A PROTOTYPE KNOWLEDGE-BASED SYSTEM FOR PAVEMENT ANALYSIS

by

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Abstract

Highway engineers have addressed the problem of pavement maintenance by developing remaining life assessment methods based on structural analysis of computer simulations of pavements tested in the field by non-destructive testing devices such as the Falling Weight Deflectometer (FWD). However the methodologies followed have been shown to be unable to provide accurate solutions without undue reliance on the knowledge of the expert engineer who conducts the analysis.

A knowledge-based system (KBS) is proposed to "inject" engineering knowledge into the conventional techniques. It has been established on a systematic basis and seeks to cover the variety of the issues which may be encountered in such systems. In its prototype form the system consists of three parts:

1. The finite element analytical program ROSTRA-1.
2. A deductive database.
3. A back-analysis subsystem.

The analytical program carries out the analysis of the pavements tested in the field. The deductive database holds the properties of a variety of paving materials and establishes the analytical model. The back-analysis subsystem seeks to perform the tasks required for the analysis of the FWD deflection bowl.

To build this system, the POPLOG-Prolog computer language operated under VAX/VMS was selected to work in connection with the analytical program.

An evaluation procedure was carried out to investigate the performance characteristics of the prototype system. The results indicated that the POPLOG-Prolog development environment is not the ideal tool for such an application. In addition, it appears unlikely that there is any other development tool available which is markedly more effective than that used. However it is felt that similar functions to those required by the POPLOG-Prolog environment, may be implemented using conventional programming. To permit this, a logical design of a KBS to conduct this task is presented.

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Chapter 1

INTRODUCTION

1.1 General

Highway networks are expected to perform their functions effectively. However, funds for construction, maintenance and rehabilitation of these networks are limited. Thus, optimization techniques are necessary to enable a proper structural characterization of the individual sections of roads which make up the network to ensure the appropriate condition is achieved for the minimum expenditure of funds [Snaith, 1990].

This has been addressed by the development of methods based on computer simulations of pavement models. The procedure usually followed by engineers to analyze the structural behaviour of pavements may be categorized as follows:

1. The formulation of the problem in terms of structural or statistical analysis.

2. The solution of the problem.

3. The interpretation of the solution and its verification in engineering terms.

However, the engineer should pursue, in all the above steps, simplicity and clarity without loosing the essentials. To achieve this he should make a number of approximations and assumptions and indeed he should use his knowledge to judge both the logic of the processes followed and the results derived from them.

To date, the engineering judgement has been provided by the experts who carry out the analysis. However it is necessary to develop methods which enable the knowledge of the experts to be available to a wider range of operators. The advances of Computer Science and especially those of Artificial Intelligence[1] enable the development of programs which, by emulating human mental procedures, seek to behave like an expert or group of experts for some chosen problem [Ritchie *et al.*, 1986]. These programs are known as Expert or Knowledge-Based Systems (KBS).

In addition, as stated by Ullidtz *et al.*, [1992],

> " ... there is an urgent need for "verifiable" models, i.e. models that can make use of any available historical data, so that the relationships and assumptions used in the design process can be verified or calibrated to the specific conditions under which the model is to be applied."

This may be addressed by a combination of KBS and databases.

However, applying such approaches to any scientific or engineering domain, such as pavement evaluation, requires

> "the generation of scientifically relevant new concepts through creation, generalization, abstraction and axiomatic formulation " [Lin *et*

[1]Artificial Intelligence is a part of Computer Science that addresses problems traditionally believed to require human intelligence in order to find a solution.

al., 1974].

This study should be considered as such an approach. It investigates the potentiality for the development of a KBS for the structural analysis of road pavements.

1.2 Modelling the Pavement Structure

Pavements, together with the loadings they sustain, should be modelled adequately so that their strength and consequently the degree of their deterioration may be quantified.

Pavements may be considered as layered systems with several courses of processed materials. Each material has its own unique mechanical properties. This layered system supports and transmits the vehicle loads to the underlying subgrade. Any analysis of such a structure to determine the properties of individual layers is complicated by a number of variables not least of which will be those due to the environment and quality control at construction. In addition

> "a method of design without application of laws of mechanics as the working hypothesis fail to indicate the logical interrelationships between the mechanical behaviour of the entire layered system, the exposure condition, the physical characteristics and properties of the various materials and the thickness and relation of the various layers involved in the system" [Finn, 1987].

Consequently, it was felt that a KBS should be developed to provide a framework for an efficient simulation of both the short-term and the long-term behavioural characteristics of a variety of pavement structures.

1.3 Pavement Evaluation, Pavement Management and KBS

Pavement evaluation is the procedure of determining the properties of an existing pavement structure by measurements carried out on the pavement [Bonnot, 1987]. Distinction should be made between:

1. Functional properties (i.e. properties related to the riding quality the pavement provides for the user).

2. Structural properties (i.e. properties related to the strength of the pavement structure).

The aim of pavement evaluation is to provide the information necessary for decisions concerning maintenance or rehabilitation works. These decisions are made at two levels [Molenaar, 1982]:

1. At the network level, where high-output, low-cost non-destructive evaluation methods give the information necessary to a long-term highway strategy.

2. At the project level, where the measurement techniques should yield those data necessary for a detailed description of the pavements and consequently for the design of maintenance or rehabilitation works.

Both at network and project level benefits can be provided for highway agencies by the development of a Pavement Management System (PMS). A PMS is a tool that

> "evaluates alternative strategies over a specified analysis period on the basis of predicted values of quantifiable pavement attributes, subject to predetermined criteria and constraints."

and

" It is a dynamic process that incorporates feedback regarding the various attributes, criteria and constraints involved in the optimization procedure" [Hudson, 1987].

As with pavement evaluation distinction should be made between network and project management level. At the network level, the management system provides information pertinent to the development of a network strategy on construction and maintenance that will optimize the use of available resources [AASHTO, 1986]. At the project level, a particular road section is considered in detail in relation to alternative design, construction or maintenance activities [Snaith *et al.*, 1984; 1986].

PMS have been developed and implemented for more than 20 years. However, general improvements are needed in order that they may become more effective. There exist three areas where improvements may be made which should enhance the performance of PMS [Hudson, 1987]:

1. Incremental improvements in existing technology (e.g. greater adoption of microcomputers to all aspects of pavement management including mechanistic analysis).

2. New equipment and methods in pavement evaluation.

3. Automation of existing methods.

In the third category, some advances are occurring in the development of KBS and the results of this work appear to be promising. However the development of such systems is essentially conducted on a research basis. In these circumstances it should be considered that, despite some attempts, the application of KBS technology to highway engineering is in its infancy.

It was felt that although there exist numerous pavement evaluation methodologies, none of them is completely satisfactory because they do not include the engineering judgement which covers the gaps of the existing techniques. Thus, it was felt advisable to collect the engineering knowledge from such techniques and subsequently to use it effectively so that the requirements of a reliable evaluation scheme in a Pavement Maintenance Management System at Project Level may be satisfied. Therefore, it was decided that a KBS should be developed to enhance and automate this procedure. This thesis reports the work effected to create the prototype development of such a KBS.

1.4 The Objectives of the Thesis

The work reported in this thesis has been a part of an ongoing research project which has the following short-term and long-term objectives, with respect to the development of a working KBS:

1. Short-term objectives; namely, the development of a prototype KBS.

   (a) To investigate the feasibility of establishing a KBS which will integrate the modules currently used individually in pavement analysis processes.

   (b) To investigate factors affecting each part of the procedure of pavement structural evaluation and how these might be considered in the KBS development.

   (c) To assess the capabilities of the analytical programs used and provide further enhancements.

   (d) To collect the information necessary for the operation of the system.

   (e) To investigate the manner in which the information included into the system may be represented.

(f) To design a prototype system that will guide the development of a working system.

(g) To investigate the capabilities of the present KBS technology.

(h) To investigate the parameters that affect the success of such a system and subsequently to suggest possible solutions.

(i) To clarify the functions required and the tools available for each of the individual modules which make up the overall system.

2. Long-term objectives; namely, the development of a working KBS.

   (a) To establish a specification for a comprehensive KBS that would address the tasks required for a pavement maintenance, evaluation and rehabilitation process at project level.

   (b) To develop a system that would provide the highway engineer with a tool able to perform the following tasks:

      i. Automatic collection and manipulation of non-destructive testing data.

      ii. Analysis of the tested pavements with a high degree of reliability.

      iii. Overlay design or selection of non-overlay maintenance and rehabilitation alternatives.

   (c) To develop an advisory system able to draw its own conclusions and create its own analysis mechanisms on the basis of previously analyzed case histories.

1.5 The Structure of the Thesis

To demonstrate the objectives detailed in the above Section, the thesis is structured as follows:

1. The overall process to be used in the prototype KBS is delineated in Chapter 2.

2. Chapter 3 presents and discusses the analytical work carried out by a number of research highway engineers, together with a variety of KBS developed for pavement structural assessment.

3. Chapter 4 discusses a number of issues associated with the collection of non-destructive field testing data with the Falling Weight Deflectometer (FWD).

4. Chapter 5 describes a comparative study carried out to investigate the potentiality of three analytical programs to be incorporated into the KBS.

5. Chapter 6 presents some of the fundamental issues involved in the development of a KBS and additionally the representation of knowledge in such systems.

6. Chapter 7 provides a collection of the properties that characterize a wide range of pavement materials and also presents a number of long-term performance models currently used. The manner in which this information may be represented in the KBS is also outlined.

7. Chapter 8 outlines the functions required by an ideal KBS.

8. Chapter 9 discusses the practical issues involved in the development of the system and presents the programmed prototype system. A justification for the software environments used is also given.

9. Chapter 10 presents the evaluation of the prototype system carried out to demonstrate its performance characteristics.

10. A discussion of the steps followed in the development of the system is conducted in Chapter 11.

11. Chapter 12 describes the logical design of a working KBS for pavement analysis which has been enabled by experience with the prototype.

12. Ultimately, the conclusions of this thesis are given in Chapter 13.

Chapter 2

THE PROCESS OUTLINED

2.1 The Overall Aim and How it is Achieved

In a "conventional" structural evaluation procedure there exist three distinct and complementary elements that permit the engineer to assess the present condition of a pavement and also to advise on the optimal remedial action [Koole, 1982]. These are:

1. An appropriate non-destructive testing technique.
2. An analytical procedure capable of determining key design parameters using a computer simulation of the pavement tested in the field and
3. A design process relying on the above.

A schematic representation of this procedure is shown in Figure 2.1.

Despite recent developments both in hardware and software, it is felt that existing schemes based on the above are unable to analyze pavements with sufficient accuracy to define the location and the cause of any observed deterioration without undue reliance on the experience of the engineer.

Consequently, as the knowledge of the expert who carries out the analysis and finally decides the optimal solution is felt to be the key, instead of eliminating the experience of the road engineer, it is worth trying to capture this experience and knowledge and converting it into a form that a computer is able to view and process. This has stimulated the development of a KBS which will effect the fault diagnosis, analysis and where necessary suggest further testing of a pavement structure to produce the remaining life of the pavement, and ultimately the optimal remedial treatment if required.

Figure 2.2 is a schematic representation of the process under development. It may be considered as two parts. The first deals with the analysis of the pavement using relatively conventional techniques namely:

1. Non-destructive field testing for the collection of the information necessary for quantifying the pavement's condition.

2. The analytical program which provides the computational tool for the determination of the structural strength of the pavement.

3. The knowledge of the expert whose engineering judgment usually draws together and augments the information from the first two.

The second part (i.e. the development of the KBS) seeks to unify the data for these and indeed to reduce the necessity for input by the operator where the necessary engineering judgement is unavailable.

The following sections examine in more detail the individual components of the process whilst the last section is a discussion of the role of the KBS itself and of the problems associated with the development of a system which simulates human behaviour in reasoning.

2.2 Individual Components of the Process

2.2.1 Non-destructive Field Testing Methods

The tests which enable the determination of the strength of the pavement and its constituent layers are undertaken as part of the overall condition evaluation process. Within this there are many types of tests which may be categorized into the following groups:

1. Condition Survey.
2. Non-destructive Tests (NDT).
3. Direct Sampling.

Condition Survey

Regular surveys of condition are necessary to obtain an indication of the strength both of the individual road sections and the network as a whole. These surveys generally provide information concerning the severity and the amount of pavement distress in the form of cracking, rutting and road roughness [AASHTO, 1986].

Both manual and automated methods are used for the collection of this information. Manual surveys enable more detailed data collection and observations of surrounding conditions whilst automated methods will increase the speed of data collection with less interference with traffic and greater objectivity [Hicks *et al.*, 1987].

Non-destructive Tests

There is much interest in NDT and several types are used. The first group are devices which measure deflection basins developed by the application of a load over a circular area at a fixed location of the road surface. The second group measures deflections developed by a standard rolling wheel constrained for convenience of measurement to move at creep speed [Smith *et al.*, 1985; Kennedy, 1982].

Devices belonging to the first group are the FWD [Tholén, 1982; Sørensen *et al.*, 1982], the Road Rater [Deen *et al.*, 1982] and the Dynaflect [Swift, 1976]. Devices such as the Benkelman Beam and the Lacroix Deflectograph can be classified into the second group of NDT [McMullen *et al.*, 1982].

The deflections or deflected shapes measured during NDT are then analyzed so that pavement layer properties may be defined. Other uses of NDT include identification of weak sections of pavements and load transfer efficiency between slabs in rigid pavements [AASHTO, 1986].

Direct Sampling

These methods are by their nature destructive since a test pit or corehole is required. They are popular due to their simplicity compared with other methods. However their use has been criticized on the grounds that they do not represent either *in situ* loading conditions or environmental influence [Pell, 1987]. Methods that could be included in this group are [Hall *et al.*, 1987; Kleyn *et al.*, 1982; Sanders *et al.*, 1992; Garrick *et al.*, 1985]:

1. The *in situ* CBR test.

2. Clegg hammer testing of the subgrade.

3. Dynamic Cone Penetrometer (DCP).

4. Pressuremeter.

The tests are empirical and their results, for unbound granular materials or subgrade soils, are usually correlated with an analytical parameter (e.g. elastic Modulus). In addition, devices like the DCP can provide an indication of the thickness of individual layers.

It may be seen from the above that there are various methods of assessing both the structural condition and serviceability of a pavement. Despite the progress made in these methods there is a need to link the two both at the time of collection and in the evaluation process [Snaith *et al.*, 1988]. However, as the principal purpose of this work is to provide a process for the determination of the structural performance, the primary tool chosen for this is the FWD with information from the other methods noted used to supplement FWD derived information. A discussion of both the factors affecting the method and the measured condition parameters used by the process is presented in Chapter 4.

2.2.2 Data Analysis

Currently available methods for the assessment of structural condition or life of pavements range from the empirical, usually based on deflection criteria, to the analytical, based on the full transient deflection bowl obtained from a NDT device such as the FWD [Kennedy, 1987]. In addition, cracking, rutting, temperature of the bituminous material and drainage may be used to supplement the information in an analytical method [AASHTO, 1986].

Modern analytical techniques offer a rational approach whereby the structural condition of the pavement may be deduced through the computation of the magnitude of the strains at critical locations within the pavement based upon the observed surface deflection produced by a known loading [McMullen *et* *al.*, 1986]. This procedure is generally known as "Back Analysis" and it is explained in the following subsection. It is schematically represented in Figures 2.3 to 2.5 together with the associated method of determining remaining life.

The Concept of Back Analysis

The term "Back Analysis" refers to an iterative procedure whereby the elastic Modulus of the constituent layers of the pavement model are adjusted until the computed deflections under a given load agree with the corresponding field values of deflection [McMullen *et al.*, 1986]. The back analysis procedure is as follows. The materials and thickness of the pavement layers are deduced either from records or from coring. Initial, or "seed", moduli appropriate to each layer are selected from research data. The pavement model is then applied with the load of the FWD and the deflection bowl is calculated. The moduli of the model layers are then varied until a close correlation with the measured deflection bowl is obtained. The model is then considered to be calibrated for transient deflection.

If Poisson's ratio is varied in addition to the elastic Modulus, the iterative procedure can become complex. Hence, the layer values for Poisson's ratios are usually fixed for the various materials.

Even following this procedure satisfactory deflection bowls may be obtained for a wide variety of moduli sets [Uddin *et al.*, 1986]. This is clearly not helpful in determining the "true" material properties and in order to obtain a unique solution, some other researchers have adopted mechanistic procedures [Brown *et al.*, 1987].

2.2.3 The Role of the KBS

This section may be seen as a brief introduction to KBS and how such systems may be used for the analysis of flexible pavements in a more logical manner than attempted heretofore. Further details may be found in Chapter 6.

The KBS automates tasks which in a traditional environment are effected, to a considerable extent, by people using computers only to store data in a database and to communicate with it. Figure 2.6 shows the conventional flow leading to a decision. It may be seen that at the point of decision-making an expert processes data with his knowledge and makes the decision. The data provides information relevant to the problem in hand. The knowledge provided by the expert has been obtained through education and experience.

It may be seen that the process unifies two components; knowledge, or information about general concepts, and information about specific instances [Wiederhold, 1986]. In order to automate the procedure it is necessary to create a system whereby the knowledge of the individual or individuals is captured within a knowledge base which may interact with the database. If the procedure is followed using Artificial Intelligence techniques, Figure 2.6 may be transformed into Figure 2.7 in which the KBS is able to permit the knowledge base and the database to communicate with each other and to provide smooth communication between these two and the user of the system.

However, it should be noted that there are feedback loops which are not shown, through which the system may gain both new data and knowledge which are essential to ensure long term stability.

> "Feedback into the data box occurs through the collection of observations modelling the real world. Feedback into the knowledge box

occurs through the development of generalizations and abstractions perhaps formalized through the scientific loop of hypothesis generation, hypothesis verification, review, publication and dissemination" [Wiederhold, 1986].

If the process of Figure 2.7 is introduced into the flowchart of the analytical procedure of Figure 2.1 the result may be idealized by Figure 2.8. The KBS procedures are used to replace, at least partially, the need for an expert engineer to intervene in the process at certain key points:

1. The selection of material properties (e.g. elastic Modulus and Poisson's ratio).
2. The assessment of the solution provided by a mechanistic analytical tool.
3. The selection of remedial treatment alternatives given certain limitations and priorities.

2.3 Summary

Modern techniques of evaluating the structural capacity of existing pavements are based on the analysis of the deflected shape of a pavement under a non-destructive device by means of a computer program suitable for this task. However, despite the developments in methodologies, the solutions provided by them are unsatisfactory unless considerable engineering judgement is "injected" in the process. This chapter has shown how and where this might be done in an analytical process based on results from an FWD using a knowledge-based approach.

FIGURES

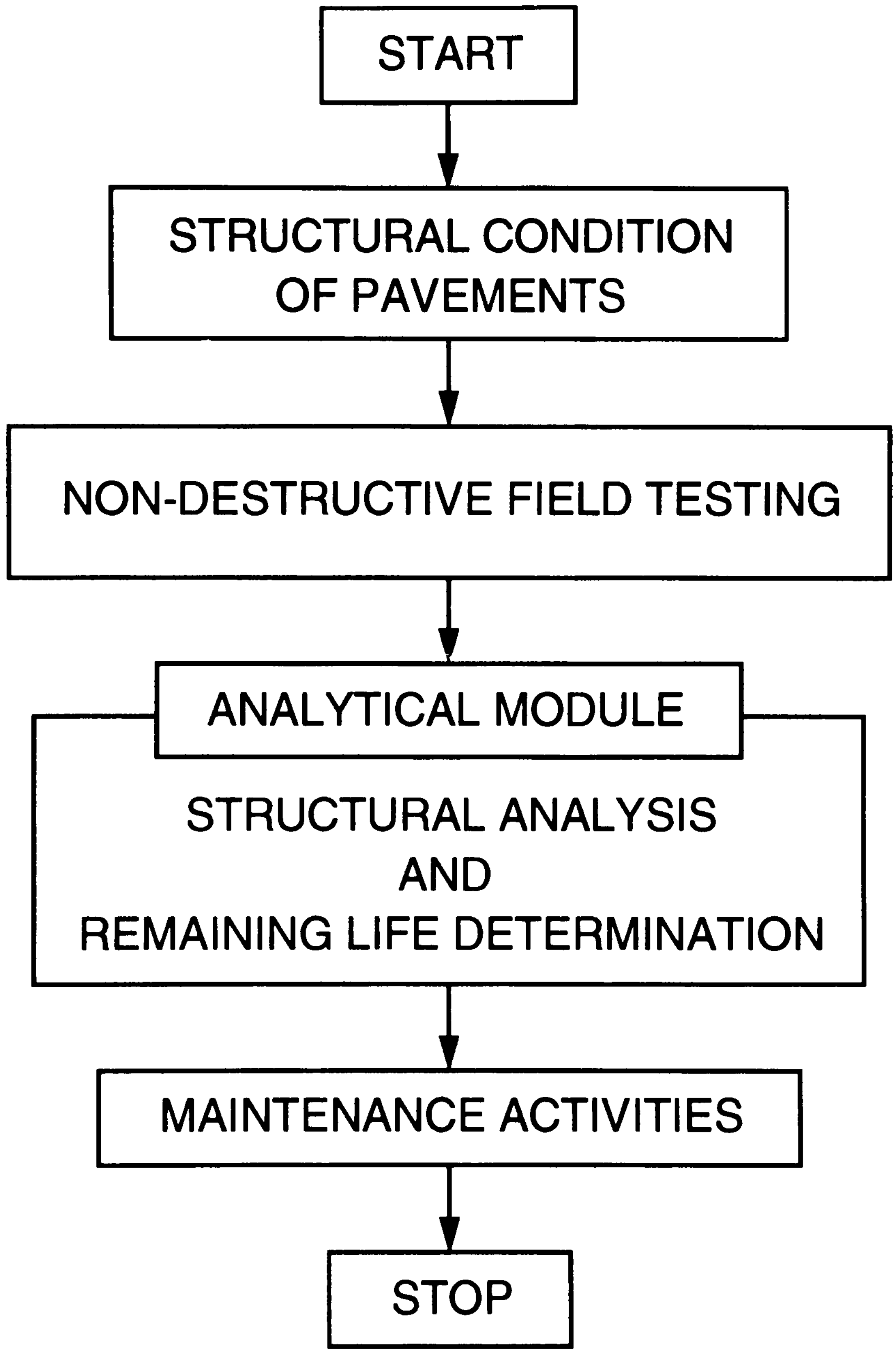

Figure 2.1: The Analytical Procedure.

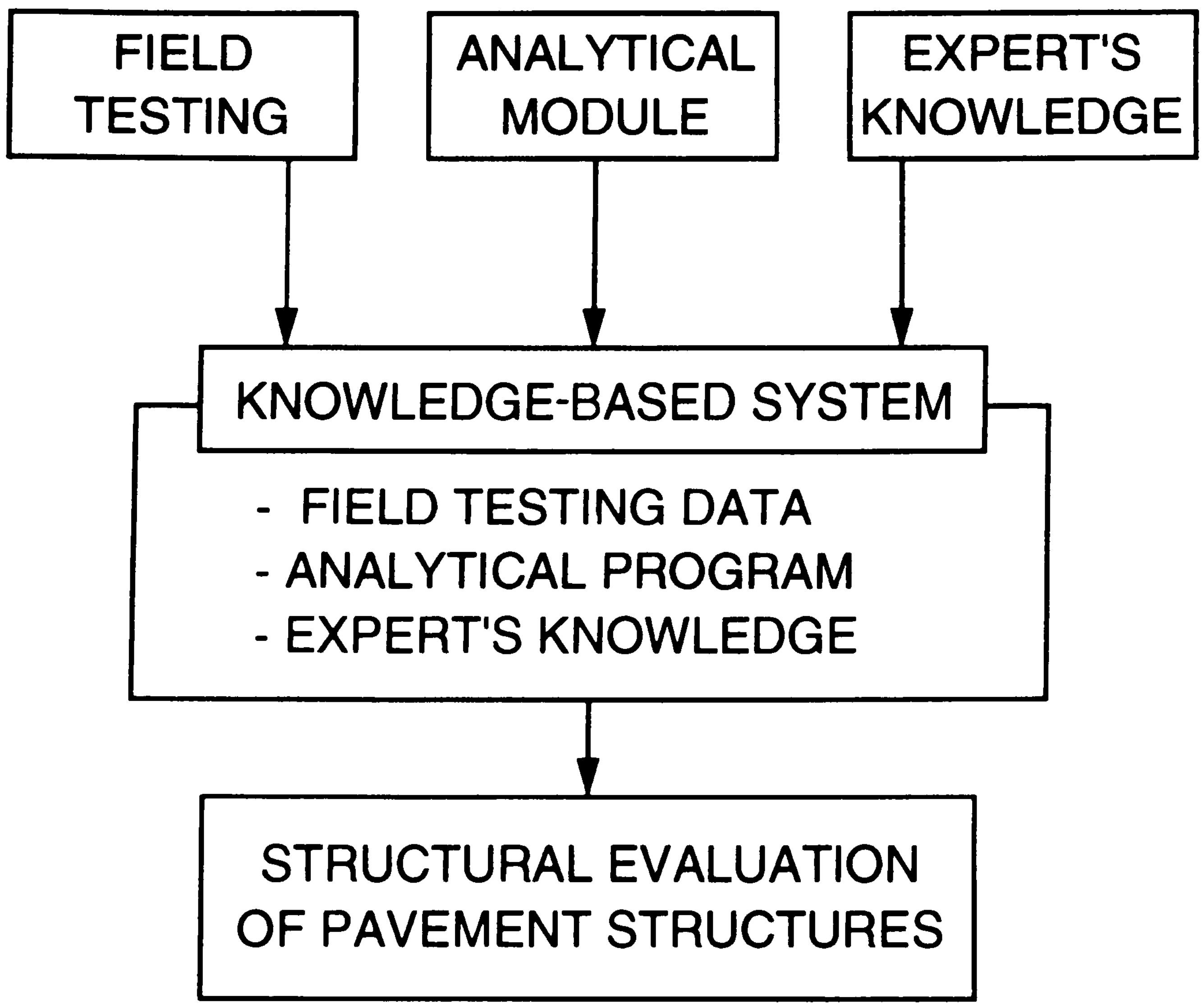

Figure 2.2: The Process Outlined.

