

General information

Description

VEROAD is a linear visco-elastic multi-layer programme. The theory behind the programme is analytical and based on the correspondence principle. This principle states that a visco-elastic problem in the time domain, is an elastic problem in the frequency domain. This enables Fourier transform techniques for the time dependent parts (position of the load and properties of the material) to be applied.

Main features

Material models used in VEROAD are frequency dependent shear modulus (such as Kelvin, Voigt, Burgers, Huet) with the bulk modulus independent in the current version.
The programme requires the following as inputs:

- Details of the load such as the circular contact area, contact stress and the velocity of the load. The contact stress is time independent i.e. no dynamics effects.
- Details of the structure: the number of layers and their respective thickness. These layers are assumed fully bonded to each other and extend infinitely in the horizontal direction with the subgrade modelled as a half-space.
- Material details: the bulk modulus, stiffness and phase angles at a minimum of three frequencies. These material input parameters are converted within the software to model parameters of the chosen material model.

Output from the main VEROAD programme is a table displaying all 15 stresses, strains and displacements. When the calculation is used to obtain the transient responses, this data is given as a function of time. Additional programmes have been included to calculate the effect of wheel configuration (dual wheels, tandem axles), of lateral wandering on both the transient response and the permanent deformation. Also the energy which is dissipated visco-elastically in the pavement can be found. Finally parameters for estimating the risk of plastic failure (Mohr-Coloumb) are calculated via calculation of principal stresses.

Operating requirements

It is recommended to run VEROAD in a DOS environment in order to minimise computation time. The code runs on any 486 PC or higher. A Pentium PC at 100MHz or faster is recommended.

Supplier

D.W.W. Road and Hydraulic Engineering Division of Rijkwaterstaat
Delft GA2600
The Netherlands

Summary of assessment

VEROAD was only used during Phase 2 of AMADEUS by Team 2.

Rather than the typical Phase 2 evaluation where absolute values of measured responses are compared to the model output, the asymmetric shape of the profile produced by VEROAD under a moving wheel load was compared to the shape of the measured profile. By assuming a number of parameters because the team had no knowledge of the correct values to describe the visco-elastic characteristics of the asphalt, it was evident that behaviour similar to that which was measured could be reproduced by VEROAD.

The conclusion of the team was that VEROAD was a promising tool but more knowledge was needed about the visco-elastic parameters to make effective use of the model.

Overview

Range of application

VEROAD is purely a response model however, it offers an opportunity to look at the effect of visco-elasticity.

The model requires extensive input parameters to define the visco-elastic behaviour of the asphalt material. Without knowledge of typical values, material testing needs to be employed to obtain these parameters. The laboratory test results can be converted into the required model parameters using supplied software tools. Nevertheless routine, extensive use of VEROAD may be expensive and impractical at present.

The most practical application may be under controlled testing for example in an accelerated load test. Here a small number of materials can be tested in the required manner for VEROAD parameters then the dynamic effect of the passing wheel load on the visco-elastic pavement can be more closely assessed than using a linear elastic model.

The model is multi-layer type and is therefore difficult to apply to composite pavements where joints in the layers are involved.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by VEROAD.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

No results for VEROAD were supplied in Phase 1 of AMADEUS.

VEROAD was tested by BRRC with the linear elastic assumption (fixing infinite values for the dashpots in the Burgers model). Agreement was found with the other programmes working with these assumptions. Further evaluation was made in Phase 2 to verify the measurements carried out in the DTU test site. It appeared that input values for the Burgers model, derived from an empirical formula, were able to fit the strain wave forms recorded at the bottom of the asphalt layer and their particular asymmetric shape.

User friendliness

VEROAD was not available to the users during Phase 1 of AMADEUS. Consequently no user questionnaires have been completed on this model.

References

Hopman P.C., Pronk A.C., Kunst PAJC., Molenaar A.A.A and Molenaar J.M.M. : Application of the visco-elastic properties of asphalt concrete. *Proceedings of the 7th International Conference on Asphalt Pavements*. Nottingham, 1992.

Hopman P.C. : The visco-elastic multi-layer programme VEROAD. *HERON, Vol. 41, No.1*, 1996. ISSN 0046-7316.

Hopman P.C., Nilsson R.N. and Pronk A.C. : Theory, validation and application of the visco-elastic multi-layer programme VEROAD. *Proceedings of the 8th International Conference on Asphalt Pavements*. Seattle 1997. pp. 693-705.

5.3 Models assessed in phase 3 and other phases

5.3.1 APAS

General information

Description

APAS is a modern software tool for pavement thickness design. It was produced by the Finnish Road Administration together with NESTE Bitumen in Finland. In addition to being able to calculate the layer thicknesses of new structures, APAS can also be used when designing rehabilitation of an existing pavement structure. This can be done because APAS can predict a lifetime or number of permissible loads on a structure.

Contained within APAS is a conventional multi-layer model, NOAH, which calculates responses at critical locations with the pavement structure. An iterative process is used to adjust the pavement structure so that critical responses are at an acceptable level according to fatigue curves.

The multi-layer model requires that the tyre load is represented as a circular uniformly distributed load. Multiple load configurations are available enabling many differently axle and vehicle loading patterns to be evaluated.

Main features

The software is designed so that the user does not need to understand the underlying design philosophy. To achieve this much effort has gone into producing an easy to use interface and also a database, which supports the work of the designer. The designer only has to input the geometry of the structure, select the pavement materials, define the traffic volumes and define the weather conditions to obtain the expected life of the structure.

The system includes a database of the materials most frequently used in Finland. The designer also has the freedom to add user defined materials to the database, but then he has to define calculation parameters for those materials. It is possible for APAS to handle specialist materials such as reinforced and stabilised materials but only if the appropriate calculation parameters can be defined.

Traffic can be defined in terms of different vehicle types which are then converted into a compound number of equivalent axle loads. The traffic can be categorised with separate growth factors applied to each category.

APAS does not take into account season variations in climate instead it uses an average air temperature to calculate material properties etc which is determined by climatic zone. APAS can perform two types of calculation; an iterative refinement of the structure in order to satisfy design criteria and a calculation of service life under prescribed conditions. APAS can also perform some cost calculations of the designs.

Rehabilitation design is based on Falling Weight Deflectometer (FWD) measurements of the existing structure. The FWD results can be directly read into the system from files in a particular format. A back calculation procedure is invoked to estimate layer parameters by fitting the calculated deflection profiles to the FWD measurements. Strengthening treatments can be freely applied to the model by the designer. Layers can be removed partly or totally from the existing structure and/or new layers added on top of the remaining layers. Thicknesses of the new layers are calculated in a similar manner for a new structure by adjusting the critical responses to acceptable levels.

Operating requirements

APAS operates under Windows 3.x, 9x or Windows NT and it is recommended that a Pentium PC or better is used.

Supplier

More information about APAS and detailed user help in English can be supplied by:

Arto Kuskelin
Finnish Road Adminstration
Tel +358 0204 44 3202
Fax +358 0204 44 3201
GSM +358 40 546 0126
E-mail arto.kuskelin@tieh.fi

Summary of assessment

Phase 1

APAS could be used in Phase 1, but only with a version of the software that was modified to allow access to the calculated responses. The contact stress directly under the centre of the contact area satisfies the natural condition of this response being equal to the applied contact pressure.

Phase 3

Further work with APAS was performed by one of the partners during Phase 3 of AMADEUS. This work did not follow the Phase 3 evaluation procedure as described in Section 3.3 however the findings of this work have been absorbed into the relevant sections of this document.

Overview

Range of application

APAS is a design model which contains a “hidden” response model.

The model is multi-layer type and is therefore it is not possible to apply to rigid or composite pavements in the vicinity of joints or cracks. The iterative design element can be used to design new structures and also assess maintenance treatments for pavement rehabilitation. Furthermore the database includes a costing element which allows for the computation of an indicative cost of each new design or rehabilitation.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by APAS.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

For Phase 1 tasks, APAS compared well with other pavement models. The results obtained were almost identical to those from other Multi-layered models (see figure 6).

User friendliness

Only one User's Questionnaire was returned.

No problems were reported with the installation of APAS. Basic instructions were provided which described some of the theory behind the model but the User thought that this was unnecessary to run the model. Furthermore it is not essential to attend a training course in APAS.

The interface supplied with APAS allows the user to define the problem, run the model and then view the results. It is considered easy to understand with efficient entry of data and the terminology used in the English version is clear.

The method of defining pavement structures is considered simple with all required data readily available. Some limitations were encountered in the method of defining the performance functions which required a correction to be performed after the calculation. In running the model iteratively the user found that the software does not use the chosen modulus in the first iteration but does thereafter. APAS uses climatic zones for which the material properties are computed. In the current version these are defined for Finnish conditions and cannot be changed by the user. The user considered that they had adequate control over the output positions and that APAS was able to calculate all the required responses. The output could be easily stored and later retrieved. It is not possible to print the results directly from the software however they are easily exported into spreadsheet where they can be printed.

When errors occur, APAS only sometimes explains the problem or suggests a solution. The user found that APAS uses a reference load which can be changed for calculations of service-life. However the software refuses to perform iterative calculation with any other load than the reference load.

References

APAS - Analytical PAvement deSign : Manual in APAS-CD package.

Pienimäki M. : Possibilities in Computer Aided Pavement Thickness Design. *5th Eurobitume Congress, Stockholm.* 1993.

Pienimäki M. : Neste - APAS, Analytical pavement design tool. *Bituminous Pavements: Materials, Design and Evaluation, Oulu.* 1995.

5.3.2 BISAR (SPDM 3.0)

General information

Description

SPDM3.0 contain modules for thickness design, rutting calculations and asphalt overlay design. This software represents the state of the art of the Shell Pavement Design Method (SPDM) which is now applicable to modified binders.

The development of the method started with the issue of Design Charts in 1963, and represented a partly analytical and partly empirical method of the thickness design of flexible pavements. In 1978 this system was extended significantly with analytical components and published as the Shell Pavement Design Method. The design were created from the results of BISAR (BItumen Stress Analysis in Roads) calculations and included temperature, traffic density etc. The asphalt was characterised by selected stiffness and fatigue classes for two types of conventional bitumens used at the time.

In 1992 the first release of SPDM-PC (Shell Pavement Design on a Personal Computer) was issued. The package essentially followed the design philosophy of the 1978 manual but the computer programme allowed the use of a wide variety of temperatures, bitumen grades etc. which avoided the cumbersome interpolations needed when using the manual. The PC version gave the possibility to provide specific material properties, but the use of nomographs and charts was still the default method.

With the release of the Windows version of SPDM (release 3.0) much more emphasis is given to specific material properties and input of such data, for example the fatigue behaviour of polymer modified asphalt, is now the standard procedure. The programme still follows the SPDM thickness design philosophy, but the default material properties listed in the 1978 manual should not be considered as part of the method and only as a fall-back position.

The rutting calculation method in the 1978 manual and in the first release of the SPDM-PC was limited with respect to variation in traffic. The shape for the traffic spectrum was fixed and only the amount of traffic loading could be adjusted. The second release was able to deal with specific traffic configurations (including super-singles), but the rutting calculations were still based on static creep characteristics which did not appear to be applicable to modified binder.

The rutting module of SPDM3.0 is now based on creep characteristics from dynamic tests. It gives the opportunity to input your own specific viscosity data. Rutting calculations for polymer modified bitumens require input of such viscosity as this cannot be estimated from the Van der Poel Nomograph.

In addition to SPDM3.0, the Shell suite of software incorporates the following:

BANDS 2.0	A tool to provide binder and mix properties for use in thickness design.
BISAR 3.0	A linear elastic response model.

Main features

The response model, BISAR 3.0, is a Windows version of this linear elastic multi-layer programme.

Loading is defined in up to 10 circular areas by specifying the uniformly distributed vertical load and also a unidirectional horizontal shear. Conventional layer parameters (E and μ) are needed to define the material and also slip can be defined between each layer.

Input is provided via a user friendly interface. This interface allows up to ten different cases to be defined and calculated simultaneously. Facilities for duplicating the cases are included allowing for easy and rapid variation of input parameters. Included in the user interface is the facility to save all three components of a BISAR run (loads, structure, output positions) independently. This in some way is a database whereby standard loads and structures can be recalled for use in other analyses.

Output is offered in two styles (a report suitable for printing or a table suitable for importing into a spreadsheet) and in two forms (block summary or detailed results).

The programme is also suited to analyse stress/strain profiles in more complex designs and loading patterns, e.g. in airfields.

Supplier

Shell International Oil Products BV
PO Box 38000
1030 BN Amsterdam
The Netherlands

Summary of assessment

Phase 1

6 Partners used BISAR for the case of full friction between all the layers, and 4 of these used the additional feature of slip between the layers.

Under the wheel loads of both the single and the dual wheels, the natural condition of stress at the surface of the pavement being equal to the contact pressure was satisfied by the results of all Partners.

4 of the 6 Partners who supplied results for the single wheel load had similar results. Also, for the dual wheel load case. However with these 4 Partners there were still some erroneous results.

The results of the 4 Partners who attempted smooth interface cases are divided into pairs with widely varying results. In some positions, some Partners predict tension and others compression. Also the magnitudes of these results vary by orders of magnitude and by relative size to each other. This indicates that there may have some confusion over the type of response to be extracted from the output file as well as the differences, which will occur by varying level on slip.

Variance of BISAR results from different users

Load	Interface	Centre load	Off axis
Single	Friction	1.64E-3	0.2582
Dual	Friction	1.84E-2	1.23E-2
Single	Smooth	3.49E-1	1.1384
Dual	Smooth	3.31E-1	1.2853

Phase 2

BISAR was evaluated by one team, Team 1, in Phase 2.

The team reported that with the exception of vertical strain, BISAR gave a good prediction of response for the LAVOC data. For the DTU data the predictions of response tended to be smaller than measured with the vertical response predictions only 50% of the measured value while the horizontal strain was predicted at approximately 80% of that measured. For the CEDEX data the team reported that predictions were not too close to the measured values, particularly the vertical responses. Furthermore modifications to the ‘Actual’ input data did produce better results for individual responses but did not produce consistent, overall improvement in the results. No problems were reported by the team in performing the work in Phase 2 with BISAR.

Phase 3

BISAR was used by Team 1 in Phase 3 to predict structural rutting and fatigue of the roadbase layer. Subsequent methods were employed to predict performance from the calculated responses. Although the results produced with BISAR concur with the observed behaviour of the test sections, i.e. that conventional forms of deterioration are not occurring, it is more a measure of the method applied to convert the responses than the accuracy of the response itself.

Overview

Range of application

BISAR is purely a response model. Input parameters are specified and calculated responses then displayed.

BISAR offers the facility of using either a single or dual wheel load. Up to 10 loads can be defined.

With respect to pavement design, BISAR includes the possibility of performing multiple runs in one calculation. This feature is useful because information can be copied between runs and then changed slightly. This is often needed when designing structure to check the effect of a change in a single parameter or to compare a number of different designs. Slip is available at the interface between any layer. However since it is difficult to define slip in practice, beyond theoretical studies this is not of practical use. The model is multi-layer type and, like all models of this type, is difficult to apply to rigid or composite pavements where joints in the layers are involved.

It is easy to learn to use BISAR and it provides consistent results. It is ideally suited as part of design methods similar to those in existence where it will give quick and reliable performance.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by BISAR. Elements 8,9 and 10 are satisfied by the complementary programme, SPDM3.0.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

For Phase 1 tasks, BISAR compares well with other pavement models. Results provided are almost identical to other Multi-layered models (see figure 6).

User friendliness

The users viewed the installation of BISAR as easy with no reported problems.

Documentation was supplied with the software in the form of a user's guide which is readily printed from an electronic document included on the programme disk. Most user's however thought that BISAR could be used without documentation and all agreed that a training course was not necessary to use this software effectively.

The user interface supplied is based on Windows 95 and was highly rated by the users on its layout, the ease of data entry and the clarity of the terminology used. All users considered the definition of the pavement structure and the loads upon the structure to be simple tasks, with the information required for these tasks readily available.

Running the model to compute the solution was swift with the users generally obtaining results in a matter of seconds. Variations in the computation time stated by the users follow the performance of their respective PC's.

Output from BISAR is in the primary form of text files, with summary sheets available showing the more common responses in a condensed format. Most users agree that the output is clearly labelled and formatted for easy printing. All users felt that the output can be easily imported into a spreadsheet for analysis and comparison.

All users felt that there was adequate control over the output positions for the calculation of responses and that all the required responses were available. The file storage and retrieval system in BISAR is wholly contained within the user interface, consequently it was highly rated by the users. The user interface is highly developed and it handles errors well. Where answers from users were given, most felt the interface offered helpful advice to solve problems.

References

BISAR-PC Users Manual : *Shell International Petroleum Company, London, UK,* 1995.

5.3.3 CIRCLY

General information

Description

CIRCLY is a software package based on multi-layered, elastic theory that allows the analysis of a comprehensive range of load types. It originates from software developed at CSIRO (Harrison, Wardle and Gerrard, 1972). CIRCLY has been under continuous development since its release in 1977. Improvements to CIRCLY include the addition of multiple loads and polynomial type radial variation in contact stresses to enable a more realistic representation of actual loading conditions (Wardle, 1977). CIRCLY became commercially available in 1988 through MINCAD Systems. Version 4.0, released in 1999, includes automatic thickness design amongst other special features. Some of the comments relate to Version 3.0 that was used in the early phases of the work; where necessary the particular version is denoted.

Special features

CIRCLY was originally designed for soil and rock engineering problems. In these problems, forces are often applied to the horizontal, or near horizontal, to man-made or stratified deposits. Additionally, due to the nature of their formation cross-anisotropic material behaviour is often observed in rock and soil deposits. This material behaviour is included in CIRCLY along with interface conditions which can develop in rocks and soils. Therefore the boundary condition at interfaces can be full friction, or frictionless.

In the area of pavement analysis, CIRCLY possesses many advanced features for design and analysis of structures. The system predicts cumulative damage induced by very general traffic spectra. Any combination of vehicle types and load configurations can be used. The method of calculating damage with traffic spectra can model multi-wheel configurations avoiding approximation by 'equivalent' single or dual wheel loads. Complex loading conditions can be included whereby interactions between the tyre and the road surface can be in both the horizontal and vertical direction. Consequently, this enables cornering, traction, braking, and gripping forces generated by pneumatic tyres to be included. Examples of these complex load cases are given in figure 36.

Damage is predicted by using Miner’s hypothesis at each analysis point. Pavements are assumed to fail when this cumulative damage reaches 1.0. Material performance can be defined by the user using the following general formula.

$$N = \left[\frac{k}{\mathrm{e}}\right]^{b}$$

Where, N is the predicted life or load repetitions, ε is the strain induced at a critical location and k and b are constants.

In addition to calculating the damage factor, any component of displacement, stress or strain can be calculated and plotted. This facility is being used by a number of research centres for studying the influence of strain pulse shapes on damage estimates.

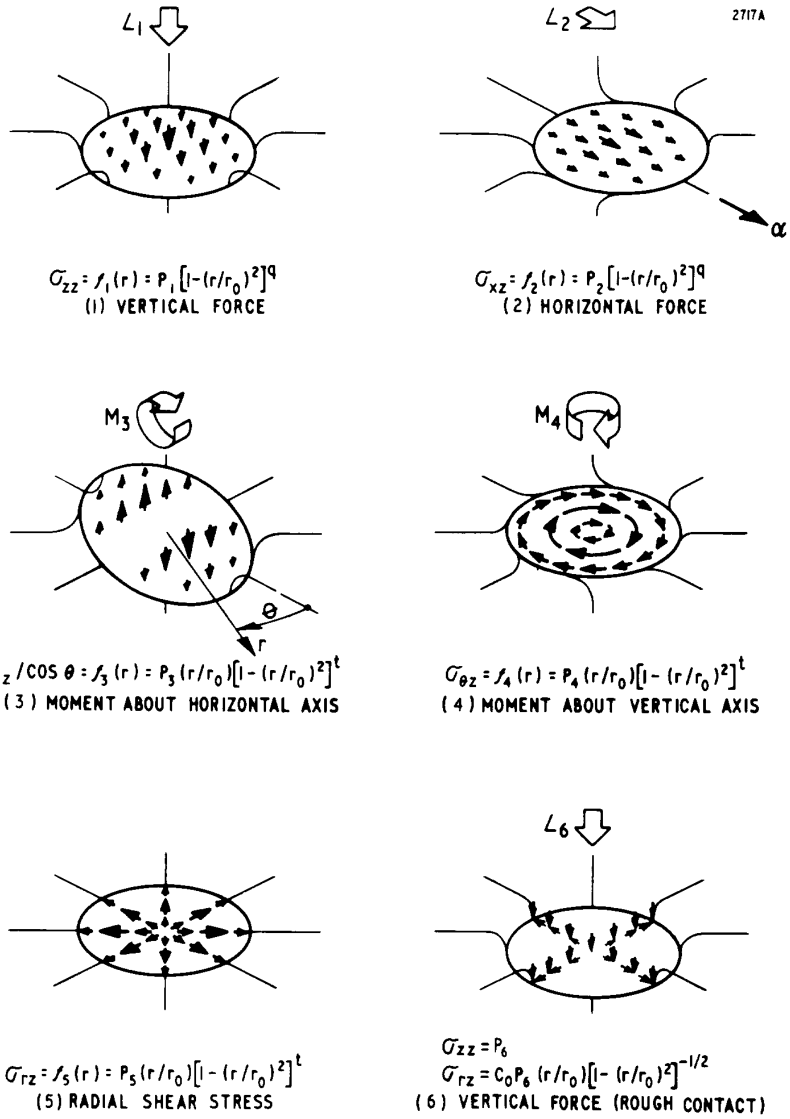


Figure 36 : Examples of different load types available in CIRCLY.

A special version of CIRCLY: APSDS (Airport Pavement Structural Design System) has been developed for heavy duty pavements such as airport pavements and industrial pavements such as container terminals. APSDS allows for lateral wander of vehicles, although wander is not used in current road design systems it is likely to be used in the future. APSDS was not evaluated in the AMADEUS project.

The CIRCLY user interface contains a database in which materials, loading and load spectra can be stored. This facility is very helpful when computing repeated runs with similar parameters.

Results are available in tabular form or graphical form by an automatic export feature, which links with the EXCEL® spreadsheet package. The tabular results are easily exported to EXCEL® and other spreadsheet packages for further processing.

Operating requirements

The current version of CIRCLY (version 4.0) runs under Windows 95, 98 and NT. As a result, it is intended to be user-friendly. Databases are utilised for material properties and load configurations eliminating the need to constantly re-key information. Computation is achieved in a matter of seconds on modern PC's.

Supplier

CIRCLY is available under license from:

MINCAD systems Pty. Ltd.
P.O. Box 2114
Richmond South
Victoria
3121 Australia
email: mincad@mincad.com.au
www.mincad.com.au

Summary of assessment

Phase 1

CIRCLY was evaluated in Phase 1 of AMADEUS however only one set of results was given therefore no comments can be made regarding the variability of results. The contact stress directly under the centre of the contact area satisfies the natural condition of this response being equal to the applied contact pressure. Other responses were predicted to be close to but not precisely the same as other models as depicted in the figure 6.

Phase 2

CIRCLY was evaluated by Teams 1 and 4 in Phase 2 of AMADEUS.

The teams reported that using the standard data, given in § 4.1.3, good agreement was found between the measured and the predicted horizontal strains at the LAVOC and the CEDEX trials but underestimated the measured horizontal strains at the DTU trial. Deflections were over-estimated by CIRCLY at the LAVOC trial. Vertical responses at all of the trials were under estimated.

Both teams attempted to use anisotropic material behaviour to improve the agreement with the measured results but both report that this generally gave no improvement. The exception was at the CEDEX test, where one team reported that anisotropic behaviour improved the prediction of vertical responses at depth. Slip at the interface between asphalt and the underlying granular layer was also tried to improve the results, without success.

The conclusion was that CIRCLY operates as well as most other models in this evaluation. Its advantage is that it has many features, some of which are unique, that can be employed. However, the team's experience was that anisotropy and slip at the interface did little to improve the results in this evaluation.

Phase 3

CIRCLY was used by Teams 1 and 3 in Phase 3 primarily to explore the viability of including traffic spectra to predict cumulative damage. The Team found these facility easy to use and the results agree with similar non-automatic calculations carried out by the team using BISAR. It was concluded that this was a worthwhile feature of CIRCLY.

Overview

Range of application

CIRCLY is primarily a pavement response model although there is the facility to predict performance using user defined transfer functions. Single and multiple wheel loads are possible enabling the possibility to analyse many types of axle/load configurations. Also the facility to define load spectra to predict damage is an additional powerful tool for pavement design.

The concurrence with other multi-layer models will allow CIRCLY to be implemented in any existing design method. Also the multi-layer type model is difficult to apply to rigid or composite pavements where joints in the layers are involved.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by CIRCLY.

1	▨ 2	3	▨ 4	▨ 5	6	7	8	9	10	▨ 11

Comparison with similar models

For Phase 1 tasks, CIRCLY compares well with other pavement response models. Results provided are almost identical to other Multi-layered models. There is a small deviance in calculated strain but this is not significant (see figure 6).

User friendliness

All the comments included here refer to Version 3.0.

All users found CIRCLY easy to install onto their machines.

Documentation was supplied to all users of CIRCLY in the form of a user’s guide, which contained the theory behind the model, descriptions of the features and how to run the model. Some users expressed differences of opinion about whether documentation is vital to run the model. However, the majority thought that documentation was necessary and that a training course would be beneficial.

The interface of CIRCLY is all-inclusive allowing input of the model data, execution of the solution procedure and viewing of the output. The rating of the user interface layout by the users ranged from adequate to confusing, while the ease of data entry and the clarity of the terminology used were both rated as adequate. The method of defining the pavement structure and prescribing loads was considered easy to carry out.

The computation of the results was reported to take between 5 and 10 seconds.