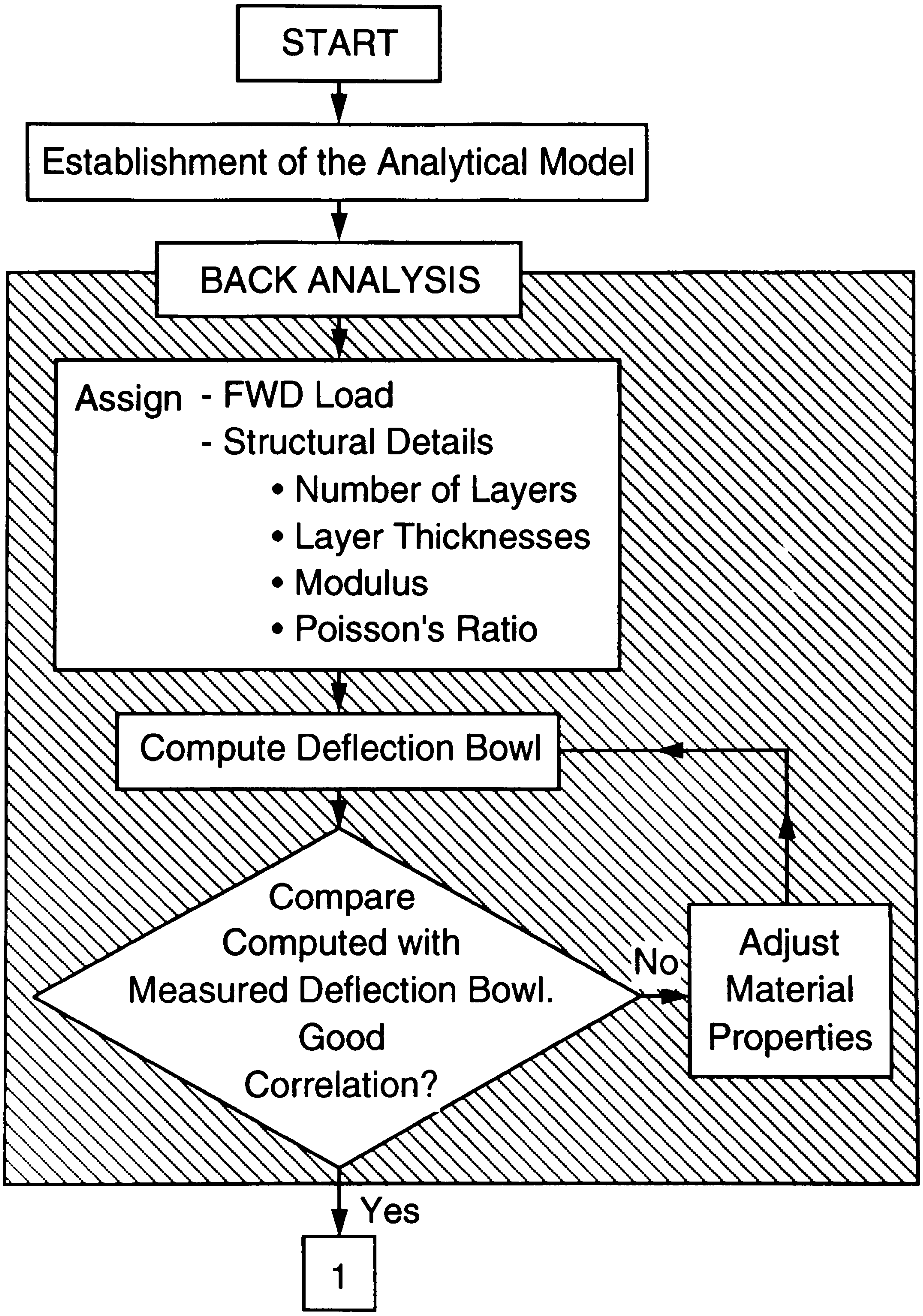

Figure 2.3: Data Analysis Process (Back Analysis).

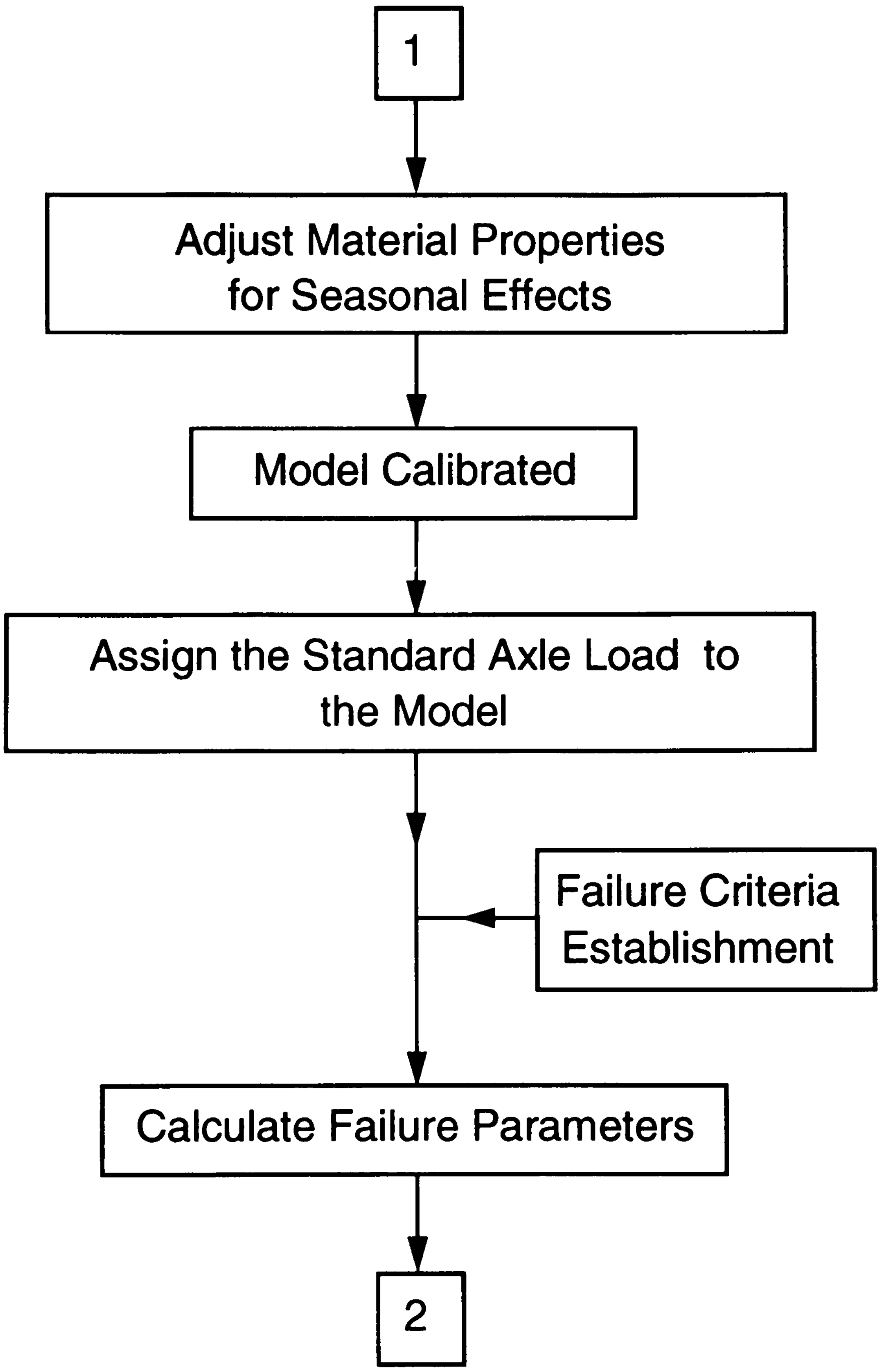

Figure 2.4: Data Analysis Process for Remaining Life Determination.

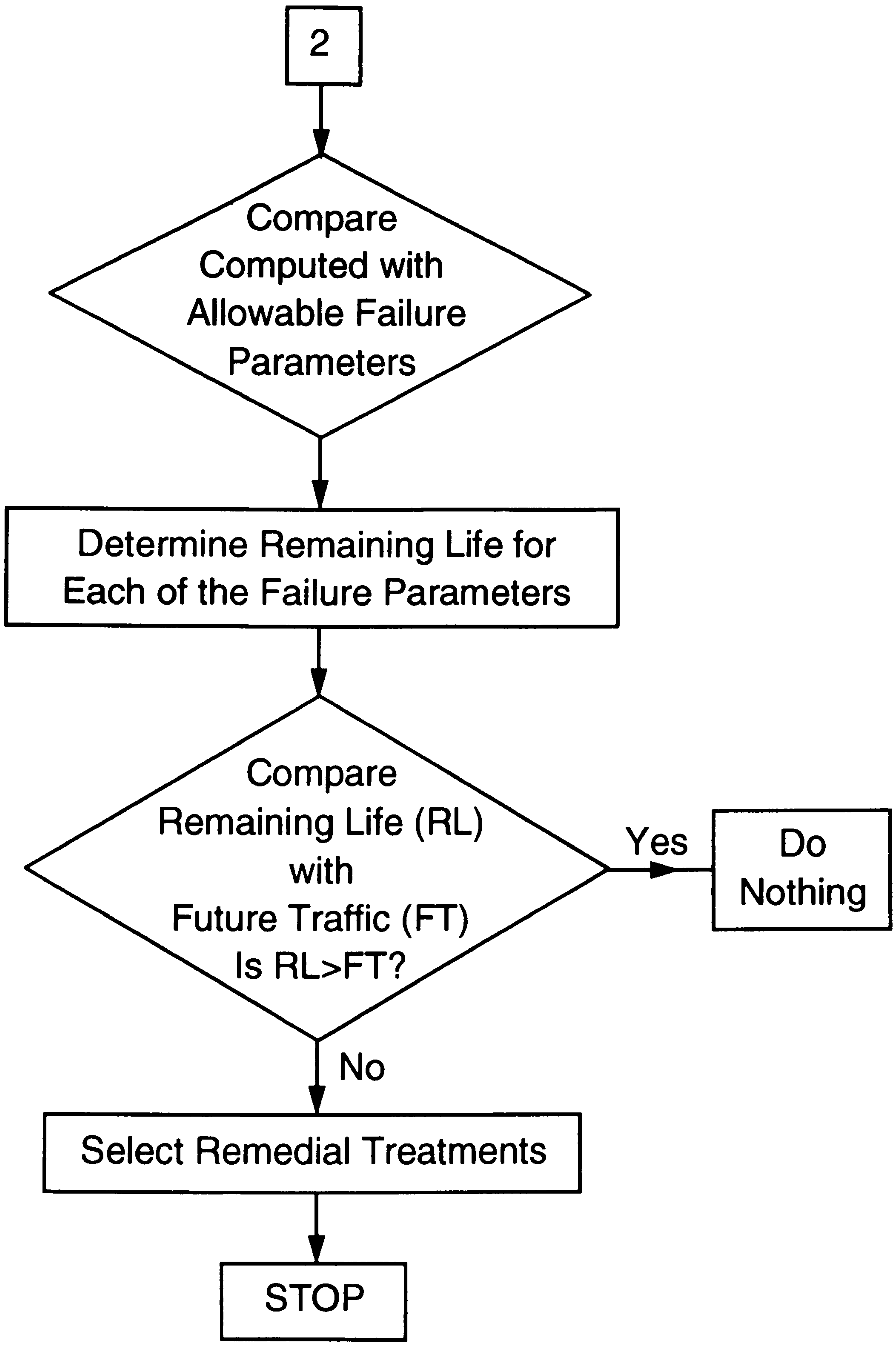

Figure 2.5: Data Analysis Process for Remedial Treatment Selection.

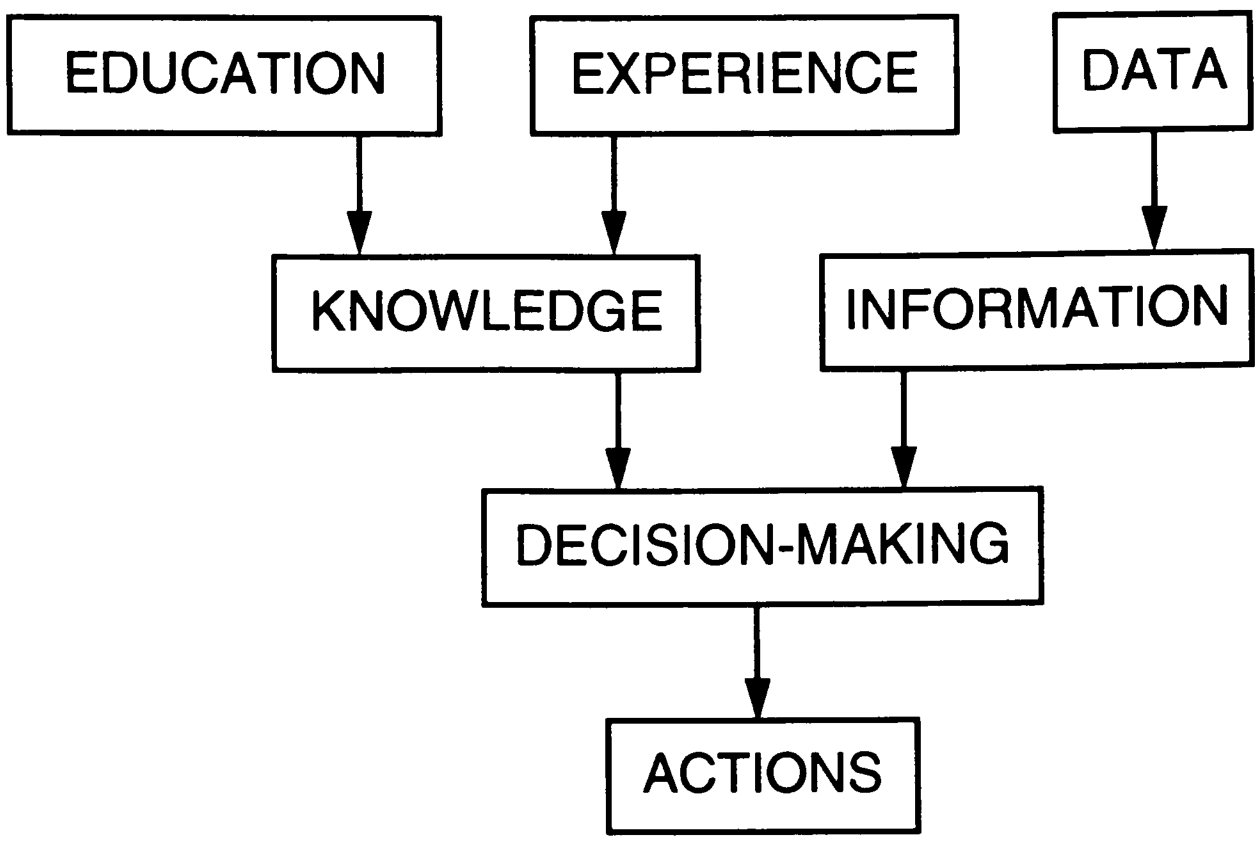

Figure 2.6: The Function of Knowledge and Data in the Decision-making Process [After Wiederhold, 1986].

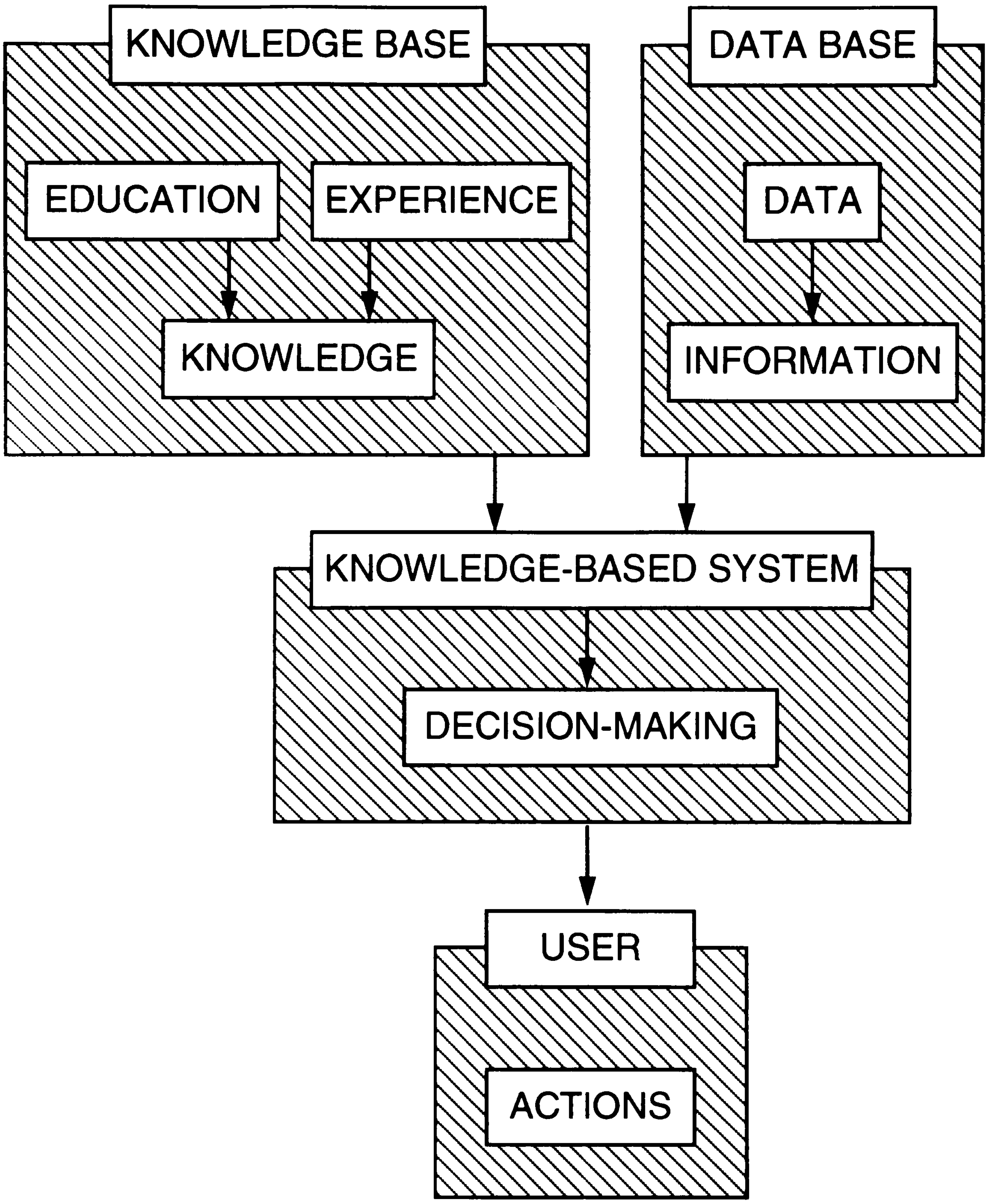

Figure 2.7: The Function of the KBS in Decision-making Process.

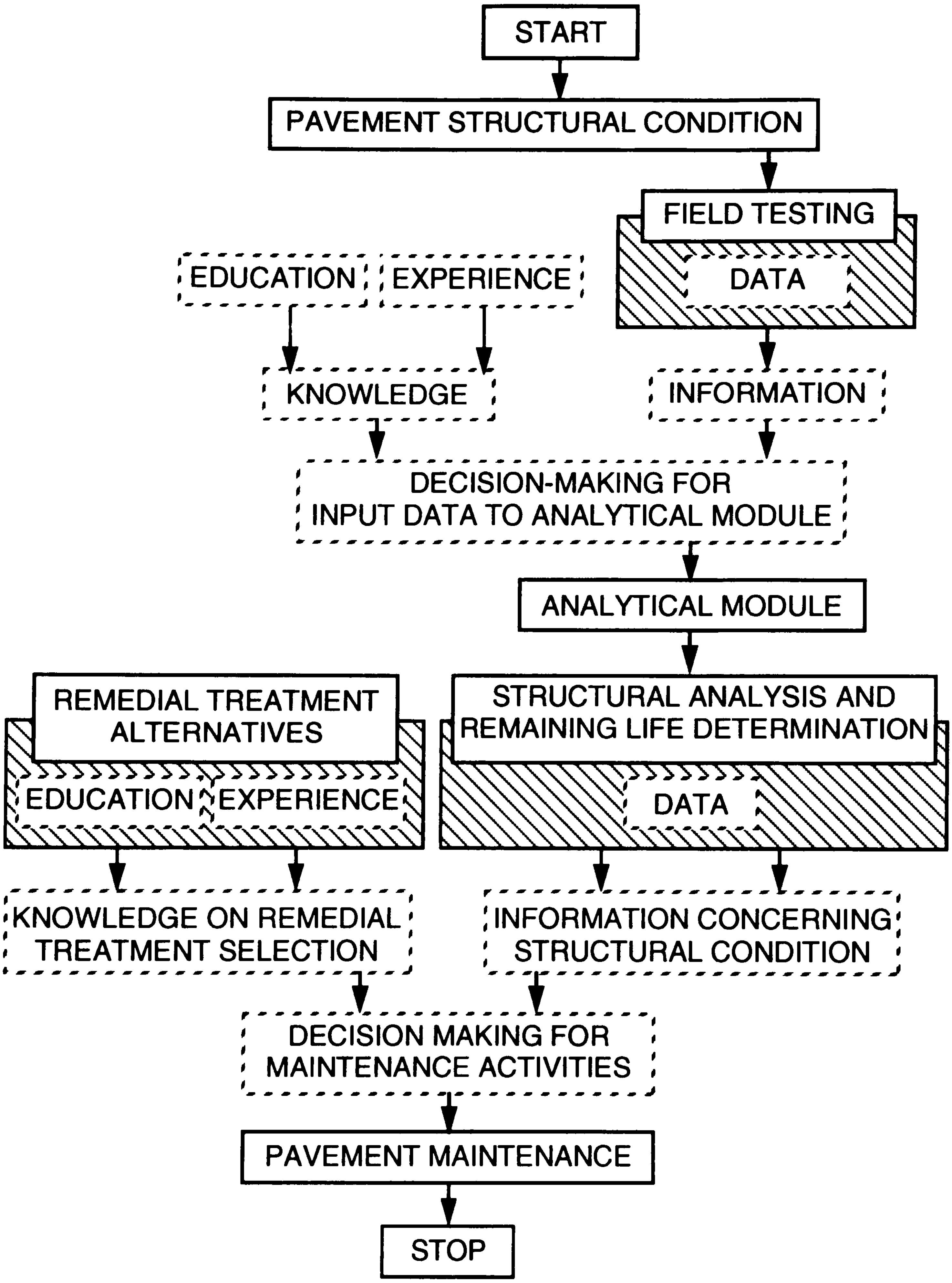

Figure 2.8: The KBS Function in the Analytical Process of Pavement Evaluation.

Chapter 3

REVIEW OF PREVIOUS WORK

3.1 Introduction

In recent years increased traffic volume and vehicle loading have created various structural problems in highway networks. Various pieces of equipment and associated methodologies have been developed to assist the engineer in the evaluation of the structural integrity of the pavement structures as outlined in Chapter 2.

This chapter presents the developments made in pavement analysis under the following headings:

1. The selection of the appropriate material properties (Modulus and Poisson's ratio).

2. The establishment of pavement performance models.

3. The structural evaluation of pavement structures and advances in KBSs.

3.2 The Selection of the Appropriate Modulus

3.2.1 General

The rational assessment of the properties of the pavement constituent layers is a key factor for the formulation of the models used for the description of both the short and long-term pavement performance. Furthermore, the analysis system should enable a proper behavioural representation of the materials subjected to an applied load.

Because of the complexity associated with modelling pavement materials, researchers use considerable simplifications and employ their engineering judgement to develop reasonably accurate models. The values of the material stiffness properties (essentially only the moduli) input to these models are usually derived from a variety of laboratory tests. The associated moduli types may be classified as follows:

1. The Young's Modulus (E).
2. The Resilient Modulus (M_r).
3. The Complex Modulus (E^*).
4. The Dynamic Modulus ($|E^*|$).

Even though many researchers have shown that the values of these various moduli derived from different procedures over a limited range of conditions can be similar, there is generally poor agreement when a wide range of temperature, loading types, materials, specimen sizes, test devices and stress or strain levels are considered [Mamlouk, 1992]. Thus, there exists a need to clarify whether complex laboratory procedures do indeed provide a significantly more accurate means for the determination of the *in situ* material properties.

The following sections present the distinctions between these types of moduli and how they may be used in the analysis of the pavement structures from the deflection bowl.

3.2.2 Bituminous Materials

Generally the response of bituminous materials is time and temperature dependent. Under rapid rates of loading and low temperatures the stress-strain relationship may be considered as elastic. At high temperatures and long loading times the behaviour of the bituminous mixtures is viscous whilst at intermediate conditions viscoelastic [Brown, 1978].

The appropriate modulus to be used is dependent on assumptions of material response, method of analysis and required accuracy [Mamlouk *et al.*, 1987]. Figure 3.1 shows a typical unconfined compression stress-strain curve for asphaltic concrete [After Mamlouk *et al.*, 1987]. A variety of different moduli may be defined which are applicable to static loading conditions. The term "Young's Modulus" should only be applied to the linear part of the stress-strain curve or when no straight portion exists, to the tangent to the curve at the origin. This is the initial "Tangent Modulus" and is of little practical significance. It is also possible to define a "Tangent Modulus" at any point on the stress-strain curve. The "Secant Modulus" is defined as the slope of the line from the origin to any specified point on the curve. It represents an average modulus between zero load and the load at which the modulus is determined.

In addition to these moduli, if a sinusoidal axial load is applied to a cylindrical specimen, the complex and dynamic moduli may be defined. The stress-strain relationship is represented in Figure 3.2. The complex modulus is a complex quantity where the imaginary part represents the material damping and the real part characterizes the Young's modulus. It is defined as follows:

$$E^* = \frac{\sigma_0 \sin \omega t}{\varepsilon_0 \sin(\omega t - \phi)} \tag{3.1}$$

or

$$E^* = E(1 + 2i\beta) \tag{3.2}$$

where:

E^*	is the complex modulus
σ_0	is the sinusoidal applied stress
ε_0	is the corresponding strain
ω	is the angular frequency of vibration (rad/s)
ϕ	is the phase difference between the stress and the strain
i	is the unit imaginary number
β	is the damping ratio
E	is the Young's modulus.

The dynamic modulus $|E^*|$ is the absolute value of the complex modulus and is defined as:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{3.3}$$

It has been suggested [Mamlouk *et al.*, 1987] that the dynamic modulus is insufficient to explain material response because it ignores the loading frequency and the phase lag between load and deformation. However the complex modulus can yield useful information on material properties such as stiffness and damping. Neither the dynamic nor the complex modulus represent simple elastic parameters and thus from a theoretical point of view are not suitable for use in elastic multi-layered computer programs.

Another modulus that represents pavement materials response is the resilient modulus. The resilient modulus is defined as the applied dynamic deviator stress divided by the total recoverable strain measured between successive applications of stress [Kirwan *et al.*, 1976]. It is often taken as the elastic stiffness of the material after many load repetitions have been applied. A definition of both the resilient and the permanent strains measured in such repeated load triaxial tests may be found in Figure 3.3 [After Brown and Snaith, 1974].