Output from CIRCLY is primarily in the form of text files. One user recognised that graphical output is possible from CIRCLY and that once mastered, it is easy to produce and print a hard copy. However this feature is not part of the user interface itself, it is a macro that launches Microsoft EXCEL in the appropriate manner.

The users did not feel that there was adequate control over the output positions, for the following reasons:

- CIRCLY is designed to calculate the responses at one depth per run, therefore multiple runs are required for multiple depths.
- The output could only be defined at the top or the bottom of a layer (Version 4.0 allows output at other locations for response calculations only).
- The software does not output the response precisely at the depth of the interface.

The file storage and retrieval system did not receive a high rating. Opinions on this ranged from adequate to poor. This is because of the first point above, in that, although CIRCLY allows different file names to be defined for the file under which the input data is saved, it make just one output file per run. When performing multiple runs for different depths in the pavement structure, the output file will unavoidably be overwritten and results lost.

Help with errors is included in CIRCLY but this occurs generally when parameters are badly defined in other parts of the users interface. Once the model is running, no helpful error messages are offered if the model encounters problems.

References

Harrison W., Wardle L.J. and Gerrard C.M. : Computer programmes for circle and strip loads on layered anisotropic media. CSIRO Australia Division of Applied Geomechanics Computing Programme No. 1. 1972.

Wardle L. J. : Programme CIRCLY User's Manual. CSIRO Australia Division of Applied Geomechanics Computing Programme No. 2. 1977.

5.3.4 MMOPP

General information

Description

The Mathematical Model Of Pavement Performance (MMOPP) simulates the deterioration of a length of road under the influence of dynamic loading, climatic effects and time. It is based around a conventional multi-layered elastic model which accepts single and dual loads by superposition.

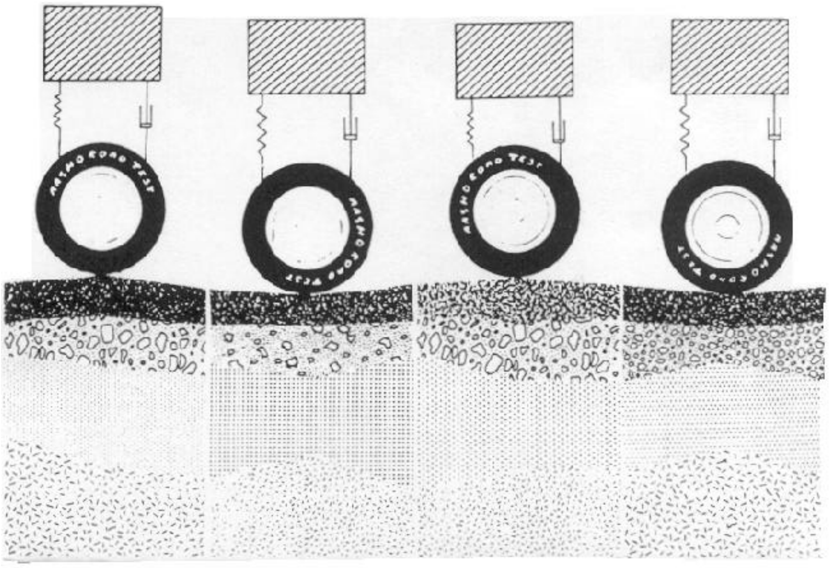


Figure 37 : Model used in MMOPP to calculate variations in layer thickness, materials and loads along the length of the road.

Main features

The first step in MMOPP is the "construction" of a length of road on the computer. As shown on figure 37, the length is composed of short pieces of road, 300mm long, with the layer thickness, elastic stiffness, plastic parameters and strength parameters varied from piece to piece. The pattern of variation is very important to the future deterioration. MMOPP uses a second order auto regressive process to generate realistic patterns of variation.

An incremental-recursive procedure is used to predict the deterioration. Structural and functional deterioration is predicted for one increment of time (season) and the output used (recursively) as input for the next increment. This allows modelling of seasonal changes due to temperature, freeze/thaw or changes in moisture content. it also means that gradual changes in pavement structure can be modelled. Cracking of the asphalt, for example, may lead to an ingress of moisture, changing the parameters of the unbound materials.

The loads are dynamic, and will depend on the present roughness of the surface, on the wheel type and suspension system and on the mass and speed of the vehicles. In MMOPP the dynamic loads are calculated at each short pieces of road, for each vehicle type and the effects of loads in terms of reduction in asphalt modulus and increase in permanent deformation in each of the pavement layers are determined, for each short piece of road. The effects of all loads during one time increment are summarised and the new condition is used as input for the next time increment, taking into consideration the effects of the climate, time etc.

MMOPP is a stochastic model, therefore several runs with identical input data will produce different outputs. This may be used to gauge the reliability of a given pavement structure.

The first version of MMOPP was developed in 1976. It has since been used to simulate the AASHO Road Test and results from full-scale testing. MMOPP is presently under consideration for use in a new Danish Standard for the design of flexible pavements.

Operating requirements

The latest version of MMOPP operates under Windows 95. It provides a comprehensive user interface which eases the task of entering input parameters, runs MMOPP and displays output in both formatted tables and graphical forms.

Supplier

Prof. Per Ullidtz
DTU
Building 115, IFP, DTU
DK2800 Lyngby
Denmark

Summary of Assessment

Although based upon a response model it is set up as a performance model rather than a response model and consequently its use is not applicable to either Phase 1 or Phase 2 of AMADEUS. Results are only given for the evaluation Phase 3 for MMOPP.

Phase 3

Team 4 used MMOPP to calculate Present Serviceability Index (PSI) and rutting in both the asphalt and unbound layers. Although MMOPP calculates the International Roughness Index (IRI) rather than PSI, the to indices can be related.

The team concluded that MMOPP can be used to provide reasonable estimates of PSI and rutting for flexible pavements. Furthermore, although MMOPP is design for use with flexible pavement, this work has found that it can also be applied to semi-rigid pavements to provide information of rutting.

Overview

Range of application

MMOPP is primarily applicable to flexible pavements. It can be used to predict performance in terms of International Roughness Index and permanent deformation. Also, this work has shown that MMOPP can also be used to evaluate rutting in semi-rigid pavements. It is not possible to use MMOPP to calculate responses alone as these are concealed within the software.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by MMOPP.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

MMOPP was not applicable to the tasks of Phase 1 of AMADEUS therefore no comparison was made.

User friendliness

MMOPP was not used during Phase 1 of AMADEUS. Consequently no user questionnaires have been completed on this model.

References

Ullidtz P. : Modelling Flexible Pavement Response and Performance. Polyteknisk Forlag, 1998.

Ullidtz P. : Mathematical model of pavement performance under moving wheel load. *Transportation Research Record 1384*, Transport Research Board, Washington. 1993.

5.3.5 NOAH

General information

Description

The purpose of the NOAH software is to enable the user to derive the maximum benefit from “multi-layer elastic stress/strain response” computation programmes in the frame of rational pavement design methods.

The central response model, an axi-symmetric multi layered elastic type, assumes circular wheel loading with a uniform, vertical stress distribution. Loading can be defined in terms of a wheel load spectrum. The layers are assumed homogenous but anisotropic behaviour can be defined in the subgrade layer. Material properties for the layers can be stored and extracted from the included materials database, making runs with common materials more efficient.

Main features

Major features of NOAH include :

- All the various parameters (structural, environmental, loading) can be treated as "design variables" and assigned several successive values. The software automatically calculates, for each set of assigned values, the response of the pavement as related to stresses and strains. This allows an optimisation of the design.
- The software includes a "Formula Generator" by which the user can enter, directly from the keyboard, mathematical relationships which may be used at various stages in the computation session. These relationships can be used to define material properties (e.g. stiffness) as a function of environmental parameters (e.g. temperature). The "Formula Generator" can also be used to define "Performance Indicators" for relating stress and strain to actual performance. These "Performance Indicators" can be a characteristic of the material and depend of the type of distress which is to be investigated (e.g. rutting, fatigue etc..)
- The NOAH software also allows the definition of statistical distributions of the design parameters. the final statistical distribution of the above mentioned "Performance Indicators" is obtained in an easy and quick manner by using the so-called "ROSENBLUETH approximation" by which the continuous statistical distributions of the input parameters are replaced by discrete equivalent "point estimate" distributions.

NOAH is applicable to sensitivity studies in which one investigates the sensitivity of pavement performance (in as far as it can be related to calculated stresses and strains) to variations of any of the involved input parameters (structural, environmental, loading). The databases and the "Formula Generator" feature enables the NOAH software to be easily adapted to different design methods.

Operating requirements

NOAH is designed to run within Windows and many other facilities such as the database function make NOAH a flexible and powerful tool.

Supplier

NOAH is commercially available from:

NYNAS N.V.
Excelsiorlaan 39
B1930 Zaventem
Belgium
Tel : +32 2 725 20 63
Fax : + 32 2 725 10 91

Summary of assessment

Phase 1

5 Partners used NOAH for the case of full friction between all layers with two of the Partners utilising the smooth interface feature.

All Partners who ran NOAH achieved exactly consistent results for the cases where full friction is assumed between layers. Consequently in all instances, the natural condition of stress at the surface of the pavement under the wheel load equal to the applied pressure was satisfied.

For the cases where smooth interfaces were used, consistent results are seen in the centre of a loaded area but differences are predicted at other positions for both the single and dual wheel cases. The difference between the consistency of the full friction results and the smooth interface results suggests that a source of error may be the value of slip entered into the NOAH model. Infinite slip is impossible to define, therefore the results may depend on how small a value was entered for the slip parameter. Under both types of wheel loads the relative magnitudes of the response between the Partners add further confidence that this is the case.

Variances of results from different users

Load	Interface	Centre load	Off axis
Single	Friction	6.727E-10	6.78E-10
Dual	Friction	0	0
Single	Smooth	0	0.25
Dual	Smooth	0	1.989E-4

Phase 2

Team 2 evaluated NOAH in Phase 2.

Horizontal strains were predicted to be close for the LAVOC and the DTU trials, but for the CEDEX trial the predictions were much lower than measured. Vertical stresses and strains were much in error, reported to be just 50% of the measured values. The prediction of deflection was said to be close.

Modifications to the standard data in order to improve the results centred around adjusting the stiffnesses of the layers. Generally no improvement was seen overall through these modifications however for the LAVOC data the work suggested that a slight reduction of the modulus of the granular layer would give a small improvement in the results. In all cases the vertical response remained fairly insensitive to the modifications.

Team 2 commented that NOAH is a user friendly programme. Also that a possible source of user error is that the loading is defined in terms of contact pressure and radius. If the user has wheel load and one of these parameters to characterise the loading then an additional external computation must be performed.

Phase 3

NOAH was used in Phase 3 to predict rutting in the asphalt layer and fatigue of the roadbase layer. Subsequent methods were employed to predict performance from the calculated responses. Although the rutting results produced with NOAH concur with the measurements of the test, it is more a measure of the method applied to convert the responses than the accuracy of the response itself. For fatigue calculations, use of the formula generator in NOAH was made to use the SHELL fatigue law. This proved a worth while feature.

Overview

Range of application

Within NOAH there is a response model. This provided extremely consistent results for the many different users. This indicates that the model could be used by a number of users without a large fear of wildly erroneous results.

NOAH’s major features are its internal databases and the facility of defining input parameters as variables to assess the resulting variation in output.

The facility to treat parameters as variables makes NOAH particularly appealing to pavement design where it is often necessary to design a structure but also consider a number of what ifs. For example, what is the effect on pavement life if, after laying, the specified design thickness of a layer varies by ±5mm. Also, it can be used to assess worst case scenarios without major recalculations.

There is no restriction on number of layers, or on the number of multiple loads. However the facility to consider load spectra is not available in NOAH, therefore cumulative damage due to a number of types of vehicles is difficult to assess.

NOAH includes several internal databases covering load configurations, materials, structures. Also, it allows the user to insert relationships between model input parameters and other variables, for example, relating asphalt modulus to temperature. The user can then simply see the effect of variables on response. Also the software includes the facility to define your own transfer functions to relative responses to performance.

The model is multi-layer type and is therefore difficult to apply to rigid or composite pavements where joints in the layers are involved. Overall NOAH is a flexible model which can be adapted to any existing design method.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by NOAH.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

For Phase 1 tasks, NOAH compares well with other pavement response models. Results provided are almost identical to other Multi-layered models for full friction cases. For the cases where slip between sub-base and subgrade was involved, large differences in calculated response were seen between NOAH and other models offering interface slip. The differences were possibly due to the different interface slip model used in NOAH, § 4.1.4.

User friendliness

No problems were encountered whilst users installed NOAH, and this was consequently considered an easy task.

Comprehensive documentation was supplied to all users in the form of user guides and training guides. These documents explained the theory behind NOAH, all the main features and how to run the model. While this documentation was supplied, the users felt that NOAH could be run without it but to make full use of NOAH a training course would be beneficial.

The NOAH model is contained within a fully interactive user interface. The layout of the interface was rated between good and adequate with similar ratings given for the terminology used and the ease of data entry.

All users felt that the method of defining the pavement structure was simple and that all the required information was readily available. The definition of loading was considered quite easy too.