There are various types of testing procedures for the determination of the resilient modulus. These differ in the type of the applied loading patterns. The most common procedures are:

1. Diametral Pulsating Loading (Indirect Tensile).

2. Axial Compressive Pulsating Loading.

3. Triaxial Compressive Pulsating Loading.

It has been stated that for bituminous materials the resilient modulus may be more appropriate than other moduli types in analyzing the FWD deflection bowl using multi-layer elastic programs, if the stress regime within the pavement layers is taken under consideration [Mamlouk *et al.*, 1987]. In addition, the moduli predicted from the dynamic nondestructive testing of pavements are more representative of the *in situ* resilient moduli of the materials [Mamlouk, 1987].

However, it has been pointed out by Mamlouk [1992], that the type of laboratory testing for the determination of the resilient modulus affects its value. Thus, the resilient modulus of the asphaltic concrete tested by means of the indirect tensile load type, is significantly different from that yielded by compressive load types especially at low temperatures. Since the asphaltic concrete layer in the field is mostly subjected to compression loading, the use of the indirect tensile modulus as an input to multi-layer elastic analytical programs could be regarded as misleading. Nonetheless, other researchers [Nunn *et al.*, 1992; Cooper *et al.*, 1989; Kennedy, 1977] have claimed that the indirect tensile test is the most suitable method for the estimation of the modulus of bituminous materials used for analysis or design purposes.

3.2.3 Cement-Bound Materials

The performance of a cement-bound material is a function of the relationship of its stiffness with its strength [Kolias *et al.*, 1978]. In other words the magnitude of the load induced stresses within the material is influenced by its stiffness whilst the resultant deformation is related to the strength of the material [Powell *et al.*, 1984]. The strength-stiffness relationship of cement-bound road materials has been investigated by Kolias and Williams [1978]. It has been suggested that although individual relationships have been established between strength and modulus for specific materials, there is no unique relationship. It has been found [Williams, 1972] that the modulus of cement-bound materials tested in the laboratory is related to their tensile strength according to the formula:

$$\mathrm{E} = \alpha \mathrm{f} + \beta \tag{3.4}$$

where:

α and β	are constants depending on mix details
f	is the flexural strength.

Flexural strength f can be estimated by using:

$$\mathrm{f} = 0.1\,\mathrm{u_c} \tag{3.5}$$

where u_c is the compressive cube strength.

Clearly, cement-treated materials are anisotropic and should ideally be modelled as such. They have a high strength in the direction of the compressive stresses and a relatively much lower strength in the direction of the tensile stresses. Hence it might be expected that the corresponding moduli will vary similarly. However, in order both to simplify the analysis process and to remain conservative, the material is treated as isotropic and a low modulus, that might be associated with the material in tension, is usually employed.

Treating paving materials with a cementitious, or hydraulic, binder has been widely practiced because it increases the strength of the material [Otte *et al.*, 1979; Wang and Kilareski, 1979a; Wang and Kilareski, 1979b; Wang and Larson, 1979]. However, the occurrence of cracks which develop in these materials prior to traffic loading, introduces a problem that is not encountered with bituminous or unbound bases. This "primary" cracking is considered to be caused by thermal and shrinkage effects [Williams, 1978]. It may later be augmented by traffic or "secondary" (i.e. traffic associated) cracking which led Pell and Brown [1972] to suggest that these materials should be considered in two stages; the first involving only primary cracking and the second involving secondary cracking. In addition, it has been claimed [Jordaan, 1992] that the presence of microcracks in an apparently uncracked cement-bound material may be the reason for the layer to behave like a material with a modulus as low as 500 MPa.

Furthermore, it has been suggested [Freeme *et al.*, 1987] that a distinction should be made between strongly and weakly cemented layers. It has been shown [Rust, 1985] that the vertical movement of a strongly-cemented cracked layer under a load is related to the ratio of crack spacing to the layer thickness. Figure 3.4 is a graphical representation of this relation. However weakly-cemented layers tend to crack quite rapidly. This can occur even under construction traffic. Thus with time the material behaves as a granular material. Figure 3.5 graphically represents the decrease of the effective modulus of a weakly-cemented layer with increased cracking.

Consequently, when cement-bound materials are analyzed for the purposes of pavement structural condition, considerable care should be exercised in selecting an appropriate modulus. The chosen modulus should be more representative of the strength of the material in service than of its stiffness in the laboratory.

3.2.4 Granular Materials

In pavement analysis there exists a continuing need for an adequate means of modelling unbound granular materials. Yet, modelling of granular materials is a difficult task because the modulus depends on the stress regime. In addition, granular materials exhibit anisotropy and heterogeneity, whilst their modulus may be increased or decreased by a number of factors. Factors which could effect the increase of the modulus are natural cementing, low moisture and high overburden or indeed an increase in all round stress, whilst those which result in a decrease of the modulus are high moisture and clay contamination [Brunton *et al.*, 1992].

Considerable effort has been made by many researchers [Brown *et al.*, 1985; Brown *et al.*, 1981; Shook *et al.*, 1982; Wolff, 1982] to model accurately unbound granular materials. The models proposed attempted to account mainly for non-linearity either indirectly or directly. The majority of the methods tried to model nonlinear behaviour indirectly. These methods use quasi-nonlinear moduli that reflected nonlinear behaviour [Freeme *et al.*, 1982; Snaith *et al.*, 1988; Gerritsen *et al.*, 1987]. Some other methods tackled the nonlinearity directly [Sweere *et al.*, 1987; Brown *et al.*, 1985]. In these cases, the stress dependent moduli were represented by models which were based on laboratory testing results. These models may take into account confinement, bulk stress effect and shear stress effect [Bonaquist *et al.*, 1992] occurring during the testing procedure.

It has been suggested [Brown *et al.*, 1985] that linear elastic system computations can analyze granular layers with sufficient accuracy when an appropriate modulus value is assigned to them. However the thickness of the layer itself and also both the thickness and the moduli of the layers below and above the granular layer, play an important role in its structural behaviour [Freeme *et al.*, 1982; Gerritsen *et al.*, 1987; Shook *et al.*, 1982]. Thus the modulus of an unbound granular layer appears to increase as:

1. The thickness of the overlying layer decreases
2. The modulus of the overlying layer decreases
3. The modulus of the underlying layer increases and
4. The quality of the unbound granular material increases.

However, it seems that the effect of the thickness of the granular layer upon the modulus is still open to further research. There is no general agreement whether an increase in thickness of the granular material results in an increase of the modulus for use in computation [Sweere *et al.*, 1987; Barker *et al.*, 1977; Hsia *et al.*, 1987].

Moreover, it has been tentatively claimed [Brown *et al.*, 1992] that the effective resilient modulus being exhibited by a granular material in the completed pavement, may be as low as four times lower than that when loading is applied directly to the granular layer.

In conclusion, it can be seen that although there are a wide variety of approaches in use, none of them is completely satisfactory. Furthermore all of them raise problems regarding the state of stress in the granular material itself.

It seems that a linear elastic analysis may yield rational results if the modulus approximates the nonlinear material characteristics. Conversely, if a detailed analysis is required then more sophisticated models which include nonlinear models for the granular layers should be used.

3.2.5 Subgrade Soil

Soil is essentially a nonlinear material and its modulus is stress dependent [Britto *et al.*, 1987]. It may exhibit a considerable amount of variability along a length of road and may be affected by the seasonal variation in moisture content. If linear elastic theory is used for analysis, an appropriate modulus should be assigned to the subgrade soil material. Considerable effort has been expended on characterizing pavement materials. The required laboratory equipment is both expensive and complex. In addition, road engineers need some simple means of estimating the modulus of the various materials without recourse to sophisticated testing equipment. This is felt to be particularly useful if computer programs, able to analyze pavements with sufficient accuracy in a relatively short time, are to be widely accepted.

To this end, a number of researchers have correlated the modulus of the subgrade soil with an empirically derived and stiffness related parameter such as CBR or R-value [Shell, 1978; AASHTO, 1986; Shook *et al.*, 1982; Lister *et al.*, 1987; Brunton *et al.*, 1987; S.H.P.D.R.M., 1987; McMullen *et al.*, 1986; Snaith *et al.*, 1988]. The concept of correlating the CBR value with the modulus of elasticity has the great advantage of its practical simplicity. Despite their wide acceptance these relationships are considered to be unsatisfactory. It has been found [Kirwan *et al.*, 1967; Kirwan *et al.*, 1976; Robnett *et al.*, 1973] that considerable errors may arise in the estimation of subgrade modulus if both moisture and compaction levels are not taken into account. In addition the CBR test is a penetration test on a very small area of soil loaded to failure. It does not represent the conditions under a pavement loaded by traffic where the repeated stress levels are well below shear failure [Pell, 1987].

Consequently, it appears unlikely that any feasible model may be developed which can accurately deal with all situations that may occur. As with unbound granular materials, it seems that linear elastic layered models are a necessary approximation for routine analysis provided that an appropriate modulus is assigned to the subgrade.

3.3 Poisson's Ratio

The Poisson's ratio is another structural characteristic required in pavement analysis. For bituminous materials the Poisson's ratio is essentially independent of the rate of loading. However it varies with temperature. The higher the temperature, the higher the Poisson's ratio [Snaith, 1973]. In addition, the influence of this parameter may become significant when considering strain at the surface of thin bituminous layers [Pell, 1987].

The Poisson's ratio of cement-bound materials is affected by the extent of cracking, the highest values occurring in the presence of the most extensive cracking [Brown, 1979]. In addition, distinction may be made between values derived from either dynamic or static methods [Kolias *et al.*, 1978]. It appears that the determination of the Poisson's ratio by means of a dynamic method (i.e. calculated from resonant frequency and pulse velocity measurements of laboratory specimens) results in higher values than those measured by more conventional methods.

The Poisson's ratio of unbound granular materials and subgrades is dependent upon the type of the material. A typical value for granular bases and subbases is 0.35. In addition, Uzan [1992, as quoted in Uzan *et al.*, 1992] has shown that the Poisson's ratio is stress-dependent (see also [Jouve *et al.*, 1987]) and reaches values in excess of 0.5. A subsequent study [Uzan *et al.*, 1992] on the same subject has drawn the following conclusions:

1. The Poisson's ratio of granular material may reach values of 0.6 to 0.7. indicating a volume increase (dilation) under high stress ratio levels.

2. When a stress-dependent Poisson's ratio with values above 0.5 is modelled, no tensile stresses occur in the granular material and the back-calculated modulus is more realistic than that based on a conventional linear elastic analysis.

For subgrade soils exhibiting plasticity the Poisson's ratio may be 0.40 or more. In addition, it was stated by Bowles [1979] that for such soils Poisson's ratio values of greater than 0.5 may be measured at relatively low strain levels.

3.4 The Establishment of Pavement Performance Models

Various models have been developed to simulate the long term behaviour of pavements under loading. These models attempt to predict the performance of pavement structures with respect to the following types of distress:

1. Fatigue Cracking.

2. Permanent Deformation.

The following sections illustrate how various researchers have modelled the progressive deterioration of pavements with time.

3.4.1 Fatigue Cracking

Bituminous Materials

The traditional criteria for fatigue cracking in design or analysis is to use a relationship between the maximum horizontal tensile strain usually assumed to occur at the bottom of the bituminous layer and the number of load applications to failure [Witczak *et al.*, 1982]. The most simple relationship is of the form:

$$N = A(\frac{1}{\varepsilon_t})^b \tag{3.6}$$

where:

N	is the number of load applications to failure
ε_t	is the tensile strain at the bottom of the bituminous layer
A and b	are factors depending on the material.

These models are based on time consuming and expensive laboratory testing and have to be adjusted to represent *in situ* behaviour more accurately. The adjustment usually consists of increasing achieved laboratory lives by a factor whose magnitude can be as high as 700 [Lister *et al.*, 1982]. However it has been suggested [Pell, 1987] that results of simple tests may be used to predict performance with respect to equation 3.6 by means of a cumulative linear damage model, such as Miner's law:

$$\sum_{i=1}^{j} \frac{n_i}{N_i} = 1 \tag{3.7}$$

where:

n_i	is the number of cycles of strain level ε_1 applied
N_i	is the number of cycles of strain ε_1 to produce failure

in continuous loading

j is the number of different strain levels.

or else

$$\frac{N_{\text{past traffic}}}{N_{\text{existing structure}}} + \frac{N_{\text{future life}}}{N_{\text{new total life}}} = 1 \tag{3.8}$$

where:

$N_{\text{past traffic}}$	is the past traffic in standard axles (SA)
$N_{\text{existing structure}}$	is the calculated fatigue life of the existing pavement in SA
$N_{\text{future life}}$	is the future life in SA
$N_{\text{new total life}}$	is the calculated fatigue life of the pavement after overlaying in SA.

Another method of fatigue analysis is that of "energy dissipation". It has been shown [van Dijk, 1975] that a unique relationship exists between the total dissipated energy per unit volume to fatigue and the number of load applications to failure when bituminous mixes are tested in dynamic bending tests. The relationship is:

$$W_F = A\,N^z \tag{3.9}$$

where:

W_F	is the total dissipated energy
N	is the fatigue life in load application cycles
A, z	are material constants obtained from fatigue experiments using sinusoidal applied loads.

The relationship appears to be independent of the type of test (controlled stress or strain) and the nature of the load application (continuous or discontinuous) [van Dijk, 1977]. Some researchers have recently used this method [Gerritsen *et al.*, 1987; Himeno *et al.*, 1987] which had previously also been incorporated into the SHELL design manual [SHELL, 1978]. It appears that this new method is very promising and it is likely that this is the reason why the bending test, on which the method is based, has been adopted by the SHRP for fatigue cracking analysis [Kennedy *et al.*, 1990].

Further research on the dissipated energy concept has resulted in the development of a predictive model given by the following equation [Hopman *et al.*, 1992]:

$$N_1 = \frac{1}{T} \left[A \, \Gamma \, \frac{T}{w_0} \right]^{\frac{1}{(1-z)}} \tag{3.10}$$

where:

N_1	is the fatigue life
T	is the loading cycle time
Γ	is a constant of about 1.2
A, z	are material constants obtained from fatigue experiments using sinusoidal applied loads
w_0	is the initially dissipated energy during the first loading cycle as follows [van Dijk, 1977]:

$$W_{N_1} = w_0 \, \frac{N_1}{\Gamma} \tag{3.11}$$

W_{N_1} is the total dissipated energy.

The method is based on the experimental determination of the four elements of the Burger's rheological model (see Figure 3.6); that is the values of the spring moduli E_1 and E_2 and also those of the viscosity coefficients n_1 and n_2 of the dashpots [Ferguson *et al.*, 1991]. Subsequently, the dissipated energy (W_{dis}) is analytically computed as a relationship between stresses and strains as follows:

$$W_{dis} = \int_0^\infty \sigma \, \delta\varepsilon \tag{3.12}$$

where:

σ is the stress and

$\delta\varepsilon$ is the changes in the corresponding strain.

During the fatigue tests the values of E_1, E_2, n_1, and n_2 decrease causing an increase in the dissipated energy. Similarly, it has been observed [Holster *et al.*, 1991, as quoted in Hopman *et al.*, 1992], that the energy dissipated during a single FWD measurement on a newly constructed road was about half of that measured in a fatigued road. Consequently, it appears feasible that a quantitative relationship may be established between the fatigue life and dissipated energy in pavements tested with the FWD [Hopman *et al.*, 1992].

However, there exists a controversy over the validity of this method. The usual analytical approach to fatigue cracking assumes that the maximum tensile strain occurs at the bottom of the bituminous layer. If the dissipated energy model is applied, then greater fatigue damage is yielded at the top than at the bottom of the surfacing layer [Gerritsen *et al.*, 1987]. Hence, further investigation is needed so that the dissipated energy method may be verified and a relationship found between the two approaches.

Cement-bound Materials

As with bituminous materials, cement-bound materials are subject to fatigue cracking. However there is limited interest in modelling the fatigue of cement-bound materials. In such cases the fatigue relationships are of the form [Witczak, 1982]:

$$\frac{\varepsilon_t}{\varepsilon_b} \quad \text{or} \quad \frac{f_t}{f_b} = a - b \log N \tag{3.13}$$

where:

ε_t and f_t are theoretical strain and stress respectively at the bottom

	of the layer
ε_b and f_b	are allowable bending strain and stress respectively from flexural strength tests
a and b	are constants and
N	is the number of load repetitions.

As with bituminous materials, the maximum tensile strain does not always occur at the bottom of the cement-treated layers [Jordaan, 1992]. Rather, its location within the layer is a function of the structural characteristics (i.e. thickness and moduli) of both the pavement constituent layers and the subgrade. This location should be determined during detailed structural analysis.

3.4.2 Permanent Deformation

The response of a bituminous material to repeated loading resulting in the accumulation of permanent deformation is essentially a creep phenomenon [Brown *et al.*, 1974]. Creep is the time-dependent strain that occurs when a material is subjected to a stress for a prolonged period of time. Hills, [1973] and Hills *et al.*, [1974] have found that the main factors affecting the creep behaviour of bituminous materials are stress level, temperature and the rheological characteristics of the bitumen. In addition, initial compaction and aggregate characteristics are important.

Laboratory creep testing of bituminous materials [Kirwan *et al.*, 1977; Brown *et al.*, 1974] and further investigation of the permanent deformation phenomenon indicated that analytical procedures based on the use of time-dependent and temperature-dependent characteristics may be developed. Moreover, the behaviour of a flexible pavement structure subjected to dynamic loadings may be simulated and hence both rut depth and lateral surface profile after trafficking may be obtained [Kirwan *et al.*, 1977].

In order to prevent a pavement structure from excessive rutting, the following approaches have been used:

1. The use of limiting strain (or stress) criteria.

2. A permanent deformation predictive system.

Limiting Strain Criteria

The most common and simplest method of dealing with permanent deformation limits the vertical strain (or stress) at the top of the subgrade by means of a relationship of the form:

$$N = A(\frac{1}{\varepsilon_z})^B \tag{3.14}$$

where:

N	is the number of load applications to failure
ε_z	is the vertical strain at the top of the subgrade
A and B	are constants.

The use of a limiting compressive strain value at the top of the subgrade simply controls the overall pavement performance by ensuring that excessive levels of permanent deformation will not occur in the pavement. It does not deal with the permanent deformation in each layer and does not predict the rut depth.

Permanent Deformation Predictive System

The road engineer desires a pavement performance model which is able to predict the rut depth as a function of material properties, traffic loading and environmental influences. The approaches followed require repeated load triaxial tests or uniaxial creep tests under either static or dynamic loading [Bolk, 1982]. The wheel tracking test is an alternative laboratory facility for checking the rutting resistance of bituminous mixes [van Dijk, 1975]. Typically such a method involves the summation of permanent strains throughout the depth of the pavement. A few researchers have developed such models. These models, have been used either in finite element programs [Kirwan *et al.*, 1977] or in more simplified approaches [Verstraeten *et al.*, 1982]. In these models the permanent strain is either of the form:

$$\varepsilon_{\mathrm{p}} = \mathrm{A}\ \sigma^{\mathrm{b}} \tag{3.15}$$

or

$$\varepsilon_{\mathrm{p}} = \varepsilon_{\mathrm{e}}\ \mathrm{f(N)} \tag{3.16}$$

where:

ε_{p}	is the permanent strain
σ	is the applied stress
A	is a function of elapsed time and the material
b	is a constant for the material
ε_{e}	is the strain related to the elastic layered theory and
N	is an elapsed time (number of load applications) related to the permanent strain.

Other researchers have tried to model the phenomenon of permanent strain using viscoelastic theory [Kenis *et al.*, 1982]. Recently, the concept of dissipated energy has also been used [Hopman *et al.*, 1992]. The procedure followed was similar to that for fatigue cracking (see Section 3.4.1).

However, the above techniques are felt to be unsuitable for routine analysis due to the need for calibration to comply with the observed *in situ* performance of the pavements. Therefore, limiting subgrade strain would appear to be the most simple and effective design parameter for the control of excessive permanent deformation.

3.5 The Structural Evaluation of Pavement Structures and Advances in KBS

3.5.1 The Use of FWD in Field Testing

In order to evaluate the relative performance of field testing equipment, Lindly *et al.*, [1987] compared various NDT devices and concluded that these all tend to give similar deflection basins. However they stated that the FWD is the most reliable device for the back-calculation of the layer moduli.

In addition Ferne [1990] showed that there is no statistically significant difference between deflections measured by FWDs made by different manufacturers. He has also suggested that the variations observed may be attributed to the different pavement temperatures occurring during the measurements. However he pointed out that despite the consistency of the deflection readings and the results of the data analysis, the FWD evaluation procedure predicted considerably longer residual lives than those found by the TRL method reported in LR 833 [Kennedy *et al.*, 1978]. This observation agrees with that reported by Sebaaly *et al.*, [1986] who stated that analyses based on FWD deflections tend to overestimate the moduli of the pavement layers.

Nonetheless, it may be seen from the above that the FWD has been used with some confidence in evaluating the strength of the pavements.

3.5.2 The Analysis of the Deflection Bowl

When a load is applied to the surface of a pavement the consequent vertical stress regime may be considered as shown on Figure 3.7 [AASHTO, 1986]. The higher the modulus in any particular layer the greater the stress gradient in the material. However it is not only the modulus of the layers that affects the transmission of the applied load within the pavement structure, but the thickness of the layers as well [Witczak *et al.*, 1982]. Thus, the deflection bowl under the FWD load is the result of the combined effects of both the thickness and the modulus of the pavement layers.

In order to estimate the *in situ* layer moduli using back-analysis techniques a number of problems that affect the accuracy of the solution should be addressed such as:

1. The determination of the optimum location of the geophones.

2. The possibility of non-uniqueness of the solution.

3. Errors due to the assumption of a semi-infinite subgrade where a rock layer exists at a shallow depth below the foundation.

Improvements to the quality of deflection data should be made, since it is desirable to place the deflection transducers at radial positions which are more sensitive to the moduli of the individual layers of the structure [AASHTO, 1986]. Thus, if reliable values of the layer moduli are to be back-calculated, the FWD geophones should be positioned with some care. Brown *et al.*, [1987] studied the influence of the individual layers on the deflected shape of a pavement. Their findings may be seen in Figure 3.8. They examined a number of flexible pavements and recommended positions for the deflection transducers. However, these general recommendations do not seem to be true in cases of very stiff pavements and of pavements having cement-bound roadbases where it appears the problem of underestimating the distance from the load centreline at which deflection is felt to be affected only by the subgrade modulus [Bonnot, 1987]. This distance seems to be greater than the maximum distance at which the last geophone is usually placed. In practice the deflections are measured at a variety of radial distances. Ferne, [1992] observing a number of different contractors, pointed out that the deflection transducers are usually located at intervals of 0.30 m up to 2.10 m.

Much debate about the non-uniqueness of the back-analyzed layer moduli from a given deflection bowl has been conducted between various researchers. Brown *et al.*, [1987] have indicated that unique solutions have been "generally obtained" when an iterative procedure was implemented. This procedure was characterized by two elements:

1. Nonlinear stress dependent subgrade modulus.

2. The use of one particular offset deflection to indicate the modulus for a particular pavement layer and two offset deflections from which to compute the subgrade modulus.

Brown *et al.*, [1987] have also presented a theoretical concept called " Influence Index" which was felt to support their argument. This "Influence Index" took into account the variation of the deflections due to the variation of the modulus in one layer. It has also been suggested that a similar index could be used to study the influence of the thicknesses of the layers. However, it is felt that the Influence Index is not sufficiently justified, and ignores the combined effects of both thickness and modulus of the individual layers in a pavement model [Witczak, 1982].

Ullidtz *et al.*, [1985] have also suggested that a unique solution may be achieved. Their method is limited to three structural layers. It is based on the

Method of Equivalent Thickness (M.E.T.) and also incorporates nonlinear elastic material modelling. The program uses the outer deflections for the determination of the subgrade modulus and the detection of a shallow bedrock. The moduli of the two remaining layers are calculated by means of an iterative procedure following the determination of the subgrade modulus. Despite the simplicity of the model proposed in comparison with the Finite Element Method (F.E.M.), it was considered by Ullidtz *et al.*, [1987] that the method was

"as good as the more complicated models".

However, other researchers [McCullough *et al.*, 1982; Uddin *et al.*, 1986; Uddin *et al.*, 1987] have pointed out that a number of combinations of layer moduli may result in a given basin slope. They have shown that the non-uniqueness of the predicted moduli may lead to substantial errors in the pavement moduli. Consequently, they developed a methodology which makes use of "seed moduli" to restrict the possible combinations of moduli in the pavement.

Furthermore Rohde *et al.*, [1992], McCullough *et al.*, [1982] and Uddin *et al.*, [1986] have claimed that the pavement model should have the ability to consider a rigid layer at a shallow depth. They suggested that the subgrade modulus may erroneously be estimated if a semi-infinite subgrade is assumed without this modification.

Many techniques have been used for the analysis of the FWD deflection bowl. To date, although the work done by various researchers is very helpful, it still needs to be developed to enhance the reliability of the findings.

3.5.3 The Use of KBS in Pavement Evaluation and Rehabilitation

The evaluation of existing pavements, their structural analysis and the selection of remedial treatments normally require the knowledge and experience of a specialized road engineer. Consequently it seems reasonable to suggest that a KBS should be developed to assist road engineers in addressing pavement maintenance problems. This section presents a selection of systems which has been formulated to tackle, albeit on a research basis, certain engineering problems related to pavement maintenance.

The feasibility of the KBS approach to pavement rehabilitation has been demonstrated with the development of a prototype system called SCEPTRE 1.1 [Ritchie *et al.*, 1986]. This system was developed to evaluate pavement surface distress in order to recommend potential rehabilitation strategies for detailed analysis and design. The KBS development software "EXSYS" [1985] was used. The expertise included into the knowledge base was derived by interviewing experts and by converting pavement condition ratings used by the Washington State Department of Transportation [Nelson *et al.*, 1983] into a suitable form.

The above system was further linked with a second program named OVERDRIVE [Ritchie, 1987]. Both systems were part of a proposed integrated set of KBSs, under development, for local highway agencies to provide an overlay design procedure based on the Asphalt Institute Method.

Hajek *et al.*, [1987] developed a KBS, ROSE, for recommending crack sealing rehabilitation measures for asphaltic concrete pavements in cold areas. As with SCEPTRE, "EXSYS" was used. The procedures and recommendations of the system were based on the pavement monitoring and evaluation techniques used by the Ontario Ministry of Transportation and Communication (MTC) [Chong *et al.*, 1983]. This system was suitably transformed to access both the Ontario MTC pavement maintenance data bank and the SAS [1985] statistical package.