Run times in NOAH are largely dependent of the type of analysis to be performed. The model offers features such as varying structural parameters, environmental conditions and loading so the possible number of combinations of these variables can be large. For each combination NOAH must perform a single calculation, therefore the run times can be long. This explains the large difference in reported run times of the users of between 3 seconds and 15 minutes.

NOAH offers both output in the form of text files and graphical output. The text files are thought to be clearly labelled and suitable for printing to a hardcopy, but the users generally though that it was not easy to import these files into spreadsheets. The graphical output was generally thought to be easy to produce within the user interface. The users obtained all required responses with adequate control given over the output positions. The file storage and retrieval facilities in the user interface were rated highly.

NOAH is particularly suited to performing parametric studies. The possibility of varying input parameters explicitly or automatically using statistical distributions contributes largely to this. The internal databases of parameters such as loading, environment and structures help too. Also the graphical output is designed to easily show the effect of a change in an input parameter.

All users agree that when an error occurs, the software only sometimes suggests advice as to the cause of or solution to the problem. A major problem encountered was that NOAH allows you to dimension the software by specifying a maximum number of layers and also a maximum number of calculation points. Any previously saved files that contain layers or calculation points in excess of the current settings cannot be read into the software. This error is not explained by the current version of the software.

References

Van Cauwelaert F. : Stresses and displacements in multi-layered orthotropic systems. *NOAH Documentation. NYNAS NV, Antwerpen,* 1995.

Eckmann B. : NOAH Computer Software for pavement design calculations. Training manual 1995.

Eckmann B. : New tools for rational pavement design *Proceedings of the 8th International Conference on Asphalt Pavements*. Seattle 1997, pp. 25-42.

5.3.6 VÄGDIM 95

General information

Description

VÄGDIM 95 was developed as a user-friendly and flexible system for pavement structural design. Design can be performed both with regard to bearing capacity and frost heave. The frost design procedure follows an earlier established Swedish method. For the bearing capacity design, the CHEVRON programme is used which is a conventional multi-layer, linear elastic programme.

Critical stresses and strains are calculated for different periods and Miner's hypothesis is used to obtain the accumulated damage. The mixed traffic load is converted to equivalent number of 100kN standard axle loads with dual wheels and 800kPa tyre pressure.

Main features

VÄGDIM 95 is intended for installation on a PC in Windows environment and consists of two modules, the design programme itself and a database for pavement materials and climatic conditions. The system is easy to use and flexible in that most of the input data can either be chosen from four different input data sheets or be defined by the user.

The database includes predefined materials and climatic conditions but the user can define their own data and include them in the database. The system calculates pavement layer thicknesses required for a chosen design period.

Finally, the system also makes it possible to calculate the cost of the structure by giving the price per unit for the various pavement materials.

Operating requirements

VÄGDIM 95 runs under Windows 3.11 on a PC which should have at least a 486/33 Processor.

Supplier

The software is freely available from Swedish National Road and Transport Research Institute. (leif.g.wiman@vti.se)

Summary of assessment

Phase 1

Only one Partner provided results for Phase 1 of AMADEUS with VÄGDIM95 because they had access to CHEVRON on which VÄGDIM95 is based. Therefore comparisons between users could not be made.

Phase 3

One team used VÄGDIM95 to assess the design of the flexible type test sections. By using the supplied material, structure, traffic and climatic information, designs were produced for a 20 year period based on the design criteria included in VÄGDIM95.

The results were that every team member reported that the design thicknesses were less than the construction thicknesses for each test section. Therefore, these test sections are ‘over-designed’ which concurs with the fact that each flexible test section was showing very little deterioration after 20 years.

Overview

Range of application

VÄGDIM95 is a flexible pavement design tool produced in Sweden for their national conditions. In order to make the software as user-friendly as possible for Swedish road engineering, a database of standard materials and climatic conditions is included however, the user can also define their own data in the database. The model is particular applicable to Sweden, which is reinforced by the user interface being in Swedish.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by VÄGDIM95.

1	2	3	4	5	6	7	8	9	10	11

Comparison with similar models

Since VÄGDIM95 is a design model rather than a performance model, the only comparison which can be performed in Phase 1 of AMADEUS is with the underlying response model, CHEVRON. For Phase 1 tasks, the CHEVRON response model compares well with other pavement response models. Results provided are almost identical to other Multi-layered models (see figure 6).

User friendliness

VÄGDIM95 was not accessible to the majority of users during Phase 1 of AMADEUS due to a software problem. Consequently no user questionnaires were completed on this model.

References

Djärf L., Wiman L.G. and Carlsson H. : A new flexible pavement design method. Formulation of a user friendly mechanistic/empirical design system for Swedish conditions. *TI Meddelande Nr. 778A.* Swedish National Road and Transport Research Institute. 1996.

5.3.7 VESYS 3PC - RD

General information

Description

The original VESYS programme was developed by the Federal Highway Administration Washington D. C. in the early 70's with the aim to calculate pavement response by means of a visco elastic solution combined with probabilistic solutions. Because of its complexity the visco elastic solution was replaced by a multi-layer solution and by phenomenological based distress models.

During the early 80's, the development of the VESYS programme was transferred to the German Ministry of Transportation. The VESYS programme was assessed with the result considerable improvements could be made so a new version of the VESYS programme was created.

The most important differences between the original and the German VESYS programme are in the distress models to predict rut depth and roughness. Also considerable improvements were made in the method of taking traffic conditions into account. This was done by taking into account the different transverse wheel path distributions caused by passenger cars and trucks, as well as velocity and lane width.

Important changes were also made to handle the necessary input data. A formula was introduced to calculate the temperature and frequency dependent stiffness of asphalt mixtures using information about the binder and the mix densities. Also a formula was developed to calculate the temperature in the middle of the asphalt layers with respect to average monthly temperatures in Germany.

The rut depth model predicts permanent deformation not only at a given position (difference between the original height and the height after some load repetitions) but at every 150 mm transverse to the moving direction in one wheel path with a maximum width of 2400 mm. The rut depth is then calculated as the difference between the deepest and the highest point of that rut profile.

The VESYS-programme was adapted to run on personal computers at the University of Wuppertal with support of Prof. Edeltraud Straube, University of Essen. The programme is large so that only the part to predict the rut depths could be taken over into the PC version. This is the reason why the name of the programme was changed to VESYS-3PC-RD.

Input data are similar to that needed to run a multi-layer programme. In addition, input data for load repetitions, load distributions and lateral wheel path distributions are required as well as parameters for the distress models. In order to take all features into account, a set of data to calculate the temperature and frequency dependent resilient moduli of the asphalt layers is recommended but it is also possible to give fixed moduli as input.

Special features

Only single wheel loads and only full friction between layers can be accounted for.

User input to the model is aided by a simple DOS based user interface. This user interface sets up formatted text input file for the VESYS-3PC-RD processor. Proficient users of VESYS-3PC-RD can edit this input directly if desired.

Output from the model is in the form of two formatted text files. One text file shows the permanent deformation on the surface, with time if required, as well as an evaluation of this profile data using the rut depth with respect to a standard of measurement of 1.22 m. The original version of VESYS was used to estimate the rut depth as part of the Present Serviceability Index [PSI]). The other text output file shows the profile data as mentioned, but as the sum of the permanent deformation of each layer. With this output file, it is possible to identify the contribution of each layer to the rut depth. Because of the very large amount of multi-layer calculations, responses as stresses, strains and displacements are not given as output.

Operating requirements

VESYS-3PC-RD is designed to run under MS-DOS, and it is recommended that the PC on which it is run should have at least a Pentium® processor. Otherwise the calculation time can exceed 30 minutes.

Supplier

The software is at present not available for public use.

Summary of assessment

Phase 1

Only one Partner provided results for Phase 1 of AMADEUS with VESYS because they had access to CHEVRON on which VESYS is based. Therefore no within model analysis is possible.

Phase 2

VESYS was not considered in Phase 2 of AMADEUS.

Phase 3

Team 3 used VESYS to evaluate rutting. Internal mix predictions were made using the input data from Deliverable D3. Each team member acted independently but regardless the range of results was small. In general, VESYS gave reasonable results for rutting in the test sections.

Overview

Range of application

Although VESYS contains within itself a pavement response programme, the software is designed to predict performance rather than response, in particular rutting. This formulation restricts the use of this version of VESYS to specifically problems of deformation.

The software allows the use of multiple loads and more significantly the use of wheel load spectra. These can be applied in a single period or the analysis split into separate periods to acknowledge the effect of change in climatic condition through a year for example.

The concentration on the prediction of performance rather than response suggests that this model could be used for pavement design and also advising on the specification of materials based on the deformation parameters. In contrast it is difficult to see VESYS used for pavement assessment purposes since responses which can be used in back-calculation algorithms are unavailable to the user.

Relevance to incremental design procedure

The following elements of the incremental design procedure given in figure 2 are satisfied by VESYS.

1	2	3	4	5	6	7	8	9	10	11

VESYS is unusual in that it follows an incremental procedure, as advocated in Section 3, and includes design element No. 2, evolution of pavement geometry. However, the version evaluated in the AMADEUS project was restricted to the evolution of permanent deformation or rutting.

Comparison with similar models

The VESYS response model, CHEVRON, appears to slightly under-estimate the results generally supplied by other Multi-layered models. However this difference is only of the order of 1%.

User friendliness

VESYS was not available to the majority of users during Phase 1 of AMADEUS due to a software problem. Consequently no user questionnaires have been completed on this model. When used later in Phase 3, it was commented that it is necessary to have training or at least a manual to use the software.

References

Beckedahl H., Buseck H., Gerlach A., Straube E. and Velske S. : Effects of different pavement rehabilitation types on the development of rut depth and fatigue cracking. *Proceedings of the 7th International Conference on Asphalt Pavements*, Nottingham, 1992.

Beckedahl H. : Rut-depth calculation using the latest VESYS-3H programme version. *Proceedings of the 6th International Conference on the Structural Design of Asphalt Pavements*. Ann Arbor, Michigan, 1987.

5.4 Overview of models and their relevance to an incremental procedure

The guidelines must help the user in making the optimal choice of the most appropriate design tool for a particular application or for specific conditions of environment or traffic.

To give an overview of the relevance of the different models to such an incremental procedure, the bar charts presented in this chapter have been gathered in table 28.

Although they are not pavement design models BANDS and PAMINA programmes are also presented in this table because they contain two of the eleven design elements and they can be incorporated in more complex procedures.

Table 28 : Relevance of the models to the incremental design procedure.

Model	Design elements										
	1	2	3	4	5	6	7	8	9	10	11
	Initial conditions	Geometry	Traffic & loads	Material properties	Climate & Environment	Response model	stress strain displacements	Performance model	Increment of damage	Accumulation of damage	History
APAS		▨				LE	▨				▨
AXIDIN		▨	▨	▨	▨	FE		▨	▨	▨	▨
BISAR-SPDM		▨				LE					▨
CAPA 3D			▨	▨	▨	FE				▨	▨
CIRCLY		▨		▨	▨	LE+NL					▨
ELSYM5		▨	▨	▨	▨	LE		▨	▨	▨	▨
KENLAYER		▨	▨	▨		LE+NL+VE				▨	▨
MICHPAVE		▨	▨	▨	▨	FE		▨	▨	▨	▨
MMOPP						LE	▨				
NOAH		▨				LE				▨	▨
SYSTUS			▨	▨	▨	FE				▨	▨
VAGDIM95		▨				LE	▨	▨	▨	▨	▨
VEROAD		▨	▨	▨	▨	VE		▨	▨	▨	▨
VESYS						LE	▨				
WESLEA		▨			▨	LE				▨	▨
BANDS	▨	▨	▨		▨	▨	▨		▨	▨	▨
PAMINA	▨	▨	▨		▨	▨	▨		▨	▨	▨

LE : Linear Elastic VE : Visco-elastic
NL : Non-linear FE : Finite elements

Care should be taken that*:*

Some of the models covering almost all the required design elements, such as for example VESYS, may still have limitations on the type of damage they are addressing. The version of VESYS tested in the project could only deal with rutting.

BANDS and PAMINA are design elements for the prediction of material properties and performance laws. They are limited to the case of bituminous materials. Similar elements have yet to be developed for soils, unbound granular materials and cement treated materials.

6. FUTURE DEVELOPMENTS

The purpose of this task was to prepare a plan for the definition of a comprehensive mechanistic/analytical model integrating the different features and advantages of the existing methods. The way to establish links and combinations between these tools must be analysed in order to propose a work plan for testing and implementing such a system.

6.1 Integration of design elements

The ideal is to produce a comprehensive design method based on an integration of deterioration models that predicts the progression of different forms of deterioration over the whole life of the road. This method would have to deal with interactions between the different deterioration models, based on an understanding of the physical processes involved. The method would require detailed inputs of traffic loading characteristics, climatic conditions, material properties and how they change with time and traffic.

Although this is a desirable goal, it should be borne in mind that, for whatever state of existing knowledge, a practical engineering solution must be available that represents the best possible interpretation of the available information. However, with the enormous developments in computational power and improvements in knowledge of material behaviour and pavement performance, it should now be possible to develop design tools that are an improvement on the present generation.