Wiseman *et al.*, [1987], developed a KBS for the evaluation and strengthening of airfields. This system initially utilized the Unified Soil Classification System and empirical knowledge of the developers to estimate the CBR of a given subgrade soil. Thereafter the system provided guidance in determining the strength of an existing runway pavement using the ACN-PCN method [ICAO, 1983].

An Expert System called PARES (Pavement Rehabilitation Expert System) has been produced to help the New Mexico State Highway and Transportation Department personnel to speed the process of pavement evaluation and rehabilitation [Denning, 1992]. The system has been designed to provide potential solutions as well as the optimal choice of maintenance activities for the roads tested, based on both strength and cost characteristics. The program has been developed to apply to the major types of flexible pavements used throughout the United States.

Oulman *et al.*, [1990], have designed an Expert System for the management of flexible pavement networks, using the commercially available spreadsheet Lotus $1-2-3^{\mathrm{TM}}$. The program seeks to represent and automate the pavement management strategy developed by the California Department of Transportation (CALTRANS). Information about the pavement condition is provided to the system which in response evaluates the data and subsequently identifies both alternative maintenance activities and the optimum economic solution as well. However, it appears that the system supplies the user with an answer possibly through the use of an overly simplistic process.

Another program, based on database techniques, has been developed by the team of Witczak [Schwartz *et al.*, 1991] to assist the management of airfield pavements. The programming tool was primarily QuickBasic [Hergert, 1989], but an assembly language, as well as FORTRAN, was used where necessary. The objective of this program was to make multi-year budget forecasts for all the airfield pavement related maintenance and rehabilitation projects. The resultant databased system enabled the storage and manipulation of a variety of data such as pavement inventory characteristics, material properties, visual survey, roughness, traffic volumes, construction history and unit costs of the maintenance and rehabilitation activities available.

In conclusion, it may be seen that the programs developed indicated that KBS technology is a feasible approach to the assessment of pavement structures. However further work is needed so that an effective procedure which would include the simulation models of pavement response and performance may be achieved. Efficient ways of encoding engineering knowledge should be implemented to formulate a procedure which would assist the operator to draw reliable conclusions and make decisions on maintenance strategies.

FIGURES

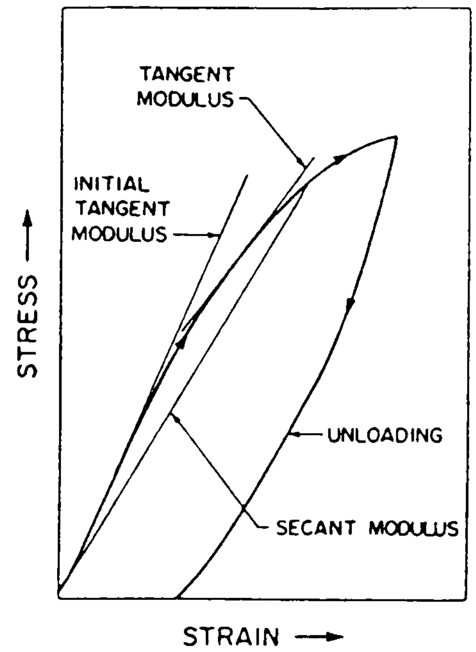

Figure 3.1: Typical Unconfined Stress-Strain Curve for Asphaltic Concrete [After Mamlouk *et al.* 1987].

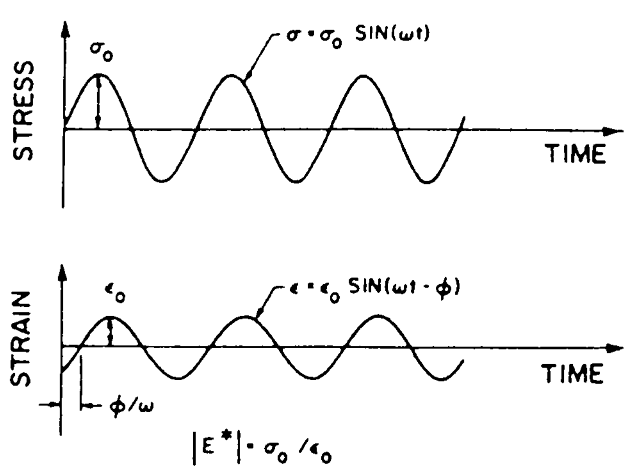

Figure 3.2: Typical Plot of Stress and Strain versus Time During the Complex (Dynamic) Modulus Test [After Mamlouk *et al.*, 1987].

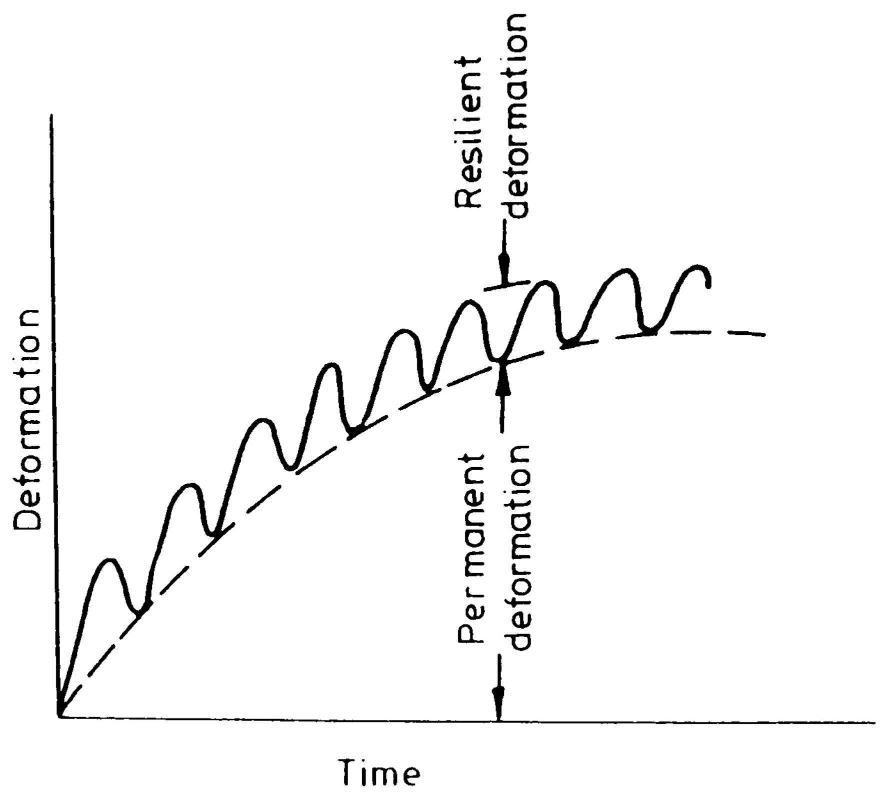

Figure 3.3: Definition of the Permanent and Resilient Deformation Components During Repeated Load Triaxial Tests [After Brown and Snaith, 1974].

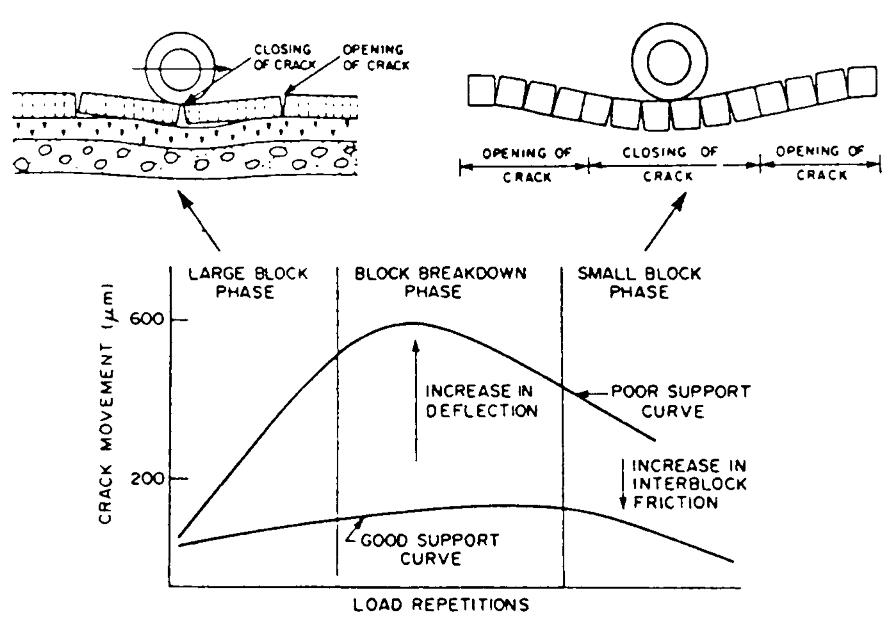

Figure 3.4: Different Response of a Cemented Material to Deformation Due to the Different Ratio of Crack Spacing in Relation to the Layer Thickness [After Freeme *et al.*, 1987].

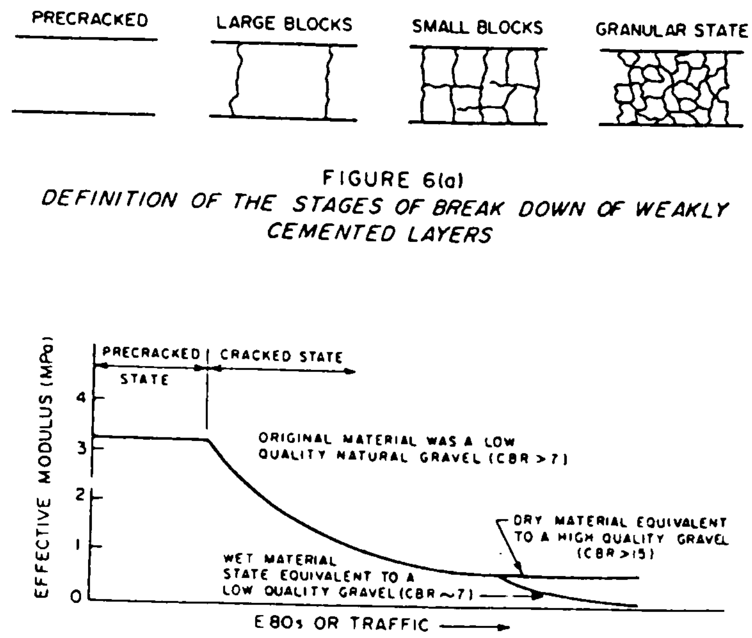

Figure 3.5: The Reduction of the Effective Modulus of Weakly Cemented Materials in Conjunction with the Extent of Traffic-associated Cracking [After Freeme *et al.*, 1987].

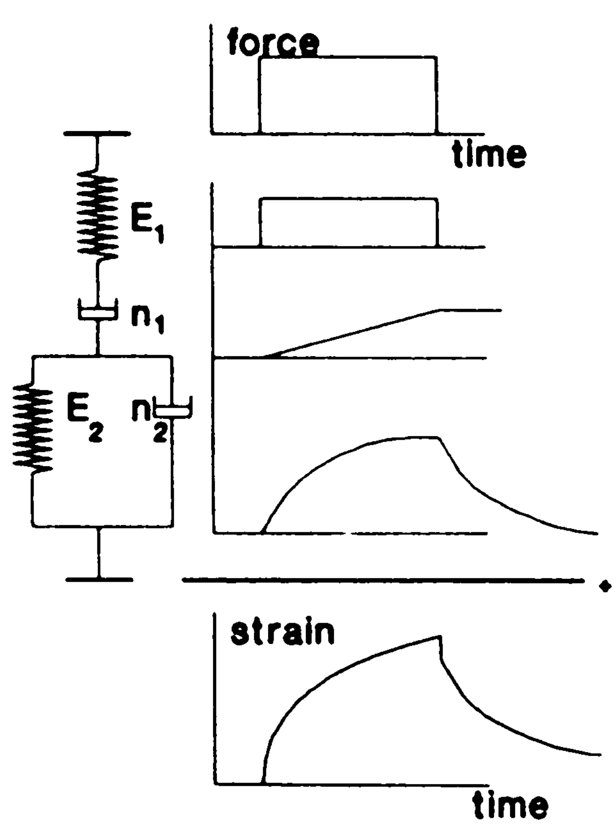

Figure 3.6: The Burger's Rheological Model [After Hopman *et al.*, 1992].

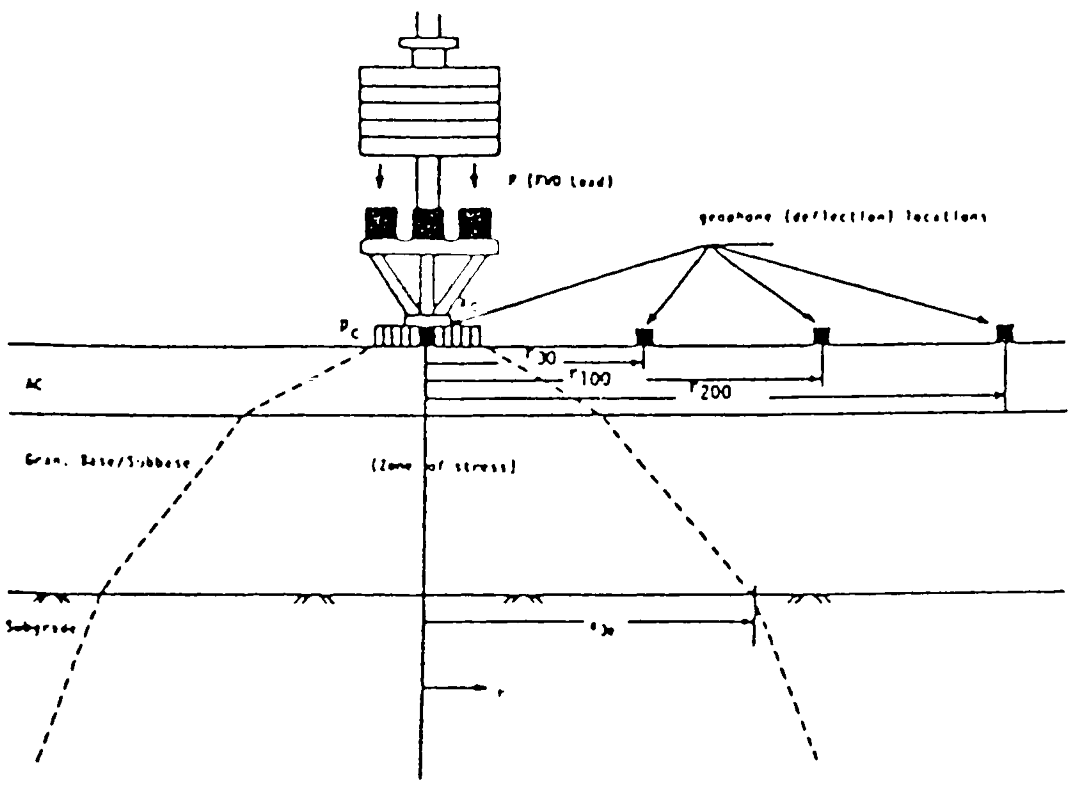

Figure 3.7: Typical Pavement Structure Subjected to FWD Loading [After AASHTO, 1986].

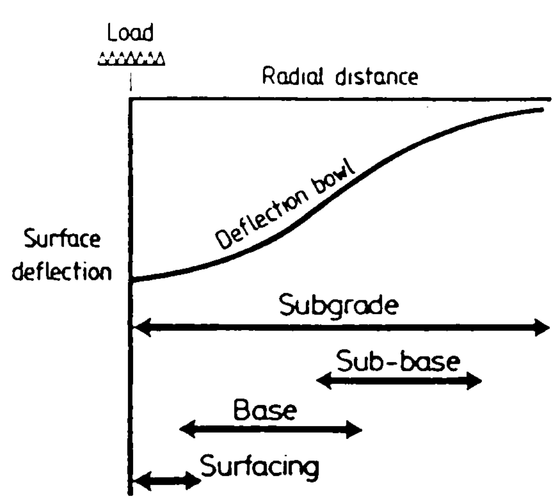

Figure 3.8: The Influence of the Different Layers on the Deflected Shape of a Pavement [After Brown *et al.*, 1987].

Chapter 4

FIELD TESTING

4.1 Introduction

The use of nondestructive field testing of pavements using load induced deflection has been an integral part of the structural evaluation and rehabilitation process for many years [Snaith, 1985]. At the initial stages of their development, the central elastic deflection under a particular load arrangement was used directly as an indicator of pavement structural strength [Snaith *et al.*, 1980; Kennedy *et al.*, 1978]. However in order to improve behavioural modelling to resolve apparent conflicts between predicted lives from a variety of criteria (e.g. deflection and critical asphalt strain) it was suggested that the deflection bowl should be used for the determination of pavement bearing capacity [Ullidtz, 1987]. A number of methodologies with associated deflection testing devices have been developed for this purpose [Lytton *et al.*, 1985; Marchionna *et al.*, 1985; Kennedy, 1982]. Their validation relies on correlating their findings with observed pavement condition. Hence it is necessary to have data collected by complementary methods such as superficial condition survey and site specific destructive testing for comparative purposes.

Despite the progress made in this area, further improvements are necessary to enhance the efficiency of such procedures [Hicks, 1987]. Specifically:

1. NDT techniques have various deficiencies in that certain of the applied parameters are liable to vary significantly (e.g. load with FWD). Standardization would overcome the lack of measurement uniformity [Tholén *et al.*, 1985].
2. Seasonal effects on measurements should be determined.
3. The speed and the productivity of evaluation techniques affect the reliability of the measurements within a given sample size.
4. There exists a need for the establishment of a method which will interrelate serviceability with structural condition as determined by a NDT technique [Molenaar, 1982].

In this work, the chosen deflection testing equipment for pavement evaluation is the FWD.

This chapter discusses both the FWD deflection testing procedure and the other methods used for its verification or calibration, together with the general procedure used for the collection of additional data to enable the development of the knowledge-based system.

4.2 Condition Survey

A relatively superficial condition survey should be conducted as a complementary part of the FWD testing procedure. Its aim is to provide information, other than traffic loading, to assist in the analysis of the measurements. Such factors are due both to the environment, such as temperature and moisture content, and structural deficiencies (i.e. thickness variation, cracking and rutting).

4.2.1 Environment

The variation of temperature in bituminous materials and of moisture content in unbound granular materials or subgrade soils, considerably affects the performance of the pavement [Hudson *et al.*, 1987]. The success in quantifying these effects in any analysis of the pavement structure and taking account of them, determines the ultimate usefulness of analytical procedures in structural condition and remaining life analysis [Koole, 1987]. Consequently, relevant work is presented and discussed.

It is widely accepted that both the daily and annual temperature variations will markedly affect the structural performance of a pavement through their direct or indirect effects on the construction materials. Consequently, the highway engineer should be aware of the various phenomena that may be encountered during testing which might give rise to any "abnormal" deflections. For example, an unusually high temperature in the bituminous mix will result in a decrease in its modulus causing very high deflections recorded by the nearby sensors of the FWD. Similarly, it has been noted that such changes in temperature will generally have only a negligible effect on the stresses in the subgrade and consequently on its modulus [van Gurp, 1992]. However, it has been shown [Chandra *et al.*, 1989], that under certain circumstances an increase in temperature could lead to a significant increase in the subgrade modulus in dry climates, during the summer. This phenomenon is caused by an increase in the confining pressure due to inability of the soil particles to expand. In order to consider this, it is obviously necessary that the temperature should be recorded at the time of FWD testing and equations established to take account of any such relationships that might become apparent [Ullidtz *et al.*, 1987]. It has been suggested that deflection measurements should be carried out at temperatures below the "Ring and Ball" temperature of the bitumen used in the surfacing [Schmith *et al.*, 1992] to avoid primarily viscoelastic behaviour of bituminous materials during testing. However, it appears that the susceptibility of bitiminous mixes to temperature may not always be estimated correctly with the "Ring and Ball" test [Leung *et al.*, 1987].

Furthermore, it is known that variations in modulus, due for example to seasonal changes in the moisture content of the subgrade and granular sub-base, will have a consequent effect on the structural performance of the pavement [Powell *et al.*, 1984; AASHTO, 1986]. Hence, it is not possible to relate deflection directly to long-term structural performance, unless account is taken of the moisture content. Moreover, it should be noted that the variations in moisture content are not the same within a pavement cross section. Zones near the pavement shoulder are more susceptible to changes in moisture content than those along the centre [van Gurp, 1992]. Hence, it is also necessary to note during field testing the crossectional position of any test result.

In addition, an analysis of field data [Saraf *et al.*, 1987] has indicated that the performance of a pavement is a function not only of seasonal variation but also of the average annual rainfall. Whilst this effect is negligible for the first few years after construction, it becomes increasingly significant as the pavement decays as progressively more of the stresses due to the traffic load are applied to the underlying subgrade. As would be expected, pavements resting on subgrades with high clay contents exhibit considerably more susceptibility to the influence of water.

Similarly, Thom and Brown [1987] have shown that the presence of moisture in unbound aggregate materials "lubricates" the particles and markedly increases the rate of permanent deformation with only a small effect on elastic modulus. Whilst moderate levels of moisture have only a minor effect on overall elastic behaviour, it has been observed that saturation of a poorly drained granular base has a drastic effect on pavement condition.

Clearly, both asphalt temperature and soil and granular material moisture levels have a considerable influence on the deflection behaviour of flexible pavements. Consequently in order to take account of this and thereby improve the quality of analysis of any data based on the structural properties of the pavement layers, both temperature and moisture must be monitored either directly or indirectly.

4.2.2 Structural Deficiencies

Significant variations occur in the properties of the different pavement layer materials, for example due to cracking, the bond between adjacent layers and variation in layer thicknesses. These will naturally have a consequent effect on the transmission of the FWD induced stress through the pavement layered system [Kennedy, 1987]. This section discusses the impact of these variations on any structural analysis and how they may be incorporated into the analytical system.

Cracking

Cracking may be caused either by repeated traffic loading or environmental factors such as thermal cycling or indeed a combination of the two mechanisms [Halim *et al.*, 1987]. In addition when overlaid, cracks in underlying pavements propagate upwards through the overlay to give what is known as "reflection cracking". The presence of cracking may lessen the influence of temperature [Jameson, 1992] and thereby considerably affect the back calculated modulus of the bituminous materials.

Since the type of cracking is indicative of a particular distress mechanism, it may require a more detailed analysis with respect to the suspected cause. As an example, Jacobs *et al.*, [1992], have found that fatigue cracking does not always start from the bottom of the bituminous layers propagating upwards, but also may be initiated at the surface of the pavement. Such cracking was assumed to have been caused by high tensile stresses occurring at the top of the road pavement due to large changes in applied stress. The simulation model formed for the analysis of the above cracking type revealed that the tensile stresses computed at the top of the layer could be as high as three times those at the bottom.

In addition, if a distinction is made between longitudinal and transverse cracking in the analysis, then it is advisable that these types of cracking should be simulated using principles of fracture mechanics [Marchand *et al.*, 1982]. According to Irwin [1957, as quoted in Dauzats *et al.*, 1987] three modes of cracking may be modelled:

1. Opening Mode (I).

2. Sliding Mode (II).

3. Tearing Mode (III).

Each type of cracking (i.e. longitudinal or transverse) may be associated with one or more of the above. Hence, longitudinal cracking is considered to be caused primarily by tear forces occurring at the tip of the crack, whilst transverse cracking is regarded as the effect of both shearing and bending forces [Jacobs *et al*, 1992]. As a result, if longitudinal or transverse cracking is modelled, using for example the finite element method, then stress intensity factors[1] for each cracking mode

[1]Stress intensity factor is a quantity expressed in $MPa * m^{\frac{1}{2}}$ which indicates the concentration of the stresses in the vicinity of a crack tip.

may be calculated (see Fenner, [1986] amongst others). Subsequently a quantitative relationship may be established between the type of cracking (transverse or longitudinal) and the intensity factors of the stresses responsible for these types of cracking.

However, it should be noted that in case of such a detailed analysis, the temperature of the surfacing should also be considered as it appears to be an important factor for the development of cracking together with the effects of applied stress distribution [Matsuno *et al.*, 1992; Irwin, 1977].

Consequently, the severity, the type and the extent of cracking should be recorded so that they may be considered with the FWD deflection in the analysis procedure.

Rutting

The other major structural distress mode is the accumulation of permanent deformation (i.e. rutting). Lister and Kennedy [1977] have reported that most or all pavement layers, including the subgrade, contribute to this deformation. Rutting occurs in the wheel track and is considered as a principal indication of failure [Croney, 1972]. At high pavement temperatures, when the stability of the mix is at its least, it appears that its primary causes are:

1. The high applied stresses occurring at the edges of the tyres.
2. The maximum energy density also occurring at the same location [Southgate *et al.*, 1992].

However, it is only with difficulty that its progression may be modelled with analytical procedures and there are few robust computer simulations [Kirwan *et* *al.*, 1977].

Despite this, it is obviously necessary to consider ruts alongside other information when analyzing a pavement with the FWD. As rutting is symptomatic of traffic damage it is possible to deduce information about the environmentally produced damage, as opposed to traffic induced damage, of a pavement by applying the FWD both within and outside the wheel paths indicated by the rutting. FWD testing in the wheel paths may be considered as testing the load deteriorated condition of the pavement, whereas analysis of the deflection bowl measured between the wheel tracks might be representative of an initial undamaged state of the structure, or at least of the structure having only sustained non-load associated changes (e.g. hardening of the bituminous layer [Arand, 1987; Hugo *et al.*, 1985]).

A useful classification of road pavement condition relying on cracking and rutting has been adopted by Kennedy *et al.*, [1978]. This may be seen in Table 4.1. It is based on a wide variety of observations of roads throughout England and Wales and has the merit of providing information on the observed structural integrity of a road pavement in an unambiguous and objective manner derived from "superficial" observations. This classification is expected to be incorporated into a comprehensive KBS (see Section 9.6.1 and Appendix F).

4.3 Nondestructive Testing

4.3.1 Apparatus Selection

According to Hicks *et al.*, [1987] a NDT device should have the following characteristics:

1. Exhibit low operating and maintenance costs.
2. Simulate actual wheel loading.
3. Be reliable, repeatable and easily calibrated.
4. Be easy to use, safe under traffic and weather resistant.
5. Have the facility to store the data directly into a computer database.
6. Be able to test a wide range of construction and material types.
7. Have the ability to link to an authoritative analysis and design methods.

Unfortunately, most apparatuses do not meet all of these requirements. However Mamlouk, [1987] amongst others, have suggested that the device that has the majority of them and simulates the nature of the moving wheel load most closely is the FWD.

4.3.2 Testing Frequency

When conducting a pavement analysis, the potential remedial works project should be divided into sections exhibiting uniform attributes and performance. However, a certain degree of variation in structural characteristics (i.e. material properties and layer thicknesses) exists within each section, which may be divided into two groups:

1. Random variation
2. Stratified or assignable variation.

Random variation is present in all pavement materials and structures. It is due to the non-uniform nature of pavement layers. Stratified, or assignable, variation occurs due to a significant change in factors, such as layer modulus and thickness, due possibly to poor construction practice [McCullough *et al.*, 1982].

The variation in structural strength is reflected in the deflection measurements [Kennedy *et al.*, 1978]. As the tests provide an estimation of the actual mean value of the strength of a pavement section, an increase in the number of tests would increase the level of confidence in determining a truly representative strength of the pavement. Therefore a statistical analysis which will determine the minimum number of tests necessary to produce a reliable solution, may be required [AASHTO, 1986].

Nevertheless, the specification of an appropriate statistical method is beyond the scope of this project. However, it will be required ultimately in order to facilitate any extensive verification programme of any working KBS.

4.4 The Falling Weight Deflectometer

4.4.1 Description

The FWD, originally constructed in France by Bretonnière [1963], was further developed in Denmark into a practical NDT device [Ullidtz, 1987]. Different versions have been designed and are in operation worldwide.

The FWD drops a weight from a variable height onto a spring system (Figure 4.1). This in turn transmits a load pulse to the road surface by means of a circular plate usually of 300 mm diameter. The impact load has a duration of 25-30 ms and a peak force of up to 120 kN. The deflection basin of the pavement is measured by velocity-sensitive transducers, one at the centre of the loaded area and up to eight others at fixed distances from the load. The equipment is carried on a single axle trailer towed by a vehicle carrying the recording equipment. Further details on typical technical specifications may be found elsewhere [Sørensen *et al.*, 1982; Tholén *et al.*, 1982].

4.4.2 The Loading Characteristics of the FWD

It is well known that the modulus of bituminous materials is, amongst other parameters, a function of the speed of loading [Pell, 1987]. Consequently in order that any analytical process may provide a reasonable assessment of the characteristics of the individual pavement layers, arguably the most important ability of an FWD is to be able to apply a load to the pavement surface similar to that of a wheel moving at normal traffic speed.

The impact load of the FWD typically lasts 25-30 ms which corresponds to a wheel speed of 60-80 km/h for the upper layer. Thus, the visco-elastic performance of the bituminous layers may be seen to be well represented by the FWD test. Although actual loading conditions are not represented at the lower layers, Ullidtz has shown that measured strains, stresses and deflections induced by the FWD when compared to those of a heavy truck wheel were essentially the same [Ullidtz, 1973].

Hoffman and Thomson [1982] showed that resonance is usually not induced by either moving wheels or FWD loading, but it seems likely that there may be a difference in the inertial effect of the NDT device as opposed to that of traffic, but it is assumed to be second order in the absence of a theoretical solution [Lysmer *et al.*, 1966]. However, due to the dynamic nature of the FWD load, multiple wave reflection and refraction is known to occur within the pavement. As a consequence, unexpected readings of the deflection transducers may be obtained which, if encountered, require further analysis to enable proper interpretation [Mamlouk, 1987].

Hence, it may be concluded that the FWD appears to be suitable for the nondestructive testing of pavements since it simulates a moving wheel load reasonably well. However further development of a generally accepted standard method for equipment calibration and usage would further improve the perceived reliability of the FWD.

4.5 Direct Sampling

Whilst emphasis has been laid on nondestructive testing, a technically sound engineering field programme should include a complementary destructive test programme from those areas where it is likely that rehabilitation works will be required. The aim of a limited number of destructive tests is to provide information for the verification or modification of historical data concerning either pavement layer thicknesses or properties. Consequently, destructive testing would reduce the likelihood of inaccurate data for use in the rehabilitation procedure.

4.6 Field Testing Procedure

The role of field testing in pavement structural evaluation has already been presented. However, within the process of the KBS development it acquires another dimension. Data from field testing with an FWD, is a major component of the initial assessment and subsequent validation of the solution obtained through the KBS using the data and knowledge included in, and manipulated by, the system. Hence, field testing may be considered as a vital process which interacts with the knowledge base and provides new information and enhances old.

Figures 4.2 and 4.3 represent the total process of field testing, divided into two stages:

1. The preliminary work.

2. The actual testing.

The preliminary work comprises all the activities which enable subsequent computer analysis of the data acquired by the FWD and ancillary testing. These include:

1. The determination of the different pavement types to be analyzed (i.e. flexible or rigid structures, pavements with granular, bituminous or cement-stabilized roadbase, etc.).

2. The selection of information concerning historical (e.g. previous remedial treatments), traffic and geometric data.

Field testing on a wide range of pavement structures provides data which permit a more efficient validation of the KBS. However the quality of the data collected will naturally affect the performance of the system, and it is therefore important that the data are determined with the highest possible accuracy.

A typical data set should include:

1. Determination of the chainage of the testing points.

2. Temperature measurements (i.e. mean air temperature or preferably pavement temperature).

3. Observation of the pavement condition in terms of cracking and rutting together with surrounding environmental conditions such as the drainage and consequent moisture content levels.

4. Deflection bowl measurements with the FWD.

   (a) Along the wheel paths for the assessment of the present condition of the pavement.

   (b) Between the wheel paths for the assessment of the structure in a relatively undamaged state.

In addition, if there are no construction records giving the layers materials and thicknesses, destructive testing such as coring or DCP testing should be conducted.

As with any other testing procedure, the following factors should be considered for the FWD:

1. Calibration of the sensors.

2. Repeatability of the readings.

3. Reproducibility of the readings.

Two levels of calibration are recognized:

1. Relative calibration.

2. Absolute or Reference calibration.

The relative calibration may be performed by the operator of the FWD and is used to ensure that all deflection transducers measure the same deflection. The absolute calibration is made by the manufacturer of each particular device. In the latter case both the load cells and the sensors are tested against independently calibrated reference devices [SHRP, 1991].

The capability of a particular FWD to reproduce a certain deflection basin at a test site for multiple drops imposed under identical testing conditions is generally termed as repeatability. As a result of work carried out by Ferne [1990], it was suggested that the repeatability is not constant but varies in proportion to the deflection level. However, this was not supported by van Gurp *et al.*, [1992].

Usually, four loading cycles are applied to each testing point. The first one is necessary so that the loading plate is brought into proper contact with the pavement surface. The readings of this cycle are omitted from the analysis. The average of the three succeeding drops is then "normalized" to a reference applied stress which is commonly 700 kPa [Brown *et al.*, 1987; Jacobs *et al.*, 1992]. However normalization of the deflections implies linear pavement response and therefore should be used with care.

The reproducibility of the measurements, that is the consistency of the measured deflections between different FWDs, has also been studied [van Gurp *et al.*, 1992; Ferne, 1990]. It appears that there exists an good level of agreement between equipment of various manufacturers despite the differences in the mode of the applied load pulse.

4.7 Summary

The FWD and its associated testing procedures have been developed on an empirical basis and they have received considerable interest worldwide. Both researchers and highway agencies have used the FWD in evaluating the structural condition of existing pavements. This chapter has presented the FWD and ancillary testing as an integral part of both the evaluation procedure and the development of the KBS.

FIGURES

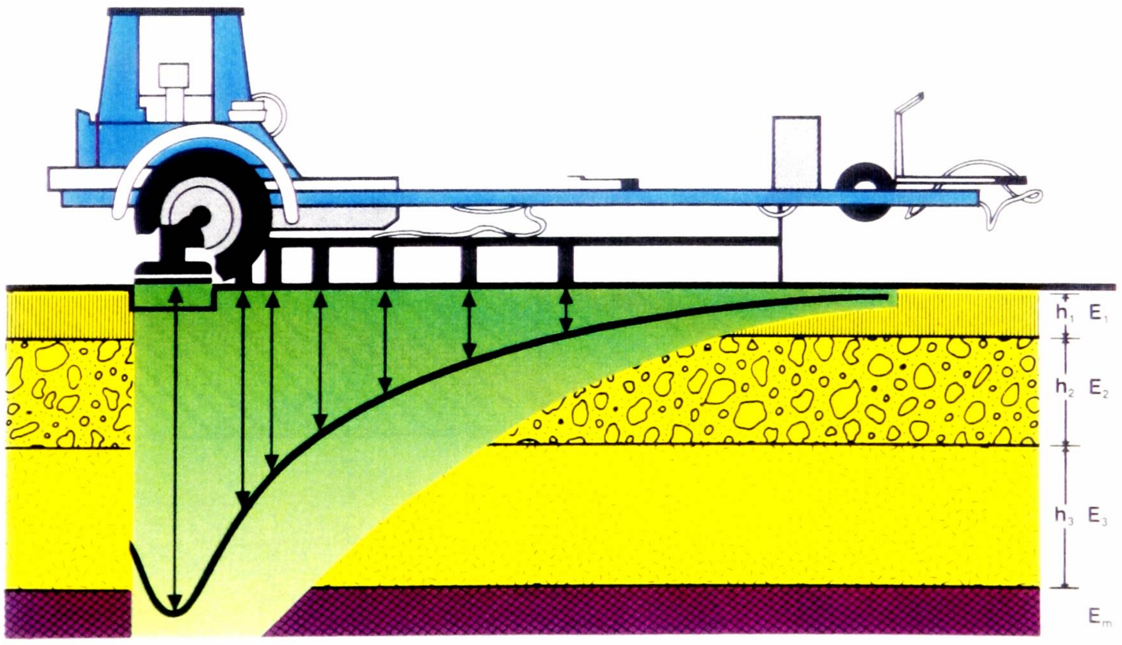

Figure 4.1: The DYNATEST 8000 Falling Weight Deflectometer.

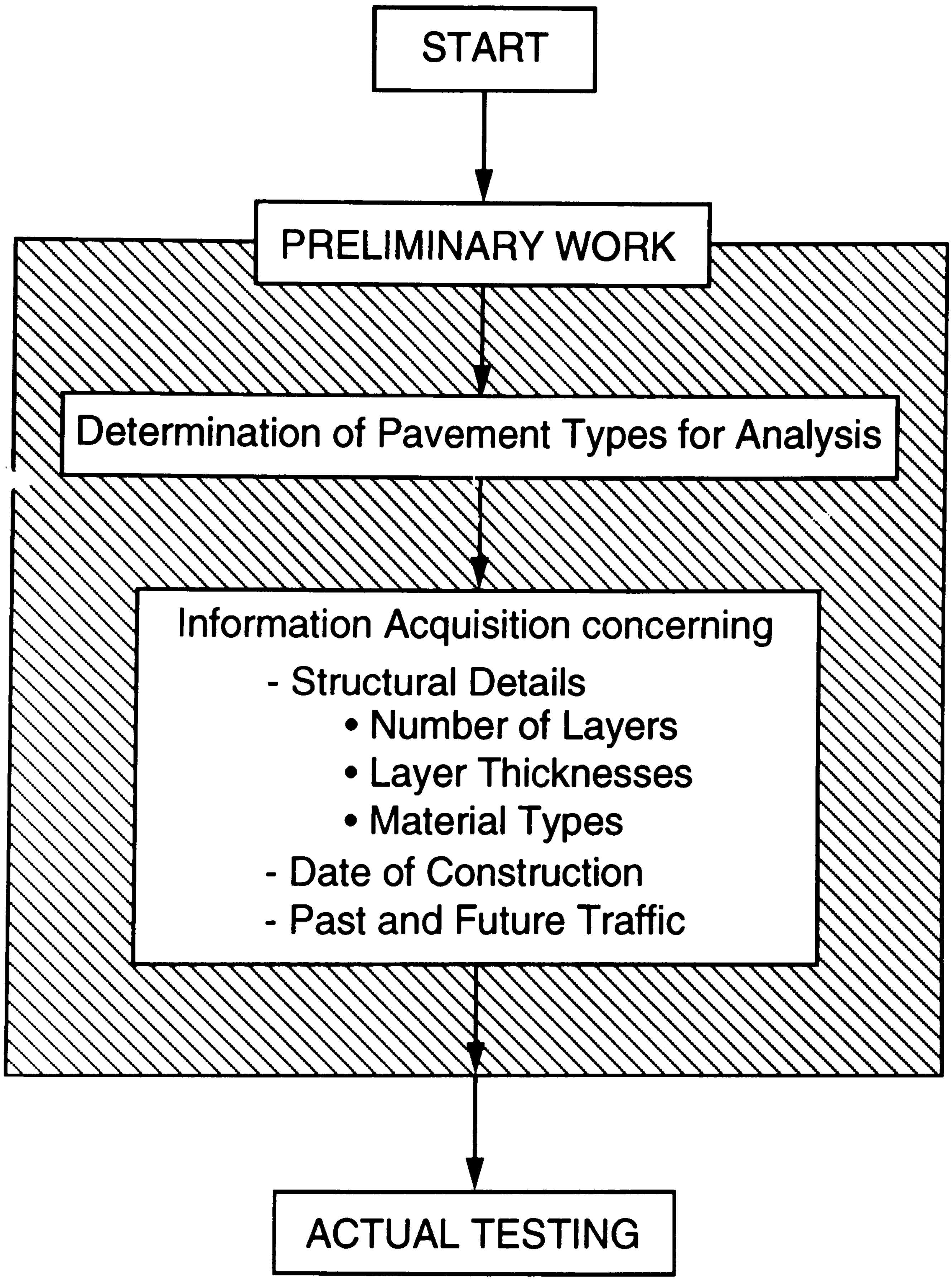

Figure 4.2: Field Testing Procedure-Preliminary Work.

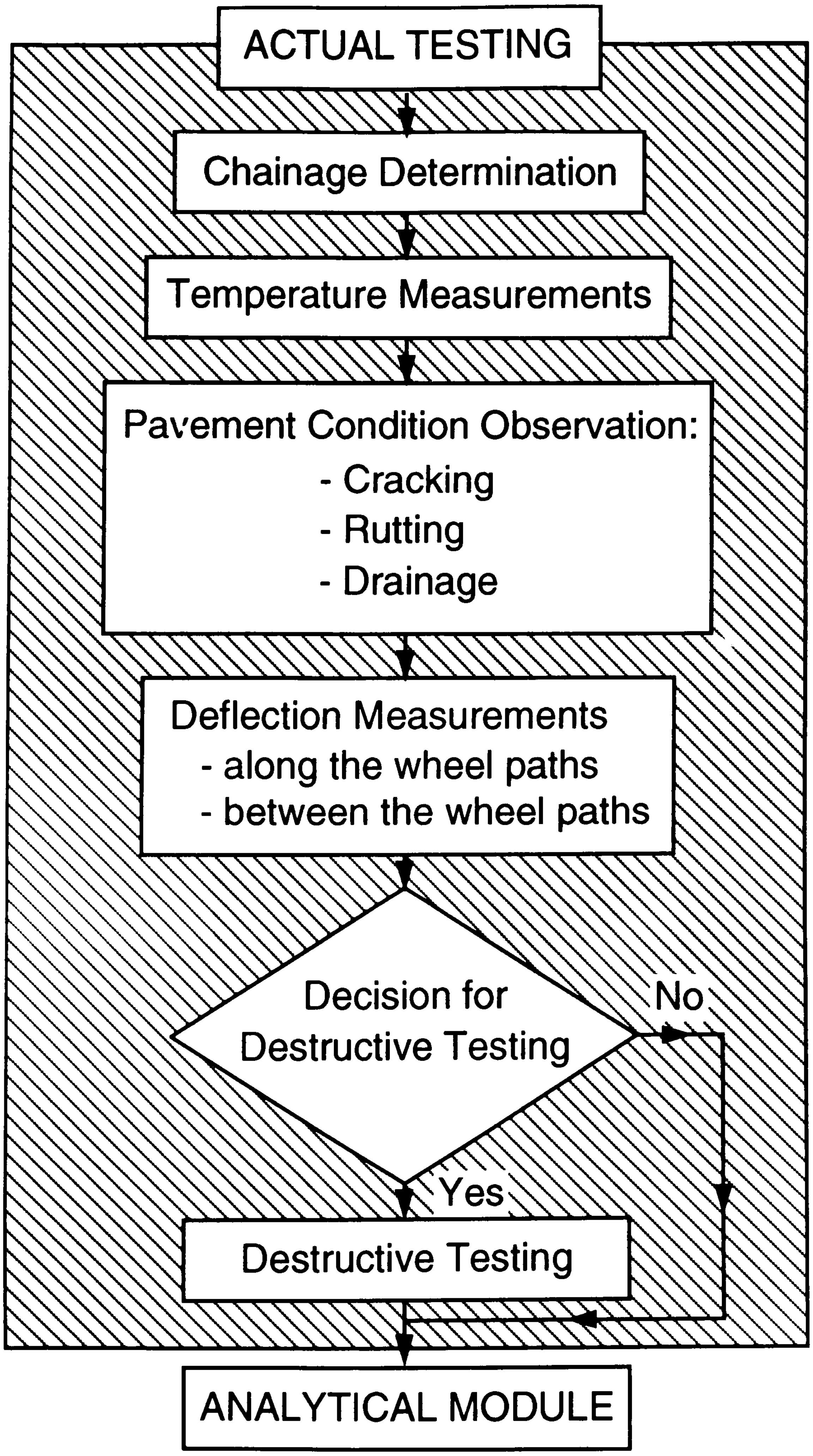

Figure 4.3: Field Testing Procedure-Actual Testing.

TABLES

Table 4.1: Classification of the Road Condition in Relation to Cracking and Rutting [After Kennedy *et al.*, 1978].

Classification	**Code**	**Visible evidence**
SOUND	1	No cracking. Rutting under a 2 m straightedge less than 5 mm.
	2	No cracking. Rutting from 5 mm to 9 mm.
CRITICAL	3	No cracking. Rutting from 10 mm to 19 mm.
	4	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 19 mm or less.
FAILED	5	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 19 mm or less.
	6	No cracking. Rutting 20 mm or greater.
	7	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 20 mm or greater.
	8	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 20 mm or greater.

Chapter 5

THE ANALYTICAL MODULE

5.1 Introduction

The analysis of the data collected in the field is a discrete part of the KBS under development. The analysis is carried out by a computer program ideally having the following characteristics:

1. The program should simulate the pavement with the highest possible accuracy.

2. The program should be able to model the behaviour of any multi-layer structure consisting of materials likely to occur in the field.

3. The program should have the ability to take into account the loading characteristics of any non-destructive testing device.

4. It should be sensitive to the nature of the materials (i.e. to temperature for bituminous materials, and to non-linearity and moisture content for granular materials).

5. It should have the ability to calculate deflections, strains and stresses at critical locations within the pavement structure.

6. The program should be calibrated to the surface deflection bowl whilst the modulus of the layers should range within rational limits.

7. The program whilst providing accurate and reliable results as noted above, should have a short run time and be user-friendly.

The purpose of this chapter is to assess a selection of such analytical programs for possible incorporation into the KBS.

5.1.1 Computer Programs Considered

Several computer simulation models have been developed and used by highway researchers. These differ in theoretical approach and sophistication. The majority of them are based upon relatively simple elastic solutions of layered systems whilst there are a few models which have used principles of plasticity, viscoelasticity and even of fracture mechanics [Monismith, 1987]. Generally, these latter approaches are more complex and as a result are less used. In addition they are not suitable for routine analysis [Monismith, 1980]. Consequently, it was felt that elastic solutions may provide the optimal computational basis within the KBS but more complicated modelling such as that of stress-dependent modulus of granular materials should not be excluded.

However even within this simplified process various problems do exist such as:

1. The non-uniqueness of the layer moduli back calculated from the measured deflection bowls.

2. Errors due to variation in thickness of pavement layers.

3. Errors involved in assuming a semi-infinite subgrade.

4. Errors due to the non-linearity of pavement materials.

5. Errors due to inaccuracies in determining the input values (i.e. layer moduli) used in the analytical model.

6. The time involved in the iteration process.

These problems have been long appreciated together with the requirement for a comprehensive system that facilitates pavement structural evaluation. Their consideration has led to the development of the KBS.

In this work the analytical programs studied are based on multi-layer elastic analysis and can compute the pavement response. Each is described and compared. The programs are:

1. DEFMET.

2. DEFPAV.

3. PAFEC.

DEFMET is a multi-layer elastic analysis program based on Boussinesq's theory using a procedure developed by Ullidtz and Peattie, [1982; 1981; 1980] whilst DEFPAV [Snaith *et al.*, 1980] and PAFEC, [1984] are finite element programs.

The aim of this comparative analysis is to investigate whether these programs may be used in the development of an analytical process for incorporation into the KBS, described in Chapter 2, so that a determinate solution of layer moduli may be obtained.

5.1.2 The Pavement Model

Successful verification of the simulation models will enable the user to accept the results of the analysis with more confidence. To this end, it has been stated that the best method of testing computer programs is to compare the computer analysis with deformation parameters such as deflections measured in the field [Abdelmigid, 1975]. Another approach is to use two or more programs to analyze a particular problem. Both approaches are used in this study.

The pavement used was a 20-metre test length of the Hillsborough By-pass in Northern Ireland [Snaith *et al.*, 1980]. As the pavement was tested with the Benkelman Beam, only the central point, or axial, deflection was considered in the back analysis procedure. However, despite the apparent weakness of this deflection measurement method, as opposed to the FWD measuring technique, it had already been shown to be a reasonable pavement to model and considerable data were available for it.

The details of the pavement structure are given in Table 5.1. The loading details are given in Table 5.2.

5.2 The Computer Program DEFMET

5.2.1 Description

The computer program DEFMET is based on the Method of Equivalent Thickness. For any computation the following data are required:

1. The field testing technique (i.e. Benkelman Beam, FWD or Road Rater).
2. Applied Load (in kN).
3. Number of pavement layers (max 10).
4. Thickness of each layer (except the final subgrade layer).
5. Poisson's ratio of each layer.

6. Elastic Modulus of each layer.

7. Calibration factors (to be used in the determination of the equivalent thickness so that a better agreement with the elastic theory may be achieved [Ullidtz, 1987]).

With these data the program calculates the deflection bowl of the pavement under the given loading and this is known as "Forward" analysis.

The program can also be used in "Backward" analysis mode. In the "Backward" analysis mode the layer moduli are not specified; rather the deflection bowl is provided and the modulus of each layer is computed therefrom.

Further details of the program may be found elsewhere [Rendel, Palmer and Tritton, 1987]. However, it should be noted that certain calibration factors (see above) were determined from field observations in Malaysia [Snaith, unpublished] which are not necessarily generally applicable.

5.2.2 Sensitivity Study

A brief sensitivity study has been carried out on the three-layer pavement model mentioned in section 5.1.2 to determine the effect of changes in modulus and Poisson's ratio of the various layers on the surface deflection. It was assumed that a constant modular ratio of 2.5 existed between the subgrade and the granular layer.

Table 5.3 shows the changes in the axial deflection of the pavement model with the variation of the elastic modulus (E_1) assigned to the surface layer. Table 5.4 gives the variation of the axial deflection with the variation of the values of E_2 and E_3 and Table 5.5 with the variation of the Poisson's ratio assigned to the three layers. The range of the values varied was selected to approach realistic values found in pavement analysis with the actual value increased and decreased by a factor of two in the case of the moduli. In the case of the Poisson's ratio a mean value of 0.35 was considered for all the layers. This was decreased and increased by units of 0.05.

Tables 5.3 to 5.5 demonstrate that when a pavement is analyzed by DEFMET the computed deflections are controlled principally by the elastic modulus of the first layer (surfacing). The variation of both the elastic moduli assigned to the granular layer and the subgrade, and the Poisson's ratio of each of the layers have only a negligible effect on the central deflection.

Thus, Table 5.3 indicates that a decrease in E_1 by 50% results in almost double the deflection. An increase by the same percentage results in 64% reduction in the deflection value. In addition, Tables 5.4 and 5.5 suggest that the program does not exhibit the same sensitivity either to a variation of E_2 and E_3 or to changes of ν_1, ν_2 and ν_3. In this case, the variations in the computed central deflection are less than 5% whilst those of the elastic parameters E_i and ν_i range from 25% to 200% and 43% to 129% respectively.

5.2.3 Conclusions

Consideration of the solutions provided by DEFMET implies that the program underestimates the importance of the granular and the subgrade layers to support loads, whilst the modulus of the surfacing may be overestimated. Thus it was concluded that the analysis carried out by DEFMET using the Malaysian calibrations was not suitable for this work.

5.3 The Computer Programs DEFPAV and ROSTRA-1

5.3.1 Introduction

The computer program DEFPAV was produced by Kirwan and Snaith, [1975] as the successor to the program DYNASTCO [Kirwan *et al.*, 1969]. The program has been extensively used in the past for the establishment of an analytical procedure of pavement structural analysis based on Deflectograph and Benkelman Beam deflection bowls [Snaith *et al.*, 1980]. However, in the light of the use of the FWD in pavement structural evaluation and the development of the KBS, the capabilities of the program had to be reconsidered. As a consequence, a further derivative has been produced entitled ROSTRA-1 (ROad STRuctural Analysis - 1).

This section presents both a brief description of the facilities provided by the program DEFPAV and a sensitivity analysis which was carried out to investigate its capabilities for the task in hand. Thereafter, the additional features of the new program ROSTRA-1 are delineated together with a comparison with DEFPAV.

5.3.2 Description

The computer program DEFPAV is a finite element program for the analysis of multi-layer pavement structures. In addition to computing elastic stresses and deflections under a circular load, it can be used to predict the permanent deformation profile of a pavement surface after any specified number of wheel passes.

The latest version of DEFPAV is known as "The Option Version". It incorporates two options which enable the user to decide whether to specify a finite element grid or to use one which was generated automatically. Thus, the two options available are:

1. The Automatic Grid Generation Option.

2. The Grid Specification Option.

5.3.3 The Automatic Grid Generation (Engineer's) Option

This option is designed for use by those with no experience of the finite element method. To enable this, a number of sophistications to the grid selection process are built into the program. The number of element rows in each layer is fixed and the horizontal dimensions of the elements are fixed as a function of the radius of the loaded area. As there are only 225 nodes available in the latest version, the resultant grid is not always ideal, particularly when there are a large number of layers. To minimize these effects, the number of pavement layers which may be modelled are limited to five.

5.3.4 Sensitivity Study

The sensitivity of the program to variations in the elastic modulus and Poisson's ratio of each layer has been investigated. Tables 5.6 and 5.7 show the changes in the axial deflection as E_1, E_2 and E_3 vary. Table 5.8 shows the changes in the axial deflection with the variation of ν_1, ν_2 and ν_3. (In this sensitivity study where the concerned parameter increased, the variation is shown as positive and conversely where the concerned parameter decreased from the "standard" value the variation is shown as negative.)

It can be seen that whilst the program is sensitive to the variations of the moduli assigned to each of the different layers, the dominant parameters are the modulus and Poisson's ratio of the surfacing. Variations in the Poisson's ratio of the granular layer and of the subgrade have a negligible effect on the computed axial deflection.

The sensitivity of the solution to variations in layer thickness has also been investigated. Table 5.9 shows the results of this study. It may be concluded that the axial deflection is sensitive only to variations in the thickness of the surfacing whereas it is not significantly affected by changes to the thickness of the granular layer.