With this in mind, COST 333 reviewed the requirements and deterioration mechanisms of the main pavement components and concluded that there are discrepancies between modes of pavement deterioration perceived to be important and those on which current pavement design methods are based. Some frequently observed deterioration mechanisms, such as rutting originating in the bituminous layers and cracking initiating in the surface, are not taken into account by current pavement design methods directly. Also material properties change over the life of the pavement. This emphasised the need for an improved pavement design method, based on models that provide better explanations to the observed deterioration mechanisms.

During the course of COST 333, it was recognised that there were many models and software packages that were in regular use for practical pavement design and pavement analysis. Therefore, the AMADEUS research project was undertaken to review and evaluate these models in order to identify the features that could be adopted in an advanced European design method.

Although AMADEUS was not an exhaustive evaluation of all pavement models, it has shown that existing pavement models contain useful features, for example, the ability to deal with material variability and traffic spectra. It also demonstrated that the response of the upper pavement layers to a wheel-load could be modelled with reasonable accuracy. This was not the case for the unbound layers deeper in the pavement structure. For some forms of deterioration current models need to be improved, and for others radically new models need to be developed but, before this can be achieved, programmes of fundamental research will be required to fully understand the mechanisms involved.

The behaviour of a pavement is extremely complex with cyclic effects and systematic changes occurring during the service life of the pavement. The material properties can change for different reasons and some of the causes of change are acting in the opposite sense, which makes the prediction of pavement life problematic. For instance, the stiffness of asphalt can increase due to age hardening, further consolidation by traffic, falling temperature or healing and it can reduce due to fatigue by traffic, thermal fatigue or rising temperature. In addition, there are interactions between all layers of the road structure. A design method that does not recognise this interdependence and the changing properties of the layers with time, traffic loading and climate will have limited capabilities.

To deal with this complexity COST 333 recommended that:

- A structured approach should be adopted that will involve the development of a new harmonised European design method in a series of stages.
- An incremental procedure should be used to predict pavement deterioration. This will enable changes in the pavement structure and in material properties that occur during the life of the pavement, to be taken into account.
- A modular framework should be developed for the design method. This will enable the method to be updated as new deterioration mechanisms are included and as improved deterioration models are developed.
- The future evolution of a new European design method will require co-ordinated and mutually supportive research programmes.

6.2 Requirements for improvement of existing design elements

COST Action 333 recommended that a number of improvements or new developments could be applied to pavement design. The AMADEUS evaluations have shown that some of the design elements already incorporated in existing software tools may be used as starting points for such improvements. These are discussed under the following headings.

6.2.1 Geometry

In Chapter 2.2.3 “Definition of the Design elements”, “Geometry” is defined as the ability of a programme to deal with changes that occur in the pavement layers. All these geometrical changes after an increment of time will automatically influence other design elements.

The modification of the layer thickness in terms of transverse unevenness (rutting) is a good example to explain these connections: if for instance, lateral wander of vehicles in the wheelpath is taken into consideration, this deviation will decrease during the increase of transverse unevenness (increase of rut depth) and this will result in a change in the loading conditions (element 3).

For some scientific projects like COST 334 (Effects of wide single and dual tyres) the question about geometry changes is very much from interest. Due to rutting, the equal load sharing of a dual tyre will probably change and therefore pavement wear effects of these tyres compared to wide single tyres will be different.

Furthermore, the actual thickness is an important input parameter to define the exact depth for the calculations of the primary responses (element 6).

But also other major changes will influence design elements: The situation of the internal boundary conditions must be included in the response model (element 6).

The development of cracks will not only influence the material properties (element 4), but probably also the performance law(s) (element 8). And longitudinal unevenness causes dynamic load effects, which means there is a change in the loading conditions (element 3).

To deal with these geometric changes, the multilayer theory will perhaps not be the best tool, considering these effects seems to be a strong argument for using other models like FE or DE method.

6.2.2 Climatic conditions

Climatic factors that are relevant to pavement design were identified during the COST 333 action (sub task 2.2) and they were classified into three main categories :

- Freezing and thawing effects.
- Temperature variations.
- Variation of hydrological conditions.

Regarding the climatic conditions and the way to handle them at the European scale, AMADEUS team suggests to present a system to characterise climatic conditions in such a way that they could be used in a flexible way in connection with pavement design models.

It is likely that the most efficient method consists in presenting the data in connection with a map or a set of maps covering Europe, and settling boundaries of climatic zones irrespective of the particular political boundaries between member countries. In each of these zones, of a size that varies with the geographical features, quantitative climatic indicators would be associated and made available from a data-base.

Although still limited to Finland, such an application already does exist within the APAS software tested in phase 2 of the evaluation. The Swiss norms also apply a similar system and the American SUPERPAVE approach also contains some interesting climatic indicators for selecting binder grades.

Here after we give a description of what the AMADEUS group considers as essential climatic information to include in such a database.

Freezing and thawing effects

In many parts of Europe, freeze/thaw effects play a crucial role in pavement design.

Most of the European pavement design methods take into account phenomena related to freezing and thawing by using the freezing index. His indicator is supposed to account for the “quantity of frost” to which a pavement was subjected for a given period (ref. OECD 1988).

Therefore it is important that deterioration mechanisms associated with freezing and thawing should be examined in detail and in the longer-term predictive models developed for freeze/thaw related deterioration.

Sunshine

Some pavement design methods consider the influence of sunshine on the Freezing-thawing phenomenon. Within the database system suggested above one should associate typical values of the solar effect (in hours per day or in KWh/m^2). These figures should be given with their seasonal variations (monthly for example) over one year.

Temperature variations

Temperature variations are playing a very important role in the mechanical behaviour of pavement materials. This is particularly important in the case of materials, such as bituminous bound materials, displaying large variations in their mechanical properties and performances with temperature.

Seasonal variations

Most of the response models incorporated in pavement design models are accounting for the temperature variations in an indirect way, by considering the corresponding variations of the material mechanical characteristics. The database associated to the different climatic zones should supply the air temperatures, solar radiation and other data that can be used to calculate the actual temperature at different depth. Special procedures are already existing (see OECD report 1988) that could be used to make such evaluations.

The temperature indicators to be supplied for each climatic zone and period (monthly, quarterly, or any other period, while COST 333 recommends a limitation to six periods per year) should include at least :

- Yearly average temperature.
- Maximum air temperature over the period considered.
- Minimum air temperature over the period considered.

Such data should be based on observations made over long periods (generally 30 years). So that a statistical estimate could also be derived from probability distribution curves and other statistical indicators (standard deviation, variance, frequency of value over the period considered).

The presentation of such data should allow their direct application in pavement design models.

Daily temperature variations

This second set of data should account for short term temperature variations. This information are useful to optimise the optimal choice of binders able to withstand large and sudden temperature variations. This information is also important for estimating and the magnitude of thermal stresses and the associated risk of thermal cracking.

The data needed for doing this for a given period and zone are:

- Maximum daily variation over the period (°C).
- Maximum rate of temperature variation (°C/h for example).

Variation of hydrological conditions

The effect of hydrological conditions and climatic variations on the characteristics of the soil and granular layers and the interaction with their mechanical behaviour are poorly understood. However, it is acknowledged that they have a strong influence on pavement performance.

On the other hand hydrological conditions are related more to geotechnical considerations than only to climate.

Therefore, further research is recommended and, in particular, more information is required on how the bearing capacity of different types of soil is affected by the drainage conditions.

Fundament knowledge is lacking on the deterioration mechanisms that are influenced by climatic effects and more detailed information is required in areas such as permanent deformation in the asphalt layers, low temperature cracking and material changes induced by climatic cycles.

Rainfall

It is interesting to note that most of the countries that are taking account of the hydrological variations are rainy countries. Precipitation is also mentioned in the OECD report as an important factor influencing the development of surface damage of pavements.

Consequently we believe that data relevant to precipitation should be added to the data relevant to frost and temperature. They should be presented by period and by climatic zone according to criteria yet to be stipulated.

6.2.3 Traffic

Heavy vehicles contribute to the deterioration of flexible pavements. The vertical and horizontal loads that truck tyres impose on the pavement surface, play a role in the many different deterioration modes that can be observed in flexible pavements, e.g.:

- structural cracking,
- surface cracking,
- reflective cracking,
- rutting in bituminous layers,
- rutting in the subgrade,
- thaw - related structural failure.

Load equivalence law

Design currently relies usually on the use of the 4th power damage law to convert the commercial traffic, all non standard axle loads into an equivalent number of standard axles. However, this damage law actually has only been derived for one single deterioration mode, i.e. loss of serviceability. A serious disadvantage of using damage laws is that they are only valid for a single deterioration mechanism. Other deterioration mechanisms may give totally different equivalency laws. The exponent of the damage law depends on the form of distress and the strength and condition of the pavement (OECD, 1988).

On the other hand, the weight of standard axle used in Europe countries varies between 80 and 130 kN. Therefore standard axle load should be harmonised to lead to conversion factors which can be compared to each other easier.

The use of conversion factors has some advantages, too. The use of conversion factors allows a simple characterisation of traffic by a single value. This allows a definition of load classes and thus a practical classification of materials and/or constructions. A major advantage is that, when using conversion factors, the design calculations only have to be made for one case, for the standard axle.

Detailed traffic data

However, because of different deterioration modes, it is recommended to use more detailed traffic data. The accuracy of pavement response calculations as well as the results from distress models is highly dependent on how close the input data represents reality. Traffic needs to be dealt with as explicitly as possible within the deterioration calculation rather than by the assumption of a damage law. Therefore axle load spectrum for different vehicle types should be measured with WIM.

Many vehicle related properties should be taken into account in traffic input data:

- tyre type :
    - dual
    - single
    - different sizes
- tyre pressure :
    - contact area between tyres and pavement
    - vertical tyre contact stresses
    - horizontal forces
- axle configuration :
    - single
    - tandem
    - tridem
    - wheel base
    - load distribution within axle combinations
- suspension/damping :
    - multi leaf
    - parabolic
    - air

Vehicle related factors and road unevenness have an important effect on dynamic loading. Vehicle speed has effect on the stiffness modulus of bituminous materials. Wheel path distribution along road lane has effect on road distress. These should be taken into account in pavement design.

Currently some response models have possibility to calculate only responses for one uniform circular load case. It is well known that the contact stress between tyre and pavement is not circular nor uniformly distributed. In future, many load cases, non uniform load distribution and horizontal forces are required for response models.

Advanced design models can take into account different pavement deterioration mechanisms but they require realistic representations of the loading conditions in order to obtain a reasonable prediction. When the full traffic spectrum is considered, a separate calculation should be made for each vehicle type and for each class from this spectrum. The calculations should be combined according to Miner's law.

6.2.4 Material properties

The present pavement design methods are dominated by the use of multi-layer, linear elastic pavement response models. More realistic models that deal with the actual elements of material behaviour that contain viscous and/or plastic elements will have the potential to predict deformation as well as the stress and strain response of the road to moving wheel loads. More sophisticated laboratory tests will be necessary to measure the materials properties required by these models.

Properties of Bound Materials

Some programmes have incorporated databases able to provide material properties to be used as input for the response model but in most cases this feature is not available. In such cases one must either proceed to experimental measurement of the relevant properties or use an existing method of assessment of the required properties and characteristics.

There are presently two such tools available in the project to assess the basic mechanical properties of bituminous materials : BANDS and PAMINA programmes, used throughout the project, are described in section 3.2.3 above.

The basic properties that are needed to describe the behaviour of materials have been reviewed during the COST 333 action and a comprehensive amount of information is available. The properties that are required for design purposes and LTPP predictions are of two categories: mechanical characteristics and performance laws. The main mechanical characteristics are :

- Complex modulus and its dependence on temperature and loading conditions.
- Poisson’s ratio.

The ideal is to dispose of a representative rheological model that can be readily used in visco-elastic models.

Performance properties required are :

- Fatigue characteristics.
- Deformation laws.
- Crack propagation parameters.
- Ageing characteristics.
- Healing properties.

For some of these properties little information exists and further research will be needed in the future. Some properties can be measured in laboratory, but very often such tests are expensive and time consuming. In many cases relationships have been found and validated between these characteristics and the composition of bituminous mixes. Such relations were already implemented in programmes such as BANDS and PAMINA, but many improvements and new recent findings in this field need to be exploited and under the form of a powerful design element.

Properties of unbound materials

Many unbound materials are particulate, and lend themselves rather poorly to modeling with solid mechanics. The material properties needed for solid mechanics models, like E-modulus and Poisson's ratio, are quite different from the material properties used in specifications and for quality control, like size and shape of particles and degree of compaction. The relationships between the two types of properties are not well understood. Use of the Distinct Element Method (DEM) could maybe improve the understanding.

Extensive material testing is necessary to obtain non-linear and plastic parameters for soil and granular materials for input into behavioral models. Therefore, standardized test procedures of a more fundamental nature need to be adopted more widely to accumulate knowledge of the behaviour of these materials. Laboratory testing should be supplemented by in situ testing, including measurements of stresses, strains and plastic deformations in real pavements, under different types of loading.

The variation in performance along a length of pavement is largely the result of material inhomogeneity. Improved knowledge on material variability will help improve the prediction of pavement performance and how the performance is influenced by the quality control.