5.3.5 The Grid Specification (Research) Option

This option of DEFPAV allows the user to specify the finite element grid although, it should be noted, the limitation of the 225 nodes still exists. The user is able to allocate the number of element rows to each layer. This enabled a study to be made of the effect of extending the overall width and depth of the finite element grid. The results of this study may be seen in Tables 5.10 and 5.11. For the Hillsborough Test Site pavement it is clear that the solution is not significantly affected either by extending the depth or the width of the grid beyond that of the engineer's version.

To investigate any possible difference in the solution provided by the Grid Specification Option, a significantly different grid from that provided by the Automatic Grid Generation Option was used to model the same pavement structure. It was found that the solution was considerably affected by the grid and in the design example resulted in higher deflection values. Table 5.12 presents the results of this study.

5.3.6 Non-linear Model

DEFPAV provides a facility that enables the user to input non-linear stress-strain characteristics for any structural layer. The effects of non-linear modelling on the calculated deflected shape have been investigated. For the pavement model, for which structural details are given in Table 5.1, the stress dependent moduli assigned to the granular layer and the subgrade are given in Tables 5.13 and 5.14 [After Snaith *et al.*, 1980]. The results of this investigation are shown in Table 5.15. It can be seen that the calculated deflections by the non-linear model are considerably different from those of the linear model and overcome the apparent problem of negative deflections at distances greater than, say, 0.90m which whilst theoretically correct for subgrades with Poisson's ratio approaching 0.50, are rarely seen in practice. The computation time compared with that of the linear model is essentially the same. Hence, it may be concluded that it is advisable to use non-linear material characterization when it is well-documented as this will enhance the solution.

5.3.7 Conclusions

There was reason to believe that DEFPAV was a powerful tool for pavement analysis. However it was felt that the program had to be modified to overcome the apparent shortcomings by increasing the number of elements. This would allow further refinement to the grid selection using the following rules:

1. The number of elements in the subgrade was increased.

2. The automatic grid generation was altered to enable deflection, stress and strain calculations at the FWD geophone positions.

3. The number of pavement structural layers to be modelled was increased.

To this end, a new program called ROSTRA-1, based on the DEFPAV algorithms, was developed. Its facilities are presented in the following subsection.

5.3.8 The Features of the Computer Program ROSTRA-1

The main changes included into the computer program ROSTRA-1 are listed below:

1. Expansion of the grid size.
2. Incorporation of a strain calculation routine.
3. Incorporation of two further automatic grid specification options suited to the two FWD geophone configurations being used.

Taking these and discussing them in further detail:

1. Expansion of the grid size.

   The size of the grid has been expanded to cope with a maximum of 500 nodes. As a consequence, when the grid specification option is used, the maximum number of element rows (or pavement layers) that may be modelled is 40. Otherwise, if an automatically generated grid is used, the maximum potential number of the structural layers that may be modelled is set to 10. However, it appears unlikely that any pavement model would consist of more than 10 layers and therefore the limitation of 500 nodes may be considered satisfactory.

2. Incorporation of a strain calculation routine.

   The latest version of DEFPAV did not provide any strain calculation. This was not very helpful when an element of the remaining life of the pavement was to be calculated as a function of the strain. Therefore, it was decided that the new program should have an appropriate routine for the calculation of strains. The formulae used are [Britto *et al.*, 1987]:

$$\varepsilon_1 = \frac{\sigma_1 - \nu(\sigma_2 + \sigma_3)}{\mathrm{E}} \tag{5.1}$$

$$\varepsilon_2 = \frac{\sigma_2 - \nu(\sigma_1 + \sigma_3)}{\mathrm{E}} \tag{5.2}$$

$$\varepsilon_3 = \frac{\sigma_3 - \nu(\sigma_1 + \sigma_2)}{\mathrm{E}} \tag{5.3}$$

$$\varepsilon_4 = \frac{2\ (1 + \nu)\sigma_4}{\mathrm{E}} \tag{5.4}$$

where:

ε_1, ε_2, ε_3	are the direct strains in the x, y, and z direction of a Cartesian system of coordinates respectively
ε_4	is the shear strain in the same system
$\sigma_1, \sigma_2, \sigma_3$ and σ_4	are the corresponding stresses
E	is the modulus
ν	is the Poisson's ratio.

3. Incorporation of two further automatic grid specification options suited to the two FWD geophone configurations being used.
   In order to facilitate the computations of deflections, stresses and strains at the radial distances where the deflections are usually measured during FWD testing, two routines have been added to the main automatic grid generation procedure. The user is now able to select two other grid options, if required. Option "2" corresponds with deflections measured up to 3.30 m at 0.30 m intervals, suitable for the Dynatest [1992] FWD. Option "3" may be used if the deflections are measured at 0.00, 0.21, 0.31, 0.51, 0.81 and 1.27 m. The options "0" and "1" are still valid and may be used either for routine Deflectograph and Benkelman Beam based analysis, or research purposes respectively. However, it should be noted that the automatic

grid generation routines create three rows per layer, unlike DEFPAV which allocated four rows per layer. This change was considered necessary for two reasons:

(a) In conjunction with the maximum number of nodes permitted and the necessary width of the grid, it provides more versatility to pavement modelling.

(b) It appears that the deflections computed are more consistent with those found when the research option is used.

Extracts from the output of ROSTRA-1, showing the features of the new program, may be found in Appendix A.

5.3.9 DEFPAV and ROSTRA-1 Comparison

To investigate differences between DEFPAV and ROSTRA-1, a brief comparison, based on the Hillsborough Test Site data, was carried out. The findings are presented in Table 5.16. It may be seen that the analysis carried out by ROSTRA-1 has resulted in higher deflection levels which are closer to those found when the grid specification (research) option was used. This may be attributed to the differences in the grid formulation and to the increased number of elements. Moreover, the apparent disagreement between the deflections computed by the two programs should be considered in the context of the accuracy provided by the Finite Element Method. Thus, the development of the new grid generation routines sought to satisfy the guidelines given below:

1. It has been stated [Zienkiewicz *et al.*, 1977], that the accuracy of any finite element program may be maximized if a suitable number of elements is assigned to locations of the model, which represents the actual structure, where the maximum strain energy density is found. The number of elements required could be estimated using a trial-and-error procedure. Also, for a

pavement model the region of high energy density is located in the vicinity of the loading plate.

2. The subgrade contribution to the resultant deflection bowl is considerable and therefore the number of elements allocated to this layer should be sufficiently large to take into account the stress gradient expected within it.

In conclusion, it appears that the program ROSTRA-1 has a better performance than DEFPAV, as the deflections computed by the new automatic grid generation options are closer to those found by the research option which is user-controlled and therefore may be considered more accurate when operated by a skilled engineer.

5.4 The Computer Program PAFEC

5.4.1 Introduction

PAFEC is a multi-task finite element structural analysis package. It has been used with some success for analyzing pavements by other researchers [Brooker *et al.*, 1987] and hence it was felt appropriate to investigate its performance against that of ROSTRA-1 and DEFMET. The apparent advantages in its use over ROSTRA-1 are:

1. There is no limitation to the number of elements available for the finite element grid.

2. Different types of elements other than that used by ROSTRA-1 are available (e.g. eight-noded quadrilateral, six-noded triangular, bar elements and others that might be useful).

3. The program provides facilities for automatic plotting of stress contours and displacements.

The following sections provide a description of the main program features together with an analysis of the Hillsborough Test Site data to determine its ability to model field performance accurately.

5.4.2 Description

Like ROSTRA-1, PAFEC may be used in axisymmetric mode. The grid may be established by dividing up the pavement to be modelled with representative blocks within which the program creates the appropriate mesh. The wheel load is simulated by a uniform stress over a circular area. The boundary conditions are set so that the lateral boundaries are restrained horizontally, whilst the base of the model is restrained in both horizontal and vertical directions (see Figure 5.1). Elastic modulus and Poisson's ratio are specified for each layer. An extract from a typical input data file is given in Appendix B.

5.4.3 Sensitivity Study

A study has been carried out to assess the sensitivity of the computed deflection bowl to variations in the following parameters:

1. The overall width and depth of the pavement model.
2. The element type (i.e. eight-noded quadrilateral or six-noded triangular).
3. The number of elements for the same overall grid dimensions.
4. The Elastic Modulus and Poisson's ratio assigned to each layer.

Tables 5.17 to 5.23 show the results of this study which may be summarized as follows:

1. The overall dimensions of the finite element grid affect the computed deflections. Any increase in the dimension either of depth or of width increases the deflection (See Table 5.17).

2. The element type has no effect on the computed deflections (See Table 5.18).

3. The number of elements does not influence the deflection. However, when careful account of the stress gradient is taken the apparent accuracy is improved (See Table 5.19).

4. The thickness of all the layers affects the calculated deflections and thus should be determined with reasonable accuracy (See Table 5.20).

5. From the variation of the axial deflection with the variation of the moduli of the layers and the Poisson's ratios, it becomes apparent that any significant variation in the structural parameters of either the surface layer or the subgrade influences the final result. For this reason, these values should be determined with considerable care (See Tables 5.21 to 5.23).

5.4.4 Conclusions

The capabilities of the computer program PAFEC have been investigated. The program proved to be very powerful but unsuitable for routine analysis of pavement structures due to:

1. The long familiarization time with the package.

2. The considerable computation time.

3. The lack of output readability.

However it is a suitable tool for detailed analysis of a pavement structure particularly to yield:

1. A detailed analysis of a cracked pavement.

2. A plastic analysis.

3. A detailed analysis of cement concrete slabs.

4. A dynamic solution.

5. A creep solution (as with ROSTRA-1, this is enabled if an appropriate creep equation is provided).

Input files for the above solutions can be found in Appendix B.

5.5 Conclusions

As a result of this work it is clear that each program has certain advantages in, for example, its apparent accuracy or speed of computation. However, the selection of the optimum analytical tool should be based on the degree of the sophistication which characterizes the program in conjunction with the necessity for such a sophistication. The ease in the formulation of the pavement model and its calibration should equally be considered.

With respect to the above factors it appears that PAFEC despite its marginally better performance compared to ROSTRA-1 and DEFMET, is unsuitable for the development of the KBS because of its considerable complexity. Furthermore, DEFMET seems to be incapable of analyzing pavements with sufficient accuracy. However, for the standard pavement subjected to a loading representative of an FWD, ROSTRA-1 performs adequately i.e.:

1. It enables a relatively easy formulation of any pavement model.

2. It converges quickly to a given measured deflection bowl.

3. The values determined by back analysis and subsequently used to characterize material properties are in good agreement with those reported by many researchers.

Therefore, ROSTRA-1 was incorporated into the analysis system outlined in Chapter 2, although it should be appreciated that there are marked differences in the product of different programs even of the same general type (e.g. between PAFEC and ROSTRA-1), and the effect of this on the performance of the overall system should not be ignored.

FIGURES

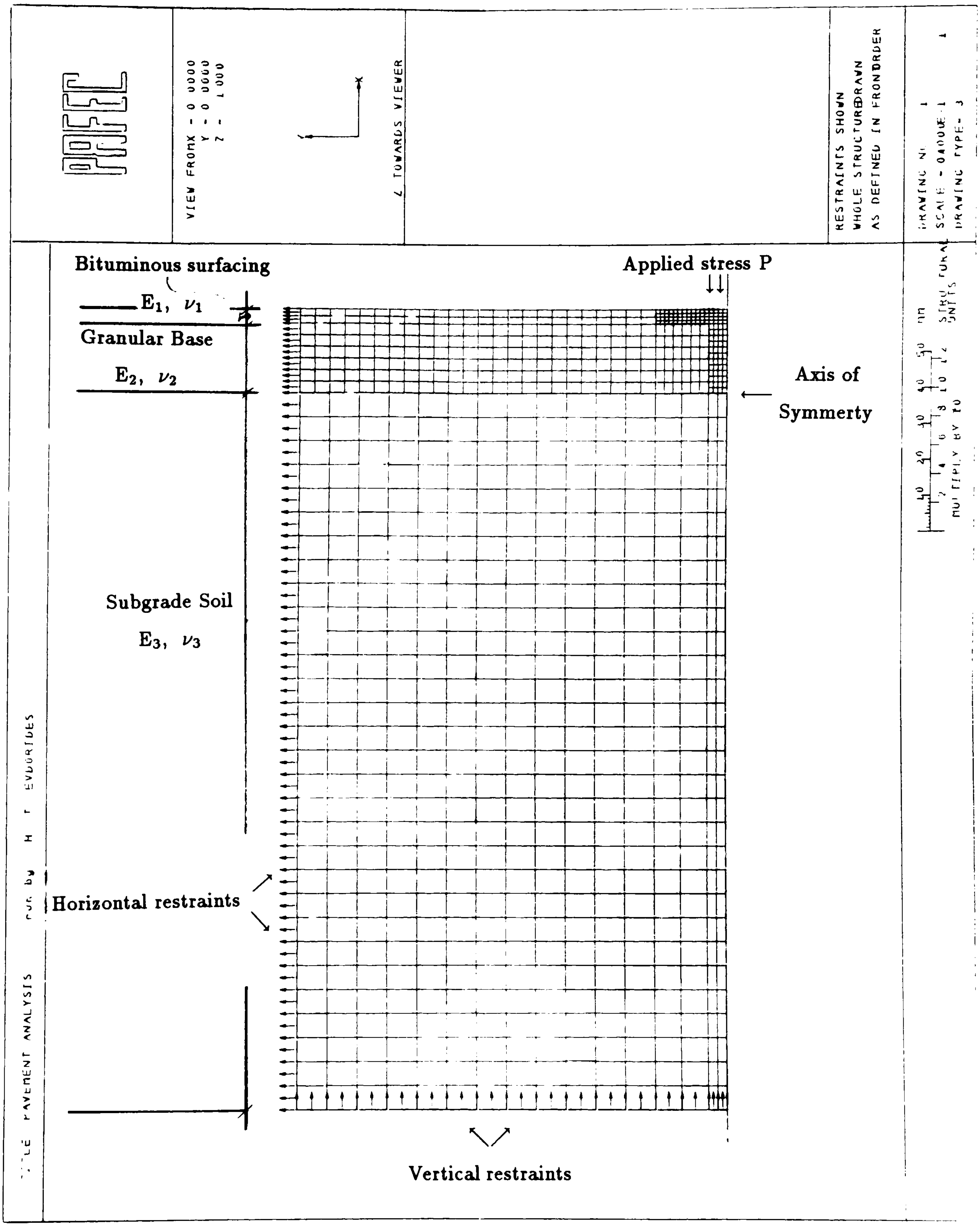

Figure 5.1: PAFEC Finite Element Grid Used for Analysis.

TABLES

Table 5.1: The Structural Characteristics of the Three-layer Pavement Model Used in the Comparative Study [After Snaith *et al.*, 1980].

Layer No	Material Type	Thickness (mm)	Young's Modulus (MPa)	Poisson's ratio
1	Bituminous	100	2500	0.4
2	Granular	485	31.25	0.3
3	Subgrade	∞	12.5	0.45

Table 5.2: The Loading Details of the Pavement Model [After Snaith *et al.*, 1980]

Wheel Assembly	Single
Contact Pressure	590 kN/m^2
Tyre loading	3175 kg
Radius of loaded area	130 mm
Required deflection	570 microns

Table 5.3: Variation of the Axial Deflection Computed by DEFMET with the Variation of the Modulus of the Surfacing Layer.

Elastic Modulus E_1 (MPa)	Variation %	d_0 (microns)	Variation %
1250	25	1050	+185
2500	50	580	+98
5000	100	283	0
7500	150	182	-46
10000	200	131	-64

Table 5.4: Variation of the Axial Deflection Computed by DEFMET with the Variation of the Modulus of the Subgrade Soil and of the Granular Layer.

E_3 (MPa)	E_2 (MPa)	Variation %	d_0 (microns)	Variation %
3.125	7.80	25	601	+4
6.25	15.625	50	594	+2
12.5	31.25	100	580	0
18.75	46.875	150	560	-4
25	62.5	200	527	-10

Table 5.5: Variation of the Axial Deflection Computed by DEFMET with the Variation of the Poisson's Ratio Assigned to the Layers.

Poisson's ratio	Variation %	d_0 (microns)	Variation %
$\nu_1 = 0.15$	43	617	+2
0.20	57	614	+2
0.25	71	609	+1
0.30	86	603	0
0.35	100	596	-1
0.40	114	588	-2
0.45	129	579	-4
$\nu_2 = 0.30$	86	586	0
0.35	100	588	0
0.40	114	587	0
$\nu_3 = 0.30$	86	580	-1
0.35	100	583	0
0.40	114	587	+1
0.45	129	588	0

Table 5.6: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Modulus of the Surfacing Layer.

Elastic Modulus (MPa)	Variation %	d_0 (microns)	Variation %
1250	25	990	+223
2500	50	567	+85
5000	100	306	0
7500	150	209	-32
10000	200	159	-48

Table 5.7: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Modulus of the Subgrade Soil and of the Granular Layer.

E_3 (MPa)	E_2 (MPa)	Variation %	d_0 (microns)	Variation %
3.125	7.813	25	636	+12
6.25	15.625	50	611	+8
12.5	31.25	100	570	0
18.75	46.875	150	537	-6
25	62.5	200	502	-12

Table 5.8: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Poisson's Ratio Assigned to the Layers.

Poisson's ratio	Variation %	d_0 (microns)	Variation %
$\nu_1 = 0.15$	43	775	+17
0.20	57	765	+16
0.25	71	746	+13
0.30	86	713	+8
0.35	100	660	0
0.40	114	570	-14
0.45	129	440	-33
$\nu_2 = 0.30$	86	570	-1
0.35	100	578	0
0.40	114	580	0
$\nu_3 = 0.35$	100	577	0
0.40	114	577	0
0.45	129	577	0

Table 5.9: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Thickness of the Structural Layers.

Thickness (mm)	Variation %	Axial Deflection (microns)	Variation %
Bituminous Layer			
50	50	1014	+78
75	75	703	+23
100	100	570	0
125	125	490	-14
Granular Layer			
242	50	581	+2
364	75	572	0
485	100	570	0
606	125	563	-1

Table 5.10: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Width of the Grid.

Grid Width (metres)	d_0 (microns)
2	568
3	598
4	593
5	592

Table 5.11: Variation of the Axial Deflection Computed by DEFPAV with the Variation of the Depth of the Grid.

Grid Depth (metres)	d_0 (microns)
1	558
2	567
3	567
4	568
5	568

Table 5.12: Variation of the Axial Deflection Computed by DEFPAV Between the Two Options Available in the Program.

OPTION	Number of Nodes	Deflections (microns)	Variation %
Automatic Generation	195	570	0
Grid Specification	224	787	+38

Table 5.13: Values of Stress-Dependent Modulus Assigned to the Granular Layer [After Snaith *et al.*, 1980].

M_r (MN/m^2)	103	137.3	171.5	205.8	240
σ_3 (kN/m^2)	0	35	70	105	140

(σ_3: minor principal stress)

Table 5.14: Values of Stress-Dependent Modulus Assigned to the Subgrade [After Snaith *et al.*, 1980].

M_r (MN/m^2)	30	25.5	21	16.5	12
σ_1 (kN/m^2)	20	30	40	50	60

(σ_1: major principal stress)

Table 5.15: Variation of the Computed Deflections by DEFPAV Due to Non-linear Modelling of the Granular Materials.

	Automatic Grid Option		Grid Specification Option	
Offset Distances (metres)	d_i Linear model (microns)	d_i Non-linear model (microns)	d_i Linear model (microns)	d_i Non-linear model (microns)
0.00	570	423	787	511
0.20	352	265	552	351
0.30	220	180	395	260
0.60	70	93	61	80
0.90	-20	8	-51	5

Table 5.16: Comparative Table Showing the Differences in the Computed Central Deflection Between the Computer Programs DEFPAV and ROSTRA-1.

Model Used	Axial Deflection d_0 (microns)
DEFPAV (Grid = 0)	580
DEFPAV (Grid = 1)	787
ROSTRA-1 (Grid = 0)	685
ROSTRA-1 (Grid = 1)	787
ROSTRA-1 (Grid = 2)	761
ROSTRA-1 (Grid = 3)	751

Table 5.17: Variation of the Axial Deflection Computed by PAFEC with Variation of Both the Depth and the Width of the Grid.

Grid Depth (m)	Axial Deflection (microns)	Grid Width (m)	Axial Deflection (microns)
2	1373	2	1369
3	1393	3	1392
4	1427	4	1415
5	1456	5	1441
7.5	1541	7.5	1473
10	1572	10	1521

Table 5.18: Variation of the Axial Deflection Computed by PAFEC with Different Element Types.

Element Type	Axial Deflection (microns)
8-noded quadrilateral	540
6-noded triangular	540

Table 5.19: Variation of the Axial Deflection Computed by PAFEC with Different Number of Elements.

Number of Elements	Axial Deflection (microns)
820	540
209	547

Table 5.20: Variation of the Axial Deflection Computed by PAFEC with the Variation of the Thickness of the Structural Layers.

Thickness (mm)	Variation %	Axial Deflection (microns)	Variation %
Bituminous Layer			
50	50	714	+32
75	75	618	+14
100	100	540	0
125	125	480	-13
Granular Layer			
242	50	791	+46
364	75	642	+19
485	100	540	0
606	125	442	-19

Table 5.21: Variation of the Axial Deflection Computed by PAFEC with the Variation of the Modulus of the Surfacing Layer.

Young's Modulus (MPa)	Variation %	d_0 (microns)	Variation %
1250	25	1886	+51
2500	50	1545	+24
5000	100	1246	0
7500	150	1093	-12
10000	200	989	-21

Table 5.22: Variation of the Axial Deflection Computed by PAFEC with the Variation of the Modulus of the Subgrade Soil and of the Granular Layer.

E_3 (MPa)	E_2 (MPa)	Variation %	d_0 (microns)	Variation %
3.125	7.813	25	3708	+154
6.25	15.625	50	2350	+62
12.5	31.25	100	1455	0
18.75	46.875	150	1090	-25
25	62.5	200	884	-39

Table 5.23: Variation of the Axial Deflection Computed by PAFEC with the Variation of the Poisson's Ratio Assigned to the Layers.

Poisson's ratio	Variation %	d_0 (microns)	Variation %
$\nu_1 = 0.15$	43	580	+5
0.20	57	557	+2
0.25	71	553	+1
0.30	86	550	+1
0.35	100	545	0
0.40	114	540	-1
0.45	129	533	-2
$\nu_2 = 0.30$	86	540	-1
0.35	100	546	0
0.40	114	553	+1
$\nu_3 = 0.35$	100	612	0
0.40	114	581	-5
0.45	129	540	-12

Chapter 6

ESTABLISHING THE KNOWLEDGE-BASED SYSTEM

6.1 Introduction

6.1.1 General

As stated in Chapter 2, KBS are computer programs which seek to perform tasks ordinarily carried out by human experts. The terms *Deductive Database Systems*, *Intelligent Knowledge-Based Systems*, *Expert Systems*, *Expert Database Systems* and *Expert Knowledge-Based Systems* are also used [Adeli, 1990; O'Shea *et al.*, 1987] and may be regarded as variants of the general term. In this study it was felt that the term *Knowledge-Based System* should be used because it appears to represent the actual computational behaviour of the programs more precisely than the others.

The information manipulated by computers may be regarded as either *knowledge* or *data*. Knowledge is information about general concepts [Wiederhold, 1986; Mylopoulos, 1986] and includes abstractions which imply logical processes. Data is information about specific instances which reflect the current state of reality. The fundamental differences between knowledge and data result in a different approach to both their representation and the design of either a knowledge or a data base. Thus,

> "any knowledge representation language must be provided with a (rich) semantic theory for relating an information base to its subject matter, while a data model requires an (effective) computational theory for realizing information bases on physical machines." [Brodie *et al.*, 1986]

6.1.2 The Declarative Nature of a KBS

Within a KBS, knowledge may be regarded as either *declarative* or *procedural.* The declarative form of knowledge representation is concerned only with the functions themselves, whilst the procedural is concerned with the order in which these functions are called [Bratko, 1990]. This is the key characteristic of a KBS which

> "allows knowledge to be represented explicitly, disentagled from the way it is used to solve problems by reasoning deductively in a manner which simulates human reasoning and which is congenial therefore to human thinking and to human-machine interaction. This means that compared with conventional software the new software helps us better to see the knowledge in an incremental fashion, because it is not tangled together with the manner in which it is used." [Kowalski, 1987]

Accordingly, the characteristics of a declarative language used for the development of a KBS may be summarized as follows [Oshuga, 1990]:

1. The knowledge is represented by units which are relatively independent of each other and consequently easy to modify.

2. Expressions may be stored in memory for direct use if required.

3. The information held by the knowledge base can be updated.

4. The information may exhibit a certain degree of uncertainty.

5. The speed of processing the information is lower than that of a procedural language.

These characteristics enable modelling of qualitative reasoning techniques. However, as the methods utilized are empirical and include heuristics (i.e. rules of thumb), the solutions obtained are not necessarily totally reliable [Buchanan *et al.*, 1984].

6.1.3 The Characteristics of a KBS

When knowledge is to be used in or by a computer program, then it is necessary to have a suitable representational form. The factors that influence this form may be considered as follows [Grant *et al.*, 1990; Liebowitz, 1989]:

1. The kinds of knowledge (e.g. numerical and non-numerical).

2. The medium available for the representation (e.g. computer software and hardware).

3. The operations to be used for the manipulation of knowledge (e.g. functions, logical procedures).

Heretofore, engineers have focused their attention on those aspects of knowledge that could be expressed in mathematical terms and hence manipulated by algorithms. However, recent advances in areas of Computer Science, such as Artificial Intelligence, Databases and Programming Languages [Bibel *et al.*, 1990], enable the representation of knowledge in words or sentences that may be acted upon by a logical process. Such knowledge representation and subsequent manipulation requires the development of systems which are based on a logical structure, such as KBS.

In effect, KBS are programs that encompass a combination of concepts, procedures and techniques derived from Artificial Intelligence research [Harmon *et al.*, 1988] which allow scientists and engineers to develop procedures that use knowledge in order to solve problems. Their most important characteristics may be summarized as follows [Liebowitz, 1989; Waterman, 1986]:

1. Predilection for problems that can be symbolically represented.

2. Ability to represent and manipulate domain-specific knowledge in a manner similar to that manifested by an expert.

3. Incorporation of explanatory mechanisms.

4. Ability to find a solution even though all the data may not be present.

It has been stated [Brachman *et al.*, 1986] that KBS may be examined from three different points of view. These are:

1. The *Symbolic Level* ; this level deals with how a computer views and processes the information held in the knowledge base.

2. The *System Engineering Level* ; this level deals with the design and other organizational aspects of a knowledge base.