6.2.5 Response models

Phase 2 of the Amadeus study has shown that several models can predict the horizontal, tensile strain at the bottom of an asphalt layer reasonably well, but that the vertical compressive strain at the top of the subgrade, cannot be correctly predicted from linear elastic models. This is unfortunate, because several well known pavement design methods rely on the strain in the subgrade, to predict the permissible number of load repetitions, in relation to a certain amount of rutting or roughness.

Presently there appears to be two options for overcoming this problem. One is to make use of a very simple model relying on Boussinesq's equations, modified for non-linear material behaviour, and Odemark's transformation of a layered system. Because of its simplicity, this method lends itself quite well to an incremental procedure.

The other option is to make use of the Finite Element Method (FEM) which can treat material non-linearity mathematically exact and which also allows visco-elastic, elasto-plastic and anisotropic materials. The drawback of this method is that it is very computer intensive, particularly if 3D problems should be treated. FEM also has certain limitations as it still basically relies on solid mechanics.

The Discrete Element Method (DEM) may become an option in the future. DEM has the advantage that it combines the response and performance models.

No matter which response model is selected, an experimental verification of the model is imperative.

6.2.6 Cumulation of damage

The estimation of damage growth and accumulation implies the use of a model that is able to predict in a quantitative way how the different forms of damage are building up in function of time during the whole service life of a pavement and how they interact with each other.

Up to now, this problem has been solved by assuming a linear accumulation of damage based on Miner’s hypothesis. This assumption supposes that any increment of damage can be simply expressed as a fraction of the total expected life, and that these fraction simply add up irrespective of the order in which they appear.

In practice, this hypothesis was mainly applied to the case of fatigue cracking, although we know that this assumption does not account for many effects such as healing, ageing, influence of rest periods etc…

Therefore it should be worthwhile to make adjustments to Miner’s hypothesis in order to improve the correspondence of predictions with field observations.

Other types of damage like rutting for example do not follow a linear behaviour that can simply be interpreted in a linear way, and here also it will be necessary to clearly define the rules that are governing the phenomena in a realistic way.

6.2.7 Probabilistic aspects

The prediction of pavement response and performance should take into account the variability of many of the input parameters to be considered. This concerns not only the natural scatter of the material properties but also structural parameters that change during construction (layer thickness, surface evenness, etc.) and also the uncertainty in the forecast of climatic conditions and traffic data.

The sensitivity of pavement performance to variation of any of the involved parameters is already applicable in the NOAH programme (in as far as it can be related to calculated response).

This type of approach should be recommended in a the proposed harmonised design procedure in order to complete the output information of design element 11 “History of the Pavement damage” with statistical data reflecting the accuracy of the information.

Table 29 : Factors that influence pavement behaviour.

Factors that influence pavement behaviour	Mechanism	Considered in present design	Comments
Cracking	Fatigue	Yes	Addressed, in current design, by limiting the horizontal tensile strain at the underside of the asphalt layer.
	Surface initiated cracking	No	Frequently occurs as a result of traffic loading possibly in combination with thermal stresses but not well understood. Age hardening of the surface course will increase the likelihood its occurrence.
	Thermal fatigue cracking	No	A form of surface initiated cracking due to cyclic thermally induced stresses. Age hardening of the surface course will increase the likelihood its occurrence.
	Low temperature cracking	No	Occurs quickly at very low temperatures when the whole thickness of asphalt is put into thermal tension under stress conditions where stress relaxation cannot occur.
	Reflection cracking	No	This is of particular importance for composite pavements and the rehabilitation of cracked pavements.
	Crack propagation	No	The crack propagation phase may be as important as the time to crack initiation.
Deformation	Asphalt deformation	No	The most frequent cause of distress in asphalt pavements.
	Structural deformation	Yes	Occurs in the subgrade and is addressed, in current design, by limiting the vertical compressive strain at the top of the subgrade.
Material changes	Age hardening of asphalt	No	This is a complicated process involving several different mechanisms. Ageing will alter the deformation, fatigue, stiffness modulus and crack propagation characteristics of the asphalt.
	Hydrological and climatic variations	No	Affects the mechanical behaviour of the soil and granular layers seasonally and in the long-term.
Load spreading ability	Plate bending action	Yes	In current design the elastic stiffness modulus is assumed to be a measure of load spreading ability.

6.3 Plans for the implementation of a new procedure

6.3.1 Proposed prediction procedure

The review of design methods carried out by Nunn and Merrill (1997) has shown that 60% of the European countries surveyed have developed an analytical design method and that these methods are very similar in concept. These methods deal only with 2 forms of deterioration, fatigue and structural deformation, in a fairly simplistic manner. There are also many assumptions inherent in the method and factors are calibrated into the method. These include climatic effects and changes that occur in material properties during the service life of the pavement. Some of the important phenomena that influence pavement performance are listed in table 29 and, apart from fatigue and structural deformation, these factors are not considered in current design.

The harmonised pavement design procedure proposed by COST 333 consists of an integrated set of models, which are able to predict the progression of deterioration for each mode of distress. The prediction process for a particular mode of deterioration is illustrated in section 1.3 of this report (figure 2). These predictions would be carried out in parallel for each mode of deterioration that affects the structural integrity of the pavement. The generalised prediction procedure is illustrated in figure 38.

With this procedure non-linear effects and changes in material properties with time, caused by either exposure to the environment or damage by traffic, can be accommodated. This prediction process will allow changes that occur during the service life of the pavement to be taken into account; these include:

- daily and seasonal temperature changes,
- age hardening of asphalt,
- seasonal changes in the moisture content of the soil and granular materials,
- varying traffic flows,
- changes in pavement geometry.

In practice, interactions between different forms of deterioration will occur. For example, fatigue damage can cause a loss of stiffness, and hence load-spreading ability, in the asphalt layers. This increases the level of traffic induced loading on the subgrade and the possibility of structural deformation. For this reason, separate calculations using the recommended format, need to be carried out in parallel for each mechanism that causes a progressive change in the structural properties of the pavement layers. These calculations need to be carried out in phase with one another and with the time being incremented simultaneously. After each time increment, the input data for all the parallel calculations will be updated to take into account changes in material properties or in pavement geometry predicted by each performance model.

AMADEUS concluded that models of many of the pavement deterioration mechanisms were not yet sufficiently developed for incorporation into a design method. However, it would be relatively easy to develop better design tools by treating the deterioration phenomena in a more sophisticated manner. This led to a staged development in which the initial stage would be to improve the current analytical approach. This concept is discussed in the next section, using fatigue as an example.

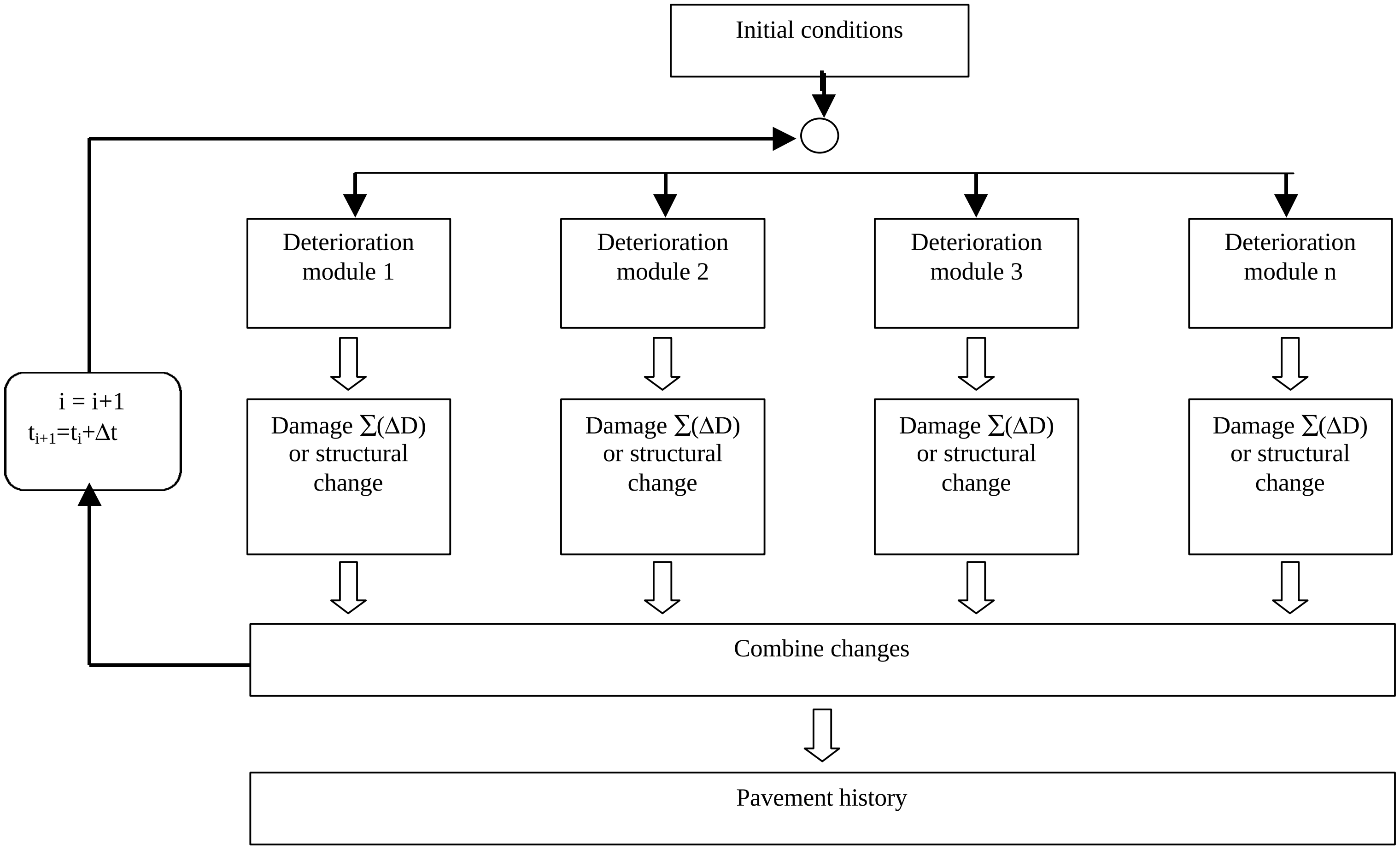


Figure 38 : Overall design procedure.

6.3.2 Integrated approach to pavement design

The application of laboratory fatigue data to the prediction of pavement performance has several shortcomings that could be improved in an integrated approach. The current design process inevitably assumes many things. Dealing with some of these factors in a more explicit manner may produce explanations for some predictions of pavement behaviour that are at variance with observation. For example, phase 3 of AMADEUS showed that asphalt pavements could become stiffer over time and not suffer weakening by fatigue. An integrated approach however, will allow the following factors to be dealt with in a more explicit manner:

- The structural properties of the asphalt change over the design life of the pavement.
- A wheel load spectrum can be used to characterise traffic rather than a conversion to ESALs using a 4th power damage law.
- The mode of loading in the laboratory is either controlled stress or controlled strain whereas in the road pavement the mode of loading is somewhere between the two.
- Structural properties of asphalt change diurnally and seasonally with temperature and traffic flows that are also not constant.

6.3.2.1 Fatigue

The flow diagram in figure 39 illustrates a possible explicit means of dealing with the items listed above using the fatigue damage mechanism as an example. Here an asphalt ageing module would run in parallel with the fatigue calculation module. Suitable time increments would be chosen and for each increment, calculations would be carried out over the wheel load spectrum for wheel loads, tyre configurations and contact stresses using the structural properties of the of the pavement materials for that point in the pavements history. The cumulative fatigue damage would be determined using Miner’s hypothesis and, for the next time increment, the values of the structural properties would be updated by taken into account changes caused by fatigue damage and ageing.

In addition, the fatigue life of the road is linked to the fatigue life of a laboratory test specimen through the load induced tensile strain. In the laboratory a simple stress/strain relationship is created whereas in the road a more complex 3-dimensional situation exists. Other options for relating laboratory data to the pavement could be examined or included, such as energy and the strain directly due to a tensile stress (ignoring Poisson’s ratio effects).

Computational processes similar to this example will eventually need to be established for other modes of pavement distress.