3. The *Knowledge Level* ; that is the contents of the knowledge base.

This Chapter discusses both the Symbolic and the System Engineering Level of a KBS. Firstly, the fundamental features of a Knowledge Base are delineated. Thereafter, the basic concepts of knowledge modelling are discussed together with the inference mechanisms used for the manipulation of the encoded knowledge. The final item, the Knowledge Level of this KBS, is presented in Chapter 7.

6.2 The Modules of a KBS

Usually, a KBS consists of three main modules [amongst others, Bratko, 1990]. These are:

1. A *Knowledge Base.*

2. An *Inference Engine.*

3. A *User Interface.*

A Knowledge Base contains *knowledge* which is specific to an application domain and organized in a formal manner. An Inference Engine is a mechanism which is able to use that knowledge. A User Interface is the module which provides smooth communication between the system and its operator. The Inference Engine when taken with the User Interface could form a more comprehensive overall module known as a *Shell.* A schematic representation of a typical KBS may be seen on Figure 6.1.

In addition to these modules, a KBS may also be supported by other programs such as a subsystem for the acquisition of knowledge, a further database, a spreadsheet, and a statistical or a graphical package.

6.3 The Knowledge Base

6.3.1 The Components of a Knowledge Base

A knowledge base consists of two principal components [Grant *et al.*, 1990; Fox, 1990]:

1. Information of three types:
   (a) Facts encoded within the knowledge base (*extensional knowledge*).
   (b) A set of laws that describe the logical relationships between the facts (*intentional knowledge*).
   (c) A rule for ensuring consistency between different information sets.
2. *Integrity constraints* which provide information about the meaning (i.e. the semantics) of the data.

To represent both the facts and the logical relationships in a manner which is both descriptive and understandable, a number of symbols are used, such as:

1. Constants.
2. Variables.
3. Functions.
4. Punctuation (e.g. parentheses).
5. Predicates (i.e. procedures).
6. Connectives (e.g. $\neg$ (not), $\vee$ (or), $\wedge$ (and), $\rightarrow$ (implies)).
7. Quantifiers (e.g. $\forall$ (for all), $\exists$ (there exists)).
8. Equality.

The above symbols are common both in mathematical approaches, such as *propositional logic*, and programming languages (e.g. Prolog). When consistent relationships are established between theoretical symbols and those used by the syntax of a certain computer language, it is possible for the programmer to automate procedures of formal logic within the computer. Further information on the applications of logic to both knowledge bases and databases may be found elsewhere [Gallaire *et al.*, 1984 as quoted in Grant *et al.*, 1990; Kowalski, 1979; Thayse, 1988; Yager, 1990]. In this study, the formulation of the logical expressions to be used in the KBS, is briefly presented in Chapter 9.

6.3.2 Forms of Knowledge Representation

When knowledge is to be represented and used by a computer, it should fulfill certain requirements:

1. It should be based on a scientific structure (such as mathematical logic).
2. It must enable the expansion of knowledge through the accumulation of new facts and the relationships between them.
3. It should be able to model ambiguities included in the information.
4. It should enable the formulation of efficient procedures with respect to computational speed.

To this end a number of representational schemes have been developed. These include [Bratko, 1990; Bibel *et al.*,1990; de Salvo, 1989]:

1. Rule-based representation.
2. Frames.
3. Semantic Networks.

In rule-based systems the knowledge is represented as a set of rules. Each rule is, in its simplest form, a pair consisting of a condition and a conclusion (or action). Frames are data structures of objects, concepts or events whose components are clustered around them in a standard manner. Semantic networks are another type of knowledge representation by which knowledge is represented as a graph consisting of nodes and links.

Each of the above schemes exhibits particular advantages and disadvantages. Detailed explanation of them may be found elsewhere [Ramsey *et al.*, 1989]. However it is important to emphasize that none of the above forms provides on its own an accurate or effective means for modelling the variety of knowledge types and human reasoning mechanisms. This has led to the development of a few systems, known as Hybrids, which seek to exploit the advantages of the individual schemes by combining either two or all three into one system. However, given the present state of computer hardware and software these are not generally practicable and the rule-based knowledge representation has been used for the majority of the KBS developed to date.

6.3.3 Rule-based Representation

Rule-based systems were first proposed by Post [1943 as quoted in Davis *et al.*, 1984] as a general computational mechanism. Rules are logical structures which embody simple pieces of information. Their usage in a KBS may be viewed as a sequence of actions chained by principles of elementary logic [Davis *et al.*, 1984]. Rules are expressed as IF-THEN statements. Hence in the expression:

IF LHS (left hand side) **THEN** RHS (right hand side)

if the LHS is a collection of conditions that must be satisfied for the rule to be applicable, then the RHS contains the actions that must be taken.

Rules have been extensively used in the development of knowledge-based systems because they provide a simple, easy and concise way to represent knowledge [Golshani, 1990]. They permit the representation of knowledge in a highly uniform and modular way [Tzafestas, 1990], which is easy to understand and modify [Williams *et al.*, 1989]. Each rule may be considered independent of the others and as a consequence, rule-based KBS can be built in an incremental manner [Ramsey *et al.*, 1989].

6.3.4 Disadvantages of Rule-Based Systems

Despite the popularity and usefulness of the rule-based knowledge representation, such systems have been criticized [Buchanan *et al.*, 1984] on the grounds that they fail to express clearly:

1. Chance associations (i.e. information which, although it may be transformed into rules, cannot be justified either scientifically or empirically).
2. Definitions.
3. Descriptions.
4. Knowledge concerned with the classification of objects.

Some of the above obstacles may be overcome if another form of knowledge representation is used, such as frames. Ideally, as stated in Section 6.3.2, if more than one knowledge representational scheme could be combined, the resultant system would exhibit an enhanced behaviour. However, such an approach is the subject of ongoing research by Artificial Intelligence scientists. At present, it has been suggested [Buchanan *et al.*, 1984] that the incapability of rule-based representation to express fine distinctions between knowledge types may be mitigated by creating more specific rules. Consequently, in this study, it was felt that the rule-based representation could provide a concise, simple and efficient way in which the knowledge required by the task in hand could be encoded and remain compatible with the requirements of the KBS (cf. section 6.1.2).

6.3.5 Learning Procedures

It has been stated [Kodratoff, 1990; 1988] that the building blocks of any Artificial Intelligence technique and consequently those of KBS, are items of knowledge which are simple, explicit, clear, and comprehensive. These characteristics enable the simulation of learning procedures which may be categorized as follows [Tzafestas, 1990, Mitchell *et al.*, 1986]:

1. Learning from instruction.

2. Learning by analogy.

3. Learning from examples.

4. Learning by discovery.

5. Probabilistic learning.

Machine learning may be viewed as an independent research unit in the domain of Artificial Intelligence. Machine learning is usually regarded as the formulation of a rule which performs two tasks:

1. The explanation of the behaviour of a set of observed objects.

2. The categorization of new objects into the classes created by this rule.

Both the objects and the classes have to be specified in some descriptive language using formal theoretical approaches [Kodratoff, 1990]. The associated theory and examples of such systems may be found elsewhere [Bratko, 1990; Michalski *et al.*, 1986; 1983; Forsyth, 1989].

6.4 The Inference Engine

In conventional (algorithmic) programming it is advisable to understand the solution in order that the necessary programming may be effected, which implies a knowledge of both engineering and programming skills. Conversely, in KBS the knowledge is stored in a manner which is readily accessible by any expert, whilst the routines that use the knowledge are included in a separate module known as the *Inference Engine*. A direct advantage of such an approach is that the expert, with no programming skills, can validate, revise or update the contents of the knowledge base, whenever it is required.

The efficient development of a sound inference engine requires both professional skills in programming and also an understanding of logical reasoning processes. The difficulties involved may be solved, to some extent, by both commercially available inference engines known as *Expert System Shells* (cf. Figure 6.1 and Section 6.1.2), and languages specially developed for Artificial Intelligence applications like *Lisp*, *Prolog* and *POP-11* [Sloman, 1987]. This section does not present any further discussion on such issues because it is beyond the scope of this study. Rather, it focuses on some aspects of the capabilities required by an efficient inference engine.

6.4.1 Reasoning Mechanisms

As noted above reasoning is an integral part of the inference engine of a KBS. It would be expected that any such system would have the ability to build upon the knowledge which is held within the knowledge base. In addition, it would have the ability to provide explanations about "why" a certain piece of information is needed or "how" a particular conclusion was drawn. This it would do by employing one or more of the typical logical processes outlined below [Bibel *et* *al.*, 1990]:

1. Deduction : the process in which a conclusion about something may be reached due to other things which are known to be true.

2. Abduction : the process in which an explanation is given to an observation by finding facts which are not clearly symptomatic of the particular observation.

3. Induction : the capability to infer a general statement from a number of particular observations.

4. Evidential or Probabilistic reasoning : the ability to support a hypothesis on the basis of conditional probabilities.

5. Commonsense reasoning : the process which allows a conclusion to be reached without explanation by taking into account circumstantial knowledge.

There is considerable difficulty in converting such reasoning mechanisms into procedures used in or by a computer. Usually, in rule-based systems, the response of the system to the operator's "why" or "how" queries is reduced to a sequential presentation of the rules or facts which support the particular piece of information being processed [Bratko, 1990].

6.4.2 Rule Execution Ordering

The strategy for the selection and use of the most appropriate rule, can significantly affect both the efficiency of, and the conclusion reached by, a KBS. This selection strategy is called *conflict resolution* and consists of the following criteria [Davis *et al.*, 1984; Ramsey *et al.*, 1989; Tzafestas, 1990]:

1. *Recency.*

   The order in which the rules are included into the knowledge base affects the order of operation of the rules, giving priority to the most recent ones.

2. *Specificity.*

   The necessity for the more specific rules to be satisfied before the more general ones.

3. *Refraction.*

   A rule is not repeated on the same data.

However it should be noted that these criteria are not in accordance with the *declarative* style of knowledge organization (cf. Section 6.1.2) within the KBS. Hence, it may be seen that procedural aspects should not be overlooked by the developer of KBS (see also [Bratko, 1990]).

Generally, there are two important ways in which rules can be used in a knowledge-based system:

1. Backward chaining.

2. Forward chaining.

In backward (or goal-driven) chaining the aim of the system is to select the best choice from many possibilities. In forward (or data-driven) chaining the system keeps track of the developing solution and seeks the appropriate rules which will move it towards the final solution [Merrit, 1989].

6.4.3 Introducing Uncertainty

Considerable effort has been put into the task of establishing a method that would enable modelling of the various forms of imperfect, imprecise, incomplete or uncertain knowledge. To this end the following approaches have been utilized [Duda *et al.*, 1979; Hamburger *et al.*, 1989; Gordon *et al.*, 1984; Barclay Adams, 1984]:

1. Certainty Factors.
2. Probabilistic Reasoning.
3. Bayesian Theory.
4. Theory of Belief Functions (or Dempster-Shafer Theory).
5. Combinations of the above methods.

Models based on the above approaches have been implemented with some success in KBS. The most popular of the approaches has been the development of models that make use of certainty factors (CF) in conjunction with rule-based knowledge representation. These factors are considered as expressions which seek to encapsulate the degree of certainty for both the facts held within the knowledge base and that provided by given or concluded rules. Pearl, [1989] argued that only with a strictly mathematical model based on the theory of probabilities, would the dangers arising from oversimpification be avoided. However, other researchers have claimed that such an approach is impracticable for the following reasons [Bratko, 1990]:

1. It requires detailed information which may be unavailable.
2. The mathematical definition of the probabilities may not correspond to the conditions that result in their actual value.
3. The assumptions included in the theory may not be justified in a specific practical application.

It has been claimed [Buchanan *et al.*, 1984] that flexibility is the key factor in creating a system which behaves satisfactorily. When validating and explaining the performance of an early certainty model, Buchanan and Shortliffe [1984] pointed out that:

1. The CFs used in the model were subjective.
2. The CF model must be viewed as a set of heuristics for combining uncertainty and utility, and not as a calculus for confirmation theory.
3. Systems with categorical rules (i.e. systems without uncertainty modelling) can perform well.
4. When using certainty models, care must be exercised with the combination of CFs to ensure that adequate resolution is obtained between different CF values to enable distinctions between alternative solutions.

Nevertheless, there is considerable difficulty in drawing conclusions about the reliability of a particular certainty model, as the most complex model may not necessarily be the most accurate. However, it is clear that if inexact reasoning has to be used, then the certainty model should allow for fine distinctions to be made between the possible solutions.

6.5 The User Interface

There are a variety of user-computer interfaces available. They should be not only friendly but also consistent with the particular application they support. Hence, in order that the end-user can access all the built-in facilities of a KBS, it is necessary that the user-interface should be carefully designed and implemented. To this end a number of tools are available to the designer of an application user interface. The most commonly used are [Jones, 1989]:

1. Conversational input and output through the computer keyboard and terminal.

2. Text processing.

3. Natural language processing.

4. Computer graphics.

5. Images, icons and symbols.

6. Menus.

7. Windows.

These facilities, supported by programming languages, operating systems and other relevant packages, can create attractive user-interfaces. However an inappropriate user-computer interface may reduce the effectiveness of the system and even a well-constructed interface could not enhance the capabilities of the overall system. In conclusion, it seems that the most effective interface is the simplest one which helps the user both to avoid errors and to exploit the facilities of the system.

6.6 Summary

The development of a KBS should be made in a systematic manner. It is important that the fundamental building blocks of such a system are sufficiently understood to enable an appropriate development strategy.

In this chapter an attempt has been made to present the distinctive role and usage of KBS. Hence, it may be seen that a KBS differs from conventional programming as follows:

1. A KBS encodes *knowledge* rather than *data*.

2. The *knowledge* is separated from *inference* and indeed from the *user interface*.

Consequently, it has been clarified that an efficient system should consist of three modules as follows:

1. A Knowledge Base.

2. An Inference Engine.

3. A User Interface.

FIGURES

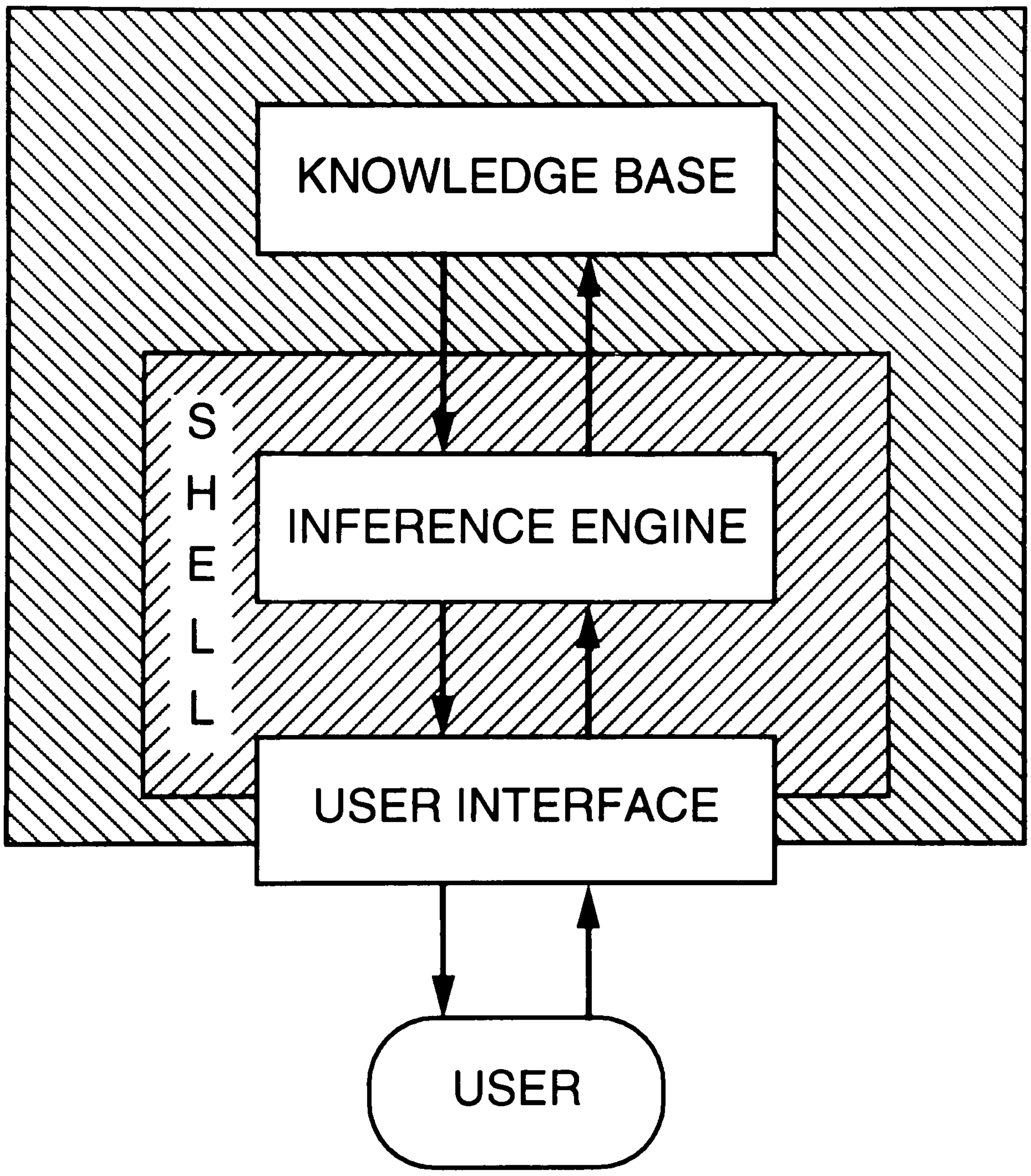

Figure 6.1: The Modules of a Knowledge-Based System.

Chapter 7

THE CONTENTS OF THE KNOWLEDGE BASE

7.1 General

It has been suggested [Gammack *et al.*, 1984] that in a relatively small technical domain such as maintenance and fault-finding on a mechanical system (e.g. a road pavement), a recognizable distinction may be made between the following kinds of knowledge:

1. Concepts and relations.

2. Routine procedures.

3. Facts and heuristics.

4. Classificatory knowledge (i.e. knowledge concerning fine distinctions between a number of similar items or making decisions on the appropriate test to employ for a particular purpose).

The following sections present such information organized into the three parts which make up the pavement structural evaluation procedure:

1. Field testing.

2. Analysis of the data collected in the field.

3. Establishment of the pavement distress model.

The objective of this chapter is to demonstrate that it is possible to develop a KBS to play an important role in the analysis of the FWD deflection bowl.

7.2 Field Testing

Field testing, other than that with the FWD, provides supplementary information to deflection data which permits the determination of the location of structural weakness of a pavement layer that could not be identified by the analysis of the deflection bowl alone. Table 7.1 [AASHTO, 1986] shows a general categorization of pavement distress types with their probable cause. The information in this table may be transformed into a rule-based knowledge representation. For example, for fatigue cracking the following rule may be formed:

If

  the *distress type* is *Fatigue Cracking*

then

  it is *primarily* caused by *Traffic Loading.*

However, unlike "*fatigue cracking*" the word "*primarily*" includes a certain degree of probability. Thus the above rule should be modified to become:

If

  the *distress type* is *Fatigue Cracking*

then

  it is caused by *Traffic Loading*

  with certainty 80%.

Similar rules could be written for all the types of distress.

Section 4.2.1 provides information that could lead to the formation of rules of a KBS. Table 7.2 presents the engineering knowledge together with the rules that might be established.

In addition, as noted in section 4.2.2, the classification of pavements given in Table 4.1 could be transformed into rules. Table 7.3 shows this transformation.

In conclusion, Tables 7.2 and 7.3 comprise the information required for the creation of a knowledge base which may assist the analysis by screening the moduli selected as input data to the analytical model by means of rules that represent empirically derived knowledge. The implied statements form the basis for the actual rules of the computer program.

7.3 Data Analysis

Quantitative information on the moduli and the Poisson's ratios of the paving materials is required for the analysis of the deflection data. When using linear elastic layered systems to analyze pavement structures tested in the field, each material is assumed to have a constant value of Poisson's ratio and modulus. To date emphasis has been given to the value of modulus since it provides a direct indication of the structural integrity of the individual layers. However the selection of an appropriate modulus in any analysis requires a number of assumptions with respect to the pavement materials, their condition and, indeed, their behaviour within the pavement structure (cf. Chapter 3).

The following sections present a collection of information on moduli and Poisson's ratios from the literature. This information will be fed into the KBS as data-driven rule representation. By this means it is hoped that a unique solution to the analysis of a pavement to fit a given deflection bowl will be possible.

7.3.1 Modulus of Bituminous Materials

As stated in Chapter 3 there are a number of different moduli used to characterize pavement materials such as the Young's Modulus, the Resilient Modulus and the Dynamic Modulus. Each type of moduli has been based on a particular testing procedure and associated theory. However, the overwhelming majority of analytical models developed are linear elastic systems that use the moduli derived from various laboratory tests (cf. Section 3.2). Although the use of different types of modulus does not change the analysis, it is felt that this approach may be regarded as a reasonable approximation. Consequently, the moduli presented herein will be used in the linear elastic variant of the program (ROSTRA-1) presented in Chapter 5 whilst the "E" will be associated with Young's Modulus which is used in elastic solutions.

Tables 7.4 and 7.5 present a collection of a wide range of bituminous materials moduli. These moduli have been derived from analyses of a variety of case studies carried out by many researchers. Thus, it is felt that their values may be used, with some confidence, as initial input data in the back-analysis process.

7.3.2 Modulus of Bound and Unbound Granular Materials

The nonlinear characteristics of unbound granular materials have long been appreciated and a number of complex procedures have been used to obtain a reasonable structural characterization. However there is a need for a simple means of estimating their modulus. To this end, two methodologies have been developed that try to model the nonlinear response of such materials [Witczak *et al.*, 1982]. These are:

1. A Modular Ratio approach.

2. The "$K - \Theta$" model.

Modular Ratio

It has been shown [Heukelom *et al.*, 1962 as quoted in Snaith *et al.*, 1980] that the modulus of the unbound granular layer E_2 depends on its thickness H_2 and the modulus of the underlying subgrade E_3 according to the relationship:

$$E_2 = k_2 \, E_3 \tag{7.1}$$

where

$$k_2 = 0.2 \, H_2^{0.45} \tag{7.2}$$

H_2 expressed in mm and $2 < k_2 < 4$.

In addition, it has been suggested [Snaith *et al.*, unpublished] that the granular layers of a pavement (i.e. base and capping layer) may be seen as behaving as a series of sublayers, each of 150 mm thickness, increasing in modulus with a modular ratio of two for each succeeding layer up to a maximum given for example by the relationship [Heukelom *et al.*, 1962]:

$$E \text{ (MPa)} = 10 \text{ CBR} \tag{7.3}$$

The "K − Θ" Model

The effects of stress on unbound granular materials may be represented by the following equation known as the "K − Θ" Model [Shook *et al.*, 1982]:

$$M_r = k_1 \theta^{k_2} \tag{7.4}$$

where:

M_r is the stress-dependent (resilient) modulus of the material defined by:

$$M_r = \frac{\sigma_1 - \sigma_3}{\varepsilon_a} \tag{7.5}$$

θ is the first stress invariant ($\theta = \sigma_1 + \sigma_2 + \sigma_3$)

σ_i are the principal stresses

ε_a is the vertical resilient strain

k_1, k_2 are coefficients determined by regression analysis.

If shear effects are taken into account [May *et al.*, 1981], Equation 7.4 could be transformed into [Uzan, 1985]:

$$M_r = k_1 \ \theta^{k_2} \ (\tau_{oct})^{-k_3} \tag{7.6}$$

where:

k_3 is a coefficient determined using regression analysis

τ_{oct} is the octahedral shear stress defined in the general case by:

$$\tau_{oct} = \frac{1}{9}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \tag{7.7}$$

In the triaxial test case, where $\sigma_2 = \sigma_3$, and $\sigma_d = \sigma_1 - \sigma_3$ (deviator stress), Equation 7.7 is reduced to:

$$\tau_{\text{oct}} = \frac{\sqrt{2}}{3}\,\sigma_{\text{d}} \tag{7.8}$$

The advantage of Equation 7.6 over Equation 7.4 is that it can model both cohesive and granular materials. As far as cohesive materials are concerned the modulus is assumed to decrease with increasing shear, whilst for granular materials the resilient modulus increases with increasing confinement.

Typical nonlinear material coefficients for the model of Equation 7.4 derived from laboratory testing are given in Table 7.6 [After Shook *et al.*, 1982], whilst those for the model of Equation 7.6 are presented in Table 7.7 [After Bonaquist *et al.*, 1992].

Tables 7.8 and 7.9 present moduli of granular materials that have been used by various researchers [Brunton *et al.*, 1992; Heleven *et al.*, 1987; Lehtonen, 1986; Powell *et al.*, 1984; Freeme *et al.*, 1987].

Approximate values for cemented materials may be found in Table 7.10 [Freeme *et al.*, 1987] and Table 7.11.

The use of either the moduli values obtained directly from Tables 7.8 and 7.9 or those derived from the empirical relationships 7.1 to 7.4, depends both on the adequacy of the documentation available for the characterization of the granular materials and the complexity required by the computer simulation of the response of the material to loading.

7.3.3 Modulus of Subgrade Soils

A number of methodologies have been developed for the determination of the modulus of the subgrade. However it was felt that for the purposes of the KBS, simple relationships had to be adopted. Thus, in order to allocate moduli to subgrade soil materials Table 7.12 may be used. It is a collection of CBR values proposed by Powell *et al.*, [1984]. The CBR values may be converted to represent moduli using the following formula [Powell *et al.*, 1984]:

$$E \ (\mathrm{MPa}) = 17.6\,(\mathrm{CBR})^{0.64} \tag{7.9}$$

where CBR is in per cent. This is a lower bound relationship used for values of CBR lying between 2 and 12%.

A similar formula has been developed by the National Danish Road Laboratory [Poulsen *et al.*, 1980, as quoted in Ullidtz, 1987]. This is:

$$E \ (\mathrm{MPa}) = 10\,(\mathrm{CBR})^{0.73} \tag{7.10}$$

Alternatively, the subgrade modulus may be related to its CBR value by equation 7.3. However Freeme *et al.* [1982] indicated that instead of a constant multiplier the following formula may be used:

$$E \ (\mathrm{MPa}) = \mathrm{k}\ \mathrm{CBR} \tag{7.11}$$

where the "k" value being itself a function of CBR as follows:

CBR (%)	k
15	8
10	9
7	10
3	15

A similar approach is followed by the Road Agency of New Zealand [S.H.P.D.R.M, 1987]. The CBR of a subgrade is related to its modulus according to the formulae:

$$\text{E (MPa)} = 20\,(\text{CBR})^{0.64} \quad \text{CBR} > 13\% \tag{7.12}$$

and

$$\text{E (MPa)} = 8\,\text{CBR} \quad \text{CBR} < 13\% \tag{7.13}$$

In addition, the stiffness of the subgrade soil (or granular materials) may be estimated with the Clegg impact tester (Clegg hammer) and the DCP. The measured values associated with these testing procedures may be further correlated with CBR values using empirically derived relationships.

For the Clegg impact tester values, the following formula may be used [Garrick *et al.*, 1985]:

$$\text{CBR}\,(\%) = 0.07\ (\text{CVI})^2 \tag{7.14}$$

where CVI is the Clegg impact value. Each unit of CVI is equivalent to ten gravities ($g = 9.81\ \mathrm{m\,s^{-2}}$) of deceleration. It has been suggested [Clegg, 1976] that for unsealed gravel roads, approximate CVIs of 30, 50 and 70 correspond to poor, average and good material performance respectively.

When the DCP penetration depth is measured, this may be correlated to CBR as follows [Harrison, 1987]:

$$\log(\text{CBR}) = 2.81 - 1.32\log(\text{D}) \tag{7.15}$$

where D is the DCP penetration depth measured in mm/blow. This relationship is valid for certain ranges of CBR for the material types given below:

Material Type	CBR (%)
Clays	2-17
Sands	17-45
Gravels	55-100

Thus, the calculated CBR values from Equations 7.14 and 7.15 could be further provide an estimation of the modulus of the materials tested, by means of the equations 7.3, 7.9, 7.11 and 7.13.

However, for the same CBR, the moduli derived from Equations 7.3, 7.9, 7.11 and 7.13 are significantly different. For example, for a soil with a CBR = 3% these relationships give moduli of 30, 35, 45 and 24 MPa respectively. This introduces an additional problem which has to be addressed by means of a further refinement of the KBS. In order that such obstacles may be overcome, it is necessary that the system should be extensively validated on a wide range of case studies.

7.3.4 Poisson's Ratio

Poisson's ratio is the other elastic parameter which is required in any elastic analysis. Unlike modulus, Poisson's ratio has not been the subject of intensive debate. Table 7.13 shows typical values which have been assigned to different materials.

If the system has detailed information about the materials of the structure under consideration, a certain value may be suggested based on previous work such as that shown in Table 7.13. Otherwise a default value will be inferred from associated information.

7.4 Structural Distress Model

In order that the system may predict the distress characteristics of a pavement, the traffic-associated structural distress model has to be established. It is usually divided into two parts:

1. Fatigue cracking in the bituminous layer.

2. Rutting.

In conventional design processes [Verstraeten *et al.*, 1982; Brunton *et al.*, 1987; Shook *et al.*, 1982; Monismith *et al.*, 1987; Lister *et al.*, 1987; Gerritsen *et al.*, 1987; Snaith *et al.*, 1980; Freeme *et al.*, 1982] each of these types of distress is related to:

1. The number of load repetitions to failure.

2. A critical strain.

The radial tensile strain at the bottom of the bituminous layer has been used as a criterion for limiting fatigue cracking whilst the vertical compressive strain at the top of the subgrade has been used as an overall criterion for limiting permanent deformation [Witczak, 1982]. Thus the relationship between the critical strains and the number of load applications to failure could be represented by one model:

$$N = A(\frac{1}{\varepsilon})^{b} \tag{7.16}$$

where

ε	is the critical strain
N	is the life in applications of standard axles associated with it
A, b	are coefficients depending on the type of distress and materials.

Using the damage model given by equation 7.16 the life associated with the particular damage model may be determined once the critical strain has been calculated by the pavement response model.

Table 7.14 shows a variety of different fatigue criterion models used by various investigators whilst Table 7.15 presents models of the deformation criterion. In addition fatigue criteria for cement treated materials are given in Table 7.16.

In the KBS, it is necessary to indicate the degree of certainty with which these damage models may be used. Thus the system should be able to select the solution with the highest possibility of success in the prediction of future life. Initially all the models should be considered. Subsequently, during the verification and validation of the system, those with the maximum degree of reliability would be identified and selected for further use.

7.5 Conclusions

Much knowledge has been accumulated for the analysis of pavement structures and for the development of models that estimate their future life. It appears, at least initially, that this knowledge is suitable to be converted into a KBS in the form of "IF-THEN" rules (cf. Section 6.3.3).

However the selection of the optimum approach with respect to the degree of its reliability, which is ordinarily made by the engineer who carries out the analysis, is a difficult problem. Consequently, in order to optimize the procedure the system will follow, it is felt that the rules should be clustered into homogeneous groups. That is, the rules should be identified by some kind of attribute such as their source (e.g. Shell's). Thus the program will move towards the "fine" solution avoiding unnecessary computations. In addition, explanatory mechanisms have to be developed to enable the user to understand how the solution provided by the KBS has been found.

TABLES

Table 7.1: General Categorization of Asphalt Pavement Distress [After AASHTO, 1986].

Distress Type	Primarily Traffic Load Caused	Primarily Climate/Materials Caused
Alligator or fatigue cracking	$\surd$	
Bleeding		$\surd$
Block cracking		$\surd$
Corrugation		$\surd$
Depression		$\surd$
Joint reflection cracking from PCC slab		$\surd$
Lane/shoulder dropoff or heave		$\surd$
Lane/shoulder separation		$\surd$
Longitudinal and transverse cracking		$\surd$
Patch deterioration	$\surd$	
Polished aggregate	$\surd$	
Potholes	$\surd$	
Pumping and water bleeding	$\surd$ (M, H)	$\surd$ (L)
Ravelling and weathering		$\surd$
Rutting	$\surd$	
Slippage cracking		$\surd$
Swell		$\surd$

M $\longrightarrow$ medium
H $\longrightarrow$ high
L $\longrightarrow$ low

Table 7.2: Engineering Knowledge and its Representation in the Knowledge-Based System - Field Testing.

Engineering Knowledge	Knowledge Representation	Certainty
A very high deflection may be due to the effect of an abnormally high temperature in bituminous mix.	If the deflection is very high and the temperature is very high and the surfacing is bituminous then assign a low modulus to the bituminous mix.	75%
A substantial decrease in subgrade soil moisture content can result in unusually low deflections being recorded.	If the deflection level is low and the moisture content of the subgrade is low then assign a high modulus to the subgrade.	75%
High deflections may be associated with an increase in moisture content of the subgrade soil caused either by adverse drainage conditions or by thawing of frozen soil.	If the deflections are high and the drainage conditions are poor or thawing of frozen soil occurs then assign a low modulus to the subgrade.	75%
The influence of the average annual rainfall on young pavements is negligible for the first few years after construction but it becomes increasingly significant as more traffic load is applied to the subgrade.	If the pavement is $<$ 2 years old then the average annual rainfall influences the modulus of the subgrade.	10%
	If the pavement is $>$ 2 years old then the average annual rainfall influences the modulus of the subgrade.	90%
Pavements resting on subgrades with high clay content exhibit considerably more susceptibility to the influence of water.	If the subgrade soil contains clay then it is susceptible to the influence of water.	80%
	If a subgrade is susceptible to the influence of water then assign a low modulus to the subgrade.	90%

Table 7.3: Knowledge Base Rules for the Identification of the Structural Condition of a Pavement During Field Testing.

Engineering Knowledge			Knowledge Representation	Certainty
Classification	Code	Visible evidence		
SOUND	1	No cracking. Rutting under a 2m straightedge less than 5 mm.	If there is no cracking and rutting is < 5mm then the pavement is sound.	95%
	2	No cracking. Rutting from 5 mm to 9 mm.	If there is no cracking and rutting is 5-9 mm then the pavement is sound.	75%
CRITICAL	3	No cracking. Rutting from 10 mm to 19 mm.	If there is no cracking and rutting is 10-19 mm then the condition of the pavement is critical.	75%
	4	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 19 mm or less.	If cracking is a single crack or $< \frac{1}{2}$ of width of wheel path and rutting is $\leq$19mm then the condition of the pavement is critical.	90%

Table 7.3: Knowledge Base Rules for the Identification of the Structural Condition of a Pavement During Field Testing *(cont'ed)*.

Engineering Knowledge			Knowledge Representation	Certainty
Classification	Code	Visible evidence		
FAILED	5	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 19 mm or less.	If cracking is severe and rutting is ≤ 20 mm then the pavement has failed.	75%
	6	No cracking. Rutting 20 mm or greater.	If there is no cracking and rutting is ≥ 20 mm then the pavement has failed.	80%
	7	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 20 mm or greater.	If cracking is a single crack with width < of wheel path and rutting is ≥ 20 mm then the pavement has failed.	90%
	8	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 20 mm or greater.	If cracking is severe and rutting is ≥ 20 mm then the pavement has failed.	95%

Table 7.4: Moduli of Various Bituminous Materials Used in Mechanistic Analysis.

Researcher	Material type	Modulus (MPa)	Remarks
Arand, 1987	Asphaltic concrete		
	T = -30^0C	31090	(Dynamic
	T = -20^0C	27975	modulus)
	T = -10^0C	22005	pen=80 mm/10
	T = 0^0C	15280	SP = 50^0C
	T = 10^0C	9015	
	T = 20^0C	3605	
	T = 30^0C	1305	
Brunton *et al.*, 1992			T = 15^0C
	Hot Rolled Asphalt	4500-7500	Wearing Course
	Hot Rolled Asphalt	8000-10000	Roadbase
	Dense Bitumen Macadam	4500-7500	Basecourse
	Dense Bitumen Macadam	7000-10000	Roadbase
	Dense Bitumen Macadam	10000-13000	Roadbase (50pen)
	Heavy Duty Macadam	11000-15000	Roadbase
Heleven *et al.*, 1987	Bituminous mix		
	winter	25000	
	spring or autumn	10000	
	summer	5000	
	mild deformation	7800	
	isolated cracks		
	mild deformation	4000	
	frequent cracks		
	crazing or repairs	1700	
	frequent cracks		
	high deformation	500	
Powell *et al.*, 1984	Dense Bitumen Macadam	3100	(100pen 20^0C)
	Hot Rolled Asphalt	3500	(50pen 20^0C)
Thomson, 1987	Asphaltic concrete		Full-depth
	very hard	13776	asphalt concrete
	hard	6888	
	medium	3444	
	low	1377	

Table 7.4: Moduli of Various Bituminous Materials Used in Mechanistic Analysis *(cont'ed)*.

Researcher	Material type	Modulus (MPa)			
Francken		Temperature			
et al.,		30^0C	15^0C	-5^0C	-20^0C
1987	Dense Bitumen Concrete	3620	9520	20000	25000
	Stone Filled Sand Sheet	2343	6901	16520	22088
	Base Course Asphalt Concrete	3418	8375	18065	23100
	Porous Asphalt	2828	5638	9657	11707
	Lean Bituminous Macadam	3233	9467	20127	24387
	Bitumen Sand	637	1777	4745	6891
	Bituminous Mortar	2316	5905	12777	16304
Hugo, 1987	Asphaltic Concrete				
		Aged Asphalt		Unaged Asphalt	
	Temperature	cont.graded	gap graded	cont.graded	gap graded
	-5^0C	9600	8800	9200	7800
	5^0C	7300	5900	6700	5000
	25^0C	2900	2200	2500	1500

Table 7.5: Moduli of Various Bituminous Materials Used in Mechanistic Analysis [After Freeme *et al.*, 1987].

MATERIAL GRADING	LAYER THICKNESS	STIFFNESS (MPa) FOR TEMPERATURE AND STATE							
		GOOD STATE OF NEW MATERIAL		STIFF DRY MIXTURE		VERY CRACKED STATE		LENSES OF UNSTABILIZED OR STRIPPED MATERIAL	
		20 °C	40 °C	20 °C	40 °C	20 °C	40 °C	20 °C	40 °C
Gap-graded	0- 50	4 000	1 500	5 000	1 800	1 000	500	1 500	1 000
	50-150	6 000	3 500	7 000	4 000	1 000	500	2 500	1 500
	150-250	7 000	5 500	8 000	6 000	1 000	500	3 000	2 000
						(equivalent granular state)			
Continuously graded	0- 50	6 000	2 200	7 000	4 000	750	500	2 000	1 500
	50-150	8 000	5 500	9 000	6 000	1 000	750	3 000	2 000
	150-250	9 000	7 500	10 000	8 000	1 000	750	3 000	2 000
						(equivalent granular state)			

Table 7.6: Experimentally Determined Coefficients of K $-$ Θ Model [After Shook *et al.*, 1982]

Material Type	k_1	k_2
Partially Crushed Gravel, Crushed Rock	1600 - 5000	0.57 - 0.73
Untreated Base	2100 - 5400	0.61
Gravel, Crushed Stone	1800 - 8000	0.32 - 0.70
Crushed Stone	4000 - 9000	0.46 - 0.64
Well Graded Crushed Limestone	8000	0.67
In-service Base and Subbase materials	2900 - 7750	0.46 - 0.65
M_r and θ in psi. 1kPa = 6.894psi.		

Table 7.7: Experimentally Determined Typical Nonlinear Material Coefficients [After Bonaquist *et al.*, 1992]

Material Type	k_1	k_2	k_3
Dense Graded Limestone Base	4062	0.80	-0.30
Dense Graded Limestone Base	3103	0.95	-0.50
Crusher Run Limestone Base	3819	0.90	-0.30
Crushed Slag Base	7873	0.90	-0.50
Bank Run Gravel Subbase	4187	0.65	-0.20
Sand Aggregate Subbase	3819	0.50	0.10
M_r, θ, τ_{oct} in kPa			

Table 7.8: Moduli of Various Roadbase and Subbase Materials Used in Mechanistic Analysis.

Researcher	Material type	Modulus (MPa)	Remarks
Brunton *et al.*, 1992	Cement Concrete	30000-70000	
	Cement Bound (intact)	10000-30000	
	Cement Bound (primary cracking)	5000-15000	
	Cement Bound (cracked)	500-5000	
	Granular Base	200-500	No cementing action
	Granular Base	300-2000	With cementing action
	Granular Subbase	50-200	
	Rockfill	100-400	
	Blocks/Pavers	500-100	
Heleven *et al.*, 1987	Crushed stone	500	
	Coarse rock	500	
	Lean concrete	15000	
	Granular subbase	200	
	Subbase of sand or		
	coarse aggregate	2680	
	Draining sand	150	
Lehtonen, 1986	Penetration macadam	700	
	Oil Gravel	350	
	Ballast	300	
	Crushed stone	150 - 350	
	Crushed gravel	150 - 350	
	Gravel	150 - 280	
	Sand (non-frost susceptible)	30 - 150	
Powell *et al.*, 1984	Wet-mix roadbase	250 - 500	
	Capping layer	50 - 100	
	Subbase	150	(upper limit)

Table 7.9: Moduli of Various Granular Materials Used in Mechanistic Analysis [After Freeme *et al.*, 1987].

MATERIAL DESCRIPTION	ABBREVIATED SPECIFICATION	DRY STATE GRANULAR SUPPORT	WET STATE (GOOD SUPPORT)	WET STATE (POOR SUPPORT)
Crushed stone	100 to 102 % Mod AASHTO	250 (150 450)	230	150
Crushed stone	98 100 % Mod AASHTO	250 (125 400)	220	140
Gravel base quality	CBR $\nless$ 80 PI $\ngtr$ 6	225 (100 375)	200	120
Gravel	CBR $\nless$ 45 PI $\nless$ 10 15	200 (75 350)	180	100
Gravel low quality subbase	CBR $\nless$ 25	200 (50 300)	150	50

Table 7.10: Moduli of Various Cement-Bound Materials Used in Mechanistic Analysis [After Freeme *et al.*, 1987].

UCS (MPa) PRE-CRACKED STATE		PARENT MATERIAL	PRE-CRACKED STATE GPa (range)	POST-CRACKED STATE (MPa)		
				LARGE BLOCKS	SMALL BLOCK/GRANULAR	
					DRY STATE	WET STATE
6-12	strongly cemented	Crushed stone	14 (7-30)	3 000	600	500
3-6		Crushed stone	10 (4-14)	2 500	500	300
1,5-3	weakly cemented	Good quality natural gravel (CBR >45)	4,5 (3-9)	2 000	350	160
		Poor quality gravel (CBR >7)	3 (2-6)	1 200	200	90
0,75-1,5		Good quality gravel	3,5 (2-6)	2 000	300	160
		Poor quality gravel	1,5(0,5-3)	500	150	70

Table 7.11: Moduli of Various Cement-Bound Materials Used in Mechanistic Analysis.

Researcher	Material Type	Modulus (MPa)	k_1	k_2	Remarks
Wang *et al.*, 1979a	Limestone-Aggregate Cement	25000	$6.56\ 10^{-21}$	6.05	6% per weight cement 94% per weight aggregate
Wang *et al.*, 1979b	Gravel-Aggregate Cement	17000	$1.83\ 10^{-8}$	2.93	6% per weight cement 94% per weight aggregate
	Slag-Aggregate Cement	22000	$4.48\ 10^{-9}$	3.08	
Wang *et al.*, 1979c	Aggregate-Lime-Pozzolan	16400	-	-	3% per weight cement 15% per weight Fly Ash 82% per weight Aggregate

Table 7.12: CBR Values for Various Types of Soil [After Powell *et al.*, 1984].

TYPE OF SOIL	PLASTICITY INDEX	HIGH WATER TABLE						LOW WATER TABLE					
		CONSTRUCTION CONDITIONS:						CONSTRUCTION CONDITIONS:					
		POOR		AVERAGE		GOOD		POOR		AVERAGE		GOOD	
		THIN	THICK	THIN	THICK	THIN	THICK	THIN	THICK	THIN	THICK	THIN	THICK
HEAVY CLAY	70	1.5	2	2	2	2	2	1.5	2	2	2	2	2.5
	60	1.5	2	2	2	2	2.5	1.5	2	2	2	2	2.5
	50	1.5	2	2	2.5	2	2.5	2	2	2	2.5	2	2.5
	40	2	2.5	2.5	3	2.5	3	2.5	2.5	3	3	3	3.5
SILTY CLAY	30	2.5	3.5	3	4	3.5	5	3	3.5	4	4	4	6
SANDY CLAY	20	2.5	4	4	5	4.5	7	3	4	5	6	6	8
	10	1.5	3.5	3	6	3.5	7	2.5	4	4.5	7	6	>8
SILT *	–	1	1	1	1	2	2	1	1	2	2	2	2
SAND (POORLY GRADED)	–	← 20 →											
SAND (WELL GRADED)	-	← 40 →											
SANDY GRAVEL (WELL GRADED)		← 60 →											

* estimated assuming some probability of material saturating

Table 7.13: Typical Poisson's Ratio Values Assigned to Various Pavement Materials.

Material	Poisson's ratio	Remarks
Bituminous Materials		
Dense Bitumen Macadam	0.35	TRRL LR 1132
Hot Rolled Asphalt	0.35	TRRL LR 1132
$T < 0^0C$	0.15	AASHTO
$T = 20^0C$	0.35	AASHTO
$T = 50^0C$	0.45	AASHTO
Typical value	0.35	
Cement Bound Materials		
uncracked state	0.15	AASHTO
badly cracked state	0.35	AASHTO
unknown cracking state	0.20	AASHTO
Granular Materials		
crushed stone	0.30	
unprocessed rounded gravel or sands	0.40	
capping layer	0.45	TRRL LR 1132
wet-mix roadbase	0.45	TRRL LR 1132
unknown material	0.35	AASHTO
Subgrade Soil		
cohesionless	0.30	AASHTO
cohesive	0.50	AASHTO
unknown	0.40	AASHTO

Table 7.14: Fatigue Criteria for Bituminous Materials.

Researcher	Model	Remarks
Verstraeten *et al.*, 1982	$\varepsilon_t = 1.60\,10^{-3}\,N^{-0.21}$	
Brunton *et al.*, 1987	$\varepsilon_t = \frac{14.39 \log V_B + 24.2 \log SP_i - k - \log N}{5.13 \log V_B + 8.63 \log SP_i - 15.8}$	k = 46.82 for life to critical conditions k = 46.06 for life to failure V_B = volumetric proportion of binder (%) SP_i = initial softening point of binder Multiplying shift factor for *in situ* conditions : 440 for failure, 77 for critical.
Shook *et al.*, 1982	$N = 18.4C[4.325\,10^{-3}(\varepsilon_t)^{-3.291}\lvert E^*\rvert^{-0.854}]$	$\lvert E^*\rvert$ is the modulus of the mix $C = 10^M$ $M = 4.84[\frac{V_b}{V_v+V_b} - 0.69]$ V_b = volume of bitumen V_v = volume of air voids
Monismith *et al.*, 1987	$\log N = 16.086 - 3.291 \log[\frac{\varepsilon_t}{10^{-6}}]$ $-0.854 \log[\frac{S_{mix}}{10^3}]$	
Powel *et al.*, 1987	$\log N = -9.78 - 4.32 \log \varepsilon_t$ $\log N = -9.38 - 4.16 \log \varepsilon_t$	HRA Roadbase DBM 85% confidence, $T = 20^0$

Table 7.15: Rutting Criteria.

Researcher	Model	Remarks
Powel *et al.*, 1984	$\log N = -7.21 - 3.95 \log \varepsilon_z$	85% confidence
Gerritsen *et al.*, 1987	$\varepsilon_z = 2.8\,10^{-2} N^{-0.25}$	50% confidence
	$\varepsilon_z = 2.1\,10^{-2} N^{-0.25}$	85% confidence
	$\varepsilon_z = 1.8\,10^{-2} N^{-0.25}$	95% confidence
Brunton *et al.*, 1987	$\varepsilon_z = \frac{250}{(\frac{N}{f_r})^{0.27}}$	For life to critical condition
	$\varepsilon_z = \frac{451.3}{(\frac{N}{f_r})^{0.28}}$	For life to failure
		f_r is a rut factor :
		1.0 for HRA base and
		1.56 for DBM base.

Table 7.16: Fatigue Criteria for Cement-treated Materials.

Researcher	Model	Remarks
Verstraeten *et al.*, 1982	$\frac{\varepsilon_t}{\varepsilon_b} = 1 - 0.05 \log N$	ε_t represents theoretical strain
		ε_b represents allowable bending strain
		for flexural strength tests
Freeme *et al.*, 1982	$\frac{\varepsilon_t}{\varepsilon_b} = 0.83 - 0.091 \log N$	

Chapter 8

THE IDEAL KNOWLEDGE-BASED SYSTEM

This chapter discusses the desirable characteristics of an ideal KBS for pavement analysis. Firstly, a justification is provided for the development of the prototype system. Thereafter, both the structure and the functions required by an ideal system are described together with some aspects about the usage of the system.

8.1 Introduction

The promise of KBS is that knowledge acquired from experts can be packaged in appropriate software and delivered to users who will then have access to the capabilities of a variety of experts to hand for solving problems. The basic notion is that the expert's knowledge is acquired and then programmed using an appropriate inference strategy [Naughton, 1989].

It has been stated [Salvo *et al.*, 1989] that in order to build a KBS in a systematic way the following steps of development should be taken:

1. Requirement Analysis: the system is described using flowcharts and narratives.

2. Knowledge Acquisition: information about facts and heuristics concerning the analytical process is collected.

3. System Development: the system is developed using structured programming techniques.

4. System Assessment: the system's behaviour is evaluated for its ability to emulate the domain experts.

However, the development of any KBS is essentially effected in a step by step manner with a small *prototype* version of the complete system being developed to demonstrate its overall feasibility [Harmon *et al.*, 1988]. The prototype stage also offers an opportunity to develop or modify the originally provided software and hardware. Furthermore the developer may identify and attempt a representation of the reasoning processes of the experts whose knowledge is to be built into the system [Harmon *et al.*, 1988]. In conclusion, developing a prototype lets the developer experiment with a reduced scale version of the final system and evaluate the difficulties that may be encountered when the full-scale program is written.

The goal of this work is to produce a *proof-of-concept* prototype KBS which will seek to fulfill the functions to be presented in Section 8.2. Furthermore, building upon the experience gained with this prototype should enable the establishment of the full working system as a next stage.

8.2 The Functions Required by an Ideal KBS

Figure 8.1 is a representation of the desirable KBS in pavement analysis. This system may be considered as the integration of three parts; an analytical program, a knowledge base and a database. Due to its specific nature it could be called an expert database system [Golshani, 1990].

The core of such a system is the knowledge base. It stores various kinds of rules which control the performance of the whole system. Ideally it performs all the tasks currently carried out by the road engineer. The database holds the data collected in the field together with both the solutions and the recommendations provided by the system. The analytical program carries out the analysis of the pavement structures. At its highest level of integration the system may have the ability to store, retrieve and update large volumes of data and also the ability to reason with the provided knowledge and produce further information based on the existing information.

With this system the field deflection testing data is stored in the database (Module D_1). In addition to deflection data, other information such as temperature, *in situ* CBR and layer thicknesses may also be collected and stored if required. The data is organized into a hierarchical scheme allowing easy access. The scheme may be defined by the chainage of the tested sections. Thus for a specific test point the data base holds information about FWD deflections, construction details and structural performance characteristics such as cracking and rutting.

The information held by the database (Module D_1) is accessed by the knowledge base (Module K_1). At this stage the knowledge-based rules (as presented in Section 7.2) attempt to draw conclusions with respect to the structural condition about the deflection tested road sections and search the wider database (Module D_2) to find previously analyzed similar structures which may act as a guide to the properties of the section under scrutiny. Provided the case histories contained within the database have been verified, the conclusions drawn will have a high possibility of soundness. Thus the system provides reasonable input data (initial estimates of layer moduli and Poisson's ratio) to enable the analytical model to function more accurately to determine the precise layer properties to achieve a good fit with the observed deflection bowl. If there are no similar cases, the system will try to obtain the required data from a factorial design of pavement structures stored also within the database (Module D_2). The factorial design used is given in Appendix C.

Once the moduli and the Poisson's ratios have been assigned to particular layers, the system carries out the Back-Analysis (Module K_2). It calls ROSTRA-1 (Module A) which calculates the deflections of the pavement subjected to the FWD load. At this point the rules of the knowledge base adjust the layer moduli until a reasonable correlation between the measured and the calculated deflection bowl is achieved. The back calculated moduli are stored in the inventory database (Module D_3) together with the other information of each test point.

The next stage is the calculation of the remaining life (Module K_3). The failure parameters are calculated by ROSTRA-1. (Typically these are the horizontal tensile strain at the bottom of the bituminous layer for fatigue cracking and the vertical compressive strain at the top of the subgrade for rutting.). Using suitable pavement performance models the remaining life of the pavement may then be estimated. This information is also sent to the database (Module D_3). Thus the database stores information about each road section concerning characteristics of both the structure and performance of the pavement.

In conclusion the ideal system should be able to perform the following tasks:

1. Model pavement structures.

2. Anticipate