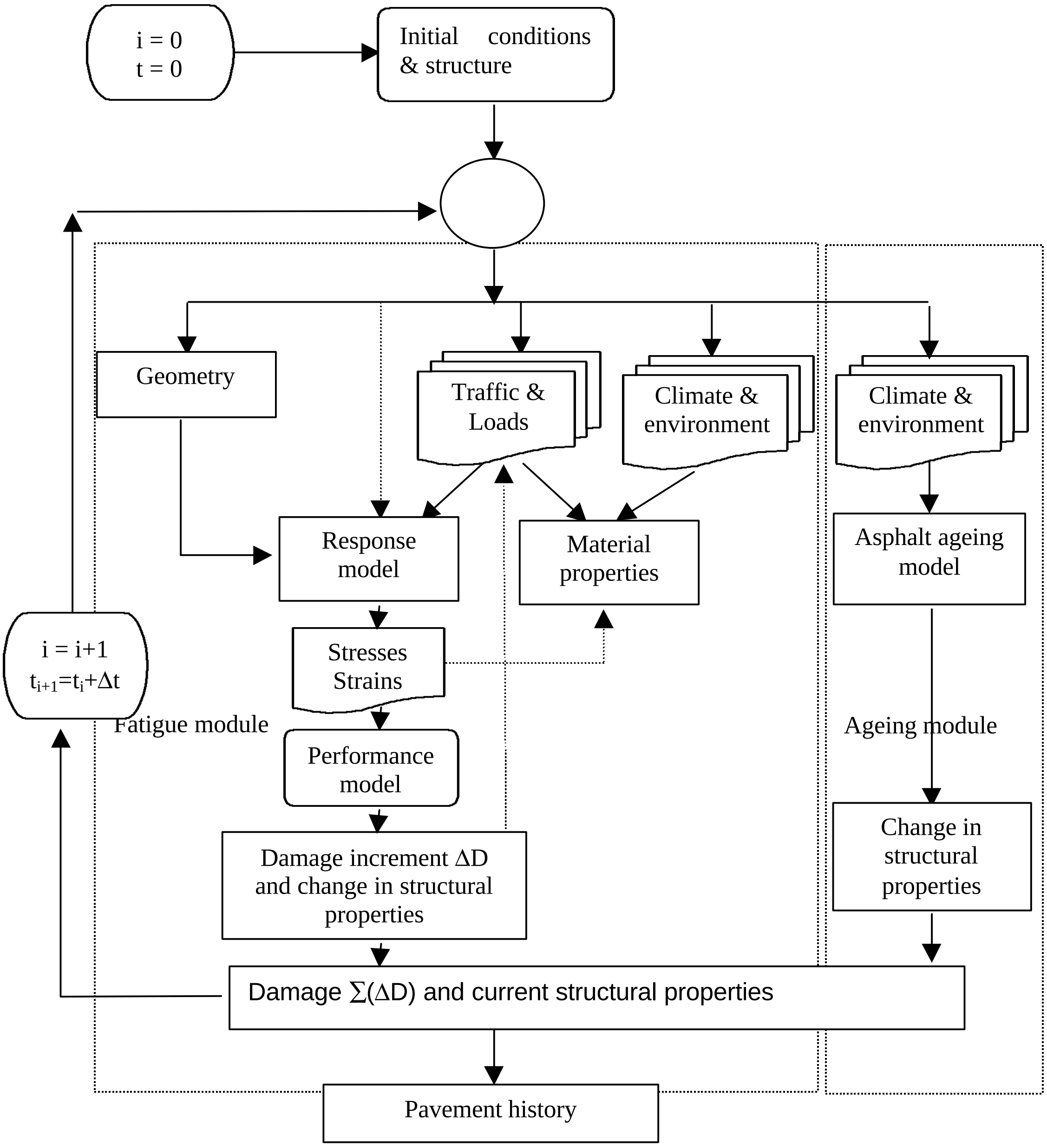


Figure 39 : An example of the incremental procedure involving fatigue only.

6.3.2.2 Discussion of other factors

Models

In an advanced design method, models are required for all the major mechanisms that influence pavement performance listed in table 29, and in addition models that deal with freeze/thaw effects can be added.

Models have been developed for the prediction of crack propagation and reflective cracking, but they have not yet reached a stage when they can be incorporated into pavement design models with confidence. The implementation of crack propagation models in flexible and composite pavements will assist the design of rehabilitation treatments.

Existing visco-elastic models are able to calculate time dependent responses, but they are normally not able to calculate the responses caused by a series of wheel loads and by temperature variations. Improved visco-elastic response models are required for incorporation into mechanistic pavement deterioration models (permanent deformation, fatigue etc). These will enable the effects of different axle loads, temperature and load repetitions to be predicted more effectively.

The existing models for low temperature cracking are still research tools. They should be adapted and developed for implementation in a future design method.

Most of the current pavement design methods do not take into account the permanent deformation of bituminous materials. There is a need to either improve existing models or develop new models to predict this mode of deterioration.

Research has shown that cracks often initiate at the surface of the road, and this form of deterioration is not considered by current pavement design methods. A better understanding is required to aid the development predictive models for pavement design and material specification purposes.

Soils and granular layers are not continuous, as is normally assumed in pavement design models, but they are particulate media. In the very long term, this feature should be taken into account in pavement design models, by using the discrete element method. At present, this technique is a research tool that requires a large computational capacity. The success of this method would provide a much better description of the material’s response to axle loads, giving a direct prediction of the permanent deformation induced by each passing wheel load. The discrete element method has potential for the future. It is recommended that research on the development of advanced techniques such as this, that offer potential for the future, should be encouraged.

Existing models should be improved or new models should be developed in order to take into account the interdependencies between the load, the dynamic effects of unevenness on the loads, the inhomogeneity of the pavement materials and the propagation of unevenness.

6.3.2.3 Development programme

The recommendation is that a comprehensive design method should be developed in stages and in a manner that enables it to be upgraded when significant developments occur.

The starting point will be to develop improved design tools. These will have a modular structure based on the flow chart shown in section 1.3 (figure 2). An incremental procedure will incorporate an improved means of dealing with the range of climatic conditions and traffic conditions experienced throughout Europe and it will take into account changes that occur in material properties due to climatic effects and traffic damage. The method will eventually allow interactions between the various forms of deterioration as illustrated in figure 38.

In the first instance it is proposed that a more fundamental method of dealing with the deterioration mechanisms considered by current analytical design methods. This is illustrated in figure 39, in which the classic fatigue damage mechanism is used as an example. In this initial stage the modular framework for the design procedure will be established that will provide the pattern for dealing with other distress mechanisms. After the first design module has been developed and validated, a feasibility study should be undertaken to define the next development stage. It is expected that a staged approach will provide a focus for research in Europe to progress in a better co-ordinated fashion with the requirements for each stage defining the research priorities. Eventually, it is envisaged that a modular design method will evolve organically as better analytical tools are developed.

7. EXPLOITATION AND DISSEMINATION

As a result of the AMADEUS project, a number of advanced pavement design models and corresponding software packages were evaluated. This evaluation was performed on tools of different levels of complexity, and addressed issues related to the use of the software, the input availability and complexity, and also validation of the models for relevant situations, through the comparison of the output from the models with measured data.

A major outcome of the project was the production of guidelines for potential users of the models evaluated, comprising both practical aspects related to the use of the software, and advise concerning which situations related to pavement design can be addressed by the model.

These guidelines can thus be used directly by different professionals working in the field of pavement design, in the following ways:

- Engineers working on pavement design will find a practical guidance on which models may be best suited for solving a specific problem related to pavement design and performance, on the input necessary to run the available software, and on the difficulties that can be encountered when using it.
- Software developers will find suggestions concerning the improvement of their products, both in terms of user friendliness and in terms of issues to be addressed by the models. In fact, during the course of the project, close co-operation was maintained with the software developers, which allowed for solving different problems encountered and eliminating software bugs detected during the evaluation.
- Researchers will find a document that can be used for identification of topics related to pavement design that are not yet addressed by the current state of the art and therefore need further investigation.

Dissemination of AMADEUS and its Deliverables has been going on throughout the project, and it is expected to go on after its completion.

As part of the work package “Elaboration”, a workshop was organised soon after the start of the project, where model developers and software producers were invited to present the main features of their models, and make demonstrations of the software. The workshop was attended by a total of 68 participants, both from inside and outside the AMADEUS consortium.

An Internet homepage (http://ww.lnec.pt/AMADEUS) based on LNEC’s server was set up, where the main goals and work plan were publicised from the beginning of the project. Links were established with the other organisations taking part in the consortium. This homepage was updated during the course of the project an it is expected to be available for sometime after its completion, in order to disseminate the key results achieved with AMADEUS.

The project has also been publicized through submission of papers and presentations in several scientific and technical events, both at national and international levels. The presentations performed at the 2nd European Road Research Conference in Brussels (June 1999) and at the Conference on Asphalt Pavements for Southern Africa in Victoria Falls (August 1999), are examples of these activities.

At the end of the project, a joint workshop was organised by COST 333 and AMADEUS, in order to disseminate the results achieved through this broad European co-operation. This workshop was organised in connection with the 2nd European Road Research Conference, and was attended by a total of 68 participants, from different fields of activity, such as universities, research organisations, consultants, road authorities, policy makers and industry. Participants originated both from Europe and from other continents, and close contacts were established with research organisations from outside Europe, namely in the United States of America and Australia.

FINAL CONCLUSIONS

The inventory of existing tools reveals a wide variety of products in terms of response models and type of damage they address, but none of them are presently accounting for all damage types nor take into account their mutual interactions.

Models based on the multi-layer elastic theory are easy to use and they give generally similar results. Some of these models, however, have limitations in precision or produce wrong results in stress/strain analysis at particular locations of the structure (particularly in the vicinity of the applied loads and in the subgrade).

Multi-layer elastic models can be used for non-linear elastic materials (with stress dependent stiffness) provided they are included in an iterative loop.

Applications made during the AMADEUS evaluation task has shown that linear visco-elastic models better describe the shape of the stress and strain waves generated by moving loads. The applicability of such models remains limited by the lack of reliable rheological input data. Their practical advantage depends mainly on the magnitude of the errors made by using the more simple linear elastic approach.

Models based on finite element approaches are more difficult to apply unless users have a thorough knowledge of basic principles. Unlike analytical multi-layer methods, FE methods need the definition of a system with horizontal and vertical limits in space. Hence their implementation needs:

1. a precise definition of the boundary conditions,
2. a decomposition into discrete elements allowing an accurate evaluation of the stresses and strains.

A distinction should be made between plane stress/strain two-dimensional methods (2D), axi-symmetrical methods and three-dimensional methods (3D).

In the context of pavement analysis, 2D FE axi-symmetrical methods are irrelevant and have little advantage over multi-layer elastic models.

True 3D methods are really worth to be applied for situations where particular boundary conditions and local discontinuities must be modelled, which is the case of crack propagation and reflective cracking.

Long term performance prediction must consider the actual history of a pavement structure, including the evolution of all the external (loads, temperatures, etc…) and internal (geometry, material properties) factors. This requires an “incremental” iterative procedure, composed, as shown on figure 2, of a response model surrounded by different design elements providing time dependent input data.

The work performed by COST 333 and AMADEUS resulted in an outline harmonised pavement design method, taking into account the present knowledge in the field of pavement design.

The incremental procedure recommended for the new design method will be able to perform life-cycle analysis throughout the whole pavement life, including not only the initial stage, but also future maintenance and rehabilitation strategies.

A staged approach is proposed, whereby the design method will be based on current best practice, and will be later improved with the incorporation of new developments in this field.
In fact, in order to be able to describe more accurately the deterioration mechanisms that pavement components undergo during their life cycle, future research is needed on several related topics, in order to reach a fundamental pavement design. These aspects can later be incorporated in the procedure, so that it will be able to take the following into account:

- Material and structure changes occurring during the life-cycle of a pavement, such as asphalt ageing.

- More detailed traffic input, taking into account different axle load and configurations, axle weights, tyre types (super single, dual wheel) (cfr Cost 334), etc.

- Most relevant forms of deterioration observed in actual pavements, including, not only the classical forms – fatigue cracking starting from the bottom of the bound layers, and permanent deformation originating in the subgrade -, but also:

  - Cracking initiated at the surface.
  - Rutting initiated at the surface layers.
  - Wear due to studded tyres, frost heave and temperature cracking, in cold climates.

BIBLIOGRAPHY

AMADEUS Deliverables:

D1	Detailed project elaboration	3 August 1998
D2	Workshop (included in D1)	1-2 April 1998
D3	Specifications and data to be treated	25 January 1999
D4-1	Evaluation report Phase 1	7 April 1999
D4-2	Evaluation report Phase 2	15 July 1999
D4-3	Evaluation report Phase 3	15 September 1999
D5	Guidelines on the use of mode For pavement design and assessment	13 September 1999

Asphalt Institute : Thickness design of asphalt pavements for highways and streets. Report MS-1. Asphalt Institute, USA, 1991.

Boussinesq J. : “Essai théorique sur l’équilibre d’élasticité des massifs pulvérulents comparé à celui de massifs solides et sur la poussée des terres sans cohésion”, Mémoires des Savants Etrangers, Académie de Belgique, 40, Bruxelles, 1876.

Boussinesq J. : “Application des potentiels á l’étude de l’équilibre et du mouvement des solides élastique”, Gauthier-Villard, Paris, 1885.

Burmister D. M. : “The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways”, Proceedings, Highway Research Board, Vol. 23, 1943.

COST 333 : “Development of New Bituminous Pavement Design Method”. European Commission Directorate General Transport. Final report of the action Brussels 1999. ISBN 92-828-6796-X.

Cundall P.A. : “BALL – A Programme to Model Granular Media using the Distinct Element Method”, Dames & Moore, Advanced Technology Group, Technical Note No. TN-LN-13, 1978.

Francken L., Eustacchio E., Isacsson U., Partl M. N. : Recent activities of RILEM TC 152PBM " Performance of Bituminous Materials". Eighth International Conference on Asphalt Pavements (ISAP) Seattle 1997, vol1 pp. 283-299.

Fröhlich : “Druckverteilung im Baugrunde”, Springer Verlag, Wien, 1934.

Harr M. E. : “Mechanics of Particulate Media”, McGraw-Hill, 1977.

Hopman P.C., Nilsson R. and Pronk A. C. : Theory, validation and application of the visco-elastic multi-layer programme VEROAD. Eighth International Conference on Asphalt Pavements (ISAP) Seattle 1997, vol. 1 pp. 693-705.

Horz H. W. : Die Datenbank "Untersuchungsstrecken"; (Handbuch). Bundesanstalt fuer Strassenwesen (Herausgeber). Bergisch Gladbach, 1991.

IRF International Road Federation : IRF World Road Statistics 1999 edition”.

Macdonald R. & Baltzer S. : "Subgrade Performance Study, Part I: Materials, Construction and Instrumentation", Danish Road Institute, Denmark, 1997.

Nunn M. E. and Merrill D. B. : Review of Flexible and Composite Pavement Design Methods". *TRL Paper PA/3298/97.* Transport Research Laboratory, Crowthorne, 1997.

Odemark N. : "Undersökning av elasticitetegenskaperna hos olika jordarter samt teori för beräkning av belägningar enligt elasticitetsteorin" Statens Väginstitut, meddelande 77, 1949.

Organisation for Economic Co-operation and Development (1991) : OECD full-scale pavement test". *IRRD 837329.* OECD, Paris.

PIARC World Road Association : XXIst World Road Congress Kuala Lumpur October 1999. Report C8 "Flexible Roads".

PIARC World Road Association : XXIst World Road Congress Kuala Lumpur October 1999 Report KL1 "Efficiency in National Road System Management".

Ruiz Rubio A., Romero Amich R. :"The CEDEX Full Scale Test Track" - Accelerated pavement testing 1999. International Conference. Paper number CS8-8. Reno (Nevada - USA). October 18th-20th, 1999.

Romain J. : Rut depth prediction in asphalt pavements. "Proceedings of the Third International Conference on the structural design of asphalt pavements". London, 1972, Vol.1 pp.7.5-710.

Romero Amich R., Ruiz Rubio A., Rodil Sierra R., Lechuga Alvaro M. A. : "Variation of deflection with the measuring equipment and with the load speed in a test track". 73 Annual meeting - Transportation Research Board - Paper 940891. Washington (USA), January 9th-13th, 1994.

Turtschy J.-Cl. and Perret J. : "Full-Scale Accelerated Loading Test at the Halle-Fosse. (LAVOC-EPFL)" Swiss contribution to COST action 333 : Development of New Pavement Design Methods. European Commission Directorate General Transport - Brussels 1999.

Ullidtz P. : "Modelling of Granular Materials Using the Discrete Element Method", Volume I, Proceedings, Eighth International Conference on Asphalt Pavements, Seattle, Washington, 1997.

Van Cauwelaert F. : "Contraintes et déplacements dans un massif semi-infini anisotrope à plan isotrope – Application au compactage", Annales des Travaux Publics de Belgique, Fascicule No 2, avril, 1980.

Veverka V. : "Modules, contraintes et déformations des massifs et couches granulaires" Rapport de Recherche, no. 162, vv, Centre de Recherches Routières, Bruxelles, 1973.

Wuerttemberg (FMPA B-W): "Langzeitbeobachtungen an ausgewaehlten Strassen-abschnitten"; Forschungsprojekte des Bundesministeriums fuer Verkehr, Koel und Stuttgart, 1970 bis 1989.

Zhang W., Ullidtz P. & Macdonald R. : "Subgrade Performance Study, Part II: Modelling Pavement Response and Predicting Pavement Performance", Danish Road Institute, Denmark, 1998.

ACKNOWLEDGEMENTS

The work described in this report was supported by the COST-programme (European Co-operation in the field of Scientific and Technical Research) of the European Commission, by the Transport RTD Programme of the Fourth Framework Programme of the European Commission and by the Forum of European Highway Research Laboratories.

The research Organisations taking part in this work, which have been listed in table 1, and their representatives in the COST 333 and AMADEUS projects are kindly acknowledged for their contribution.

The AMADEUS partners are thankful to the software producers for allowing the use of their products during the execution of this project. They express thanks to all those who gave their advises, support and assistance during this research, and the following persons in particular : Prof. Brian Shackel from the University of New South Wales in Australia, Leigh Wardle of MINCAD, Bernard Eckmann of NYNAS, Piet Hopman of NPC, Jan. Lijsenga and Lito Achimastos from SHELL, David Newcomb of Minnesota State University and Ronald Harichandran of Michigan State University.

The AMADEUS Co-ordinator wants to acknowledge ir. René Bastiaans, Project Officer from the European Commission, Directorate General of Transport, and all those who efficiently contributed to the execution of this comprehensive evaluation exercise. He expresses thanks to Mrs A.Thomas who took care of the final lay out of this report.

AWP-FR/007/FL/TA

APPENDIX A: ROAD EXPENDITURES IN EUROPEAN COUNTRIES DURING THE YEAR 1996

	Total Costs (IRF 1999)	Length (Km)	Percentage per type % (COST333)			Length per type (Km)		
Country	MioEURO	Total	Flexible	Composite	Rigid	Flexible	Composite	Rigid
Austria	996	12000	90	5	5	10800	600	600
Belgium	940	15700	70	13	17	10990	2041	2669
Croatia		7000	94	4	1	6580	280	70
Denmark	757	7000	98	2	0	6860	140	0
Finland	961	13400	95	5	0	12730	670	0
France	7043	36300	50	40	10	18150	14520	3630
Germany	20696	52900	36	36	28	19044	19044	14812
Greece		12000	100	0	0	12000	0	0
Hungary	278	6800	60	40	0	4080	2720	0
Iceland	90	4300	99	1	0	4257	43	0
Ireland	391	2700	100	0	0	2700	0	0
Netherlands	1052	2200	86	10	4	1892	220	88
Norway	909	26645	98	0	2	26112	0	533
Portugal	1037	10000	95	4	1	9500	400	100
Slovenia		4700	95	0	5	4465	0	235
Spain	2936	24100	79	17	4	19039	4097	964
Sweden	1483	15000	99	1	1	14850	75	75
Switzerland	2149	1500	75	3	22	1125	45	330
UK	5557	18800	85	5	10	15980	940	1880
Total	47275	273045	74	17	10	201154	45835	25986

APPENDIX B: LIST OF CONTACT PERSONS
http://ww.lnec.pt/AMADEUS

PROJECT CO-ORDINATOR

BRRC-BELGIUM

Dr Louis FRANCKEN
Belgian Road Research Centre
Boulevard de la Woluwe 42
1200 BRUXELLES
Belgium
Tel : 00/32/2/766.04.01
Fax : 00/32/2/767.17.80
E-mail : l.francken@brrc.be

MEMBERS

ISTU-AUSTRIA

Mr Christian HOCHREITER
Vienna University of Technology
Institut for Road Construction and Maintenance
Gusshausstrasse 28
A – 1040 WIEN
Austria
Tel : 00/43/1/58/801.233.14
Fax : 00/43/1/58801.23399
E-mail: chochreiter@istu.tuwien.ac.at

DTU-DENMARK

Dr P. ULLIDTZ
Technical University of Denmark
IFP Building 115
DK - 2800 LYNGBY
Denmark
Tel : 00/45/45/25.15.18
Fax : 00/45/45/93.64.12
E-mail : pullidtz@ivtb.dtu.dk

VTT-FINLAND

Mr Jari PIHLAJAMAKI
VTT Communities and Infrastructures
P.O. Box 19031
FIN - 02044 VTT
Finland
Tel : 00/358/9456.46.88
Fax : 00/358/946.32.51
E-mail : jari.pihlajamaki@vtt.fi

BUGH-GERMANY

Prof. Dr. –Ing. Hartmut BECKEDAHL
Strassenentwurf und Strassenbau
Pauluskirchstrasse 7
D – 42285 WUPPERTAL
Germany
Tel : 00/49/202/439.42 11
Fax : 00/49/202/439.42 48
E-mail : beckedah@uni-wuppertal.de

NTUA-GREECE

Dr Andreas LOIZOS
National Technical University of Athens (NTUA)
Department of Transportation Planning and Engineering
Iroon Polytechnionstreet 5
GR – 15773 ATHENS
Greece
Tel : 00/30/1/772.13.41
Fax : 00/30/1/807.86.92
E-mail : aloizos@central.ntua.gr

KTI -HUNGARY

Dr Laszlo GASPAR
Institute for Transport Sciences Ltd (KTI Rt)
Temesvar u. 11-15
H - 1116 BUDAPEST
Hungary
Tel : 00/36/1/204.79.86
Fax : 00/36/1/204.79.79
E-mail : kttuh@mail.matav.hu

PRA/IBRI-ICELAND

Mr Thorir INGASON
Icelandic Building Research Institute
Rb – Keldnaholt
Is - 112 REYKJAVIK
Iceland
Tel : 00/354/570.73.00
Fax : 00/354/570.73.11
E-mail : ingason.th@rabygg.is

TUD- THE NETHERLANDS

Mr A. SCARPAS
TU DELFT
Faculty of Civil Engineering
Laboratory of Road Railroad Engineering
Stevinweg 1
NL - 2628 CN DELFT
The Netherlands
Tel : 00/31/15/278.40.17
Fax : 00/31/15/278.57.67
E-mail : a.scarpas@ct.tudelft.nl

LNEC-PORTUGAL

Dr Maria de LURDES ANTUNES
Laboratorio Nacional de Engenharia Civil (LNEC)
Avenida do Brasil 101
P – 1700-066 LISBOA CODEX
Portugal
Tel : 00/351/21/844.35.36
Fax : 00/351/21/844.30.29
E-mail : mlantunes@lnec.pt

FCT/UNL - PORTUGAL

Mr João Rocha de Almeida
FCT/UNL - Dep. Eng. Civil
2825-114 Caparica,
Portugal
Tel. : 00/351/1/294.85.80
Fax : 00/351/1/294.83.98
E-mail: jr@mail.fct.unl.pt

DDC-SLOVENIA

Mr Boris LIPOGLAVSEK
DDC Engineering Company for Public Roads
Trzaska 19a
SI - 1000 LJUBLJANA
Slovenia
Tel : 00/386/61/178.84.42
Fax : 00/386/61/178.83.78
E-mail : boris.lipoglavsek@dd-ceste.s"

DDC-SLOVENIA

Mrs Julijana JAMNIK
DDC Engineering Company for Public Roads
Trzaska 19a
SI - 1000 LJUBLJANA
Slovenia
Tel : 00/386/61/178.83.80
Fax : 00/386/61/178.83.78
E-mail: julijana.jamnik@dd-ceste.si

CEDEX-SPAIN

Mr Angel MATEOS MORENO
CEDEX
Centro de Estudios y Experimentación de Obras Públicas
Autovia de Colmenar viejo, km 18.2
E - 28790 EL GOLOSO (MADRID)
Spain
Tel : 00/34/91/335.78.00
Fax : 00/34/91/335.78.22
E-mail : amateos@cedex.es

LAVOC/EPFL -SWIZERLAND

Mr Jacques PERRET
Laboratoire des Voies de Circulation (LAVOC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Département de Génie Civil
CH - 1015 LAUSANNE
Suisse
Tel : 00/41/21/693.23.41
Fax : 00/41/21/693.63.49
E-mail : jacques.perret@epfl.ch

VTI-SWEDEN

Mr Leif G. WIMAN
Swedish National Road and Transport Research Institute
Olaus Magnus väg 37
S - 58195 LINKÖPING
Sweden
Tel : 00/46/13/20.42.70
Fax : 00/46/13/14.14.36
E-mail : leif.g.wiman@vti.se

Mr Vincent JANOO
CRREL
Cold Regions Research and
Engineering Laboratory, U.S. Army
Corps of Engineers
75, Lyme Road
Hanover, NH03755-1290
United States
Tel : 00/1/603 646 4702
Fax : 00/1/603 646 4843
E-Mail : vjanoo@crrel.usace.army.mil

TRL-UNITED KINGDOM

Mr Michael NUNN
Transport Research Laboratory (TRL)
Old Wokingham Road
Crowthorne
UK – BERKSHIRE RG 456AU
United Kingdom
Tel : 00/44/1344/77.02.10
Fax : 00/44/1344/77.03.56
E-mail : mnunn@trl.co.uk

Mr Darren MERRIL
Transport Research Laboratory (TRL)
Old Wokingham Road
Crowthorne
UK – BERKSHIRE RG 456AU
United Kingdom
Tel : 00/44/1344/77.02.10
Fax : 00/44/1344/77.03.56
E-mail : mnunn@trl.co.uk

CORRESPONDING MEMBERS

Dr Fritz JOOSTE
CSIR Transportek
PO Box 395
Pretoria 0001
South Africa
Office #1: 00/27/12/ 734.44.88
Office #2: 00/27/12/841.22.24
Cell: 00/27/82/578.56.28
Fax: 00/27/12/841.26.90
E-mail : fritzj@icon.co.za
fjooste@csir.co.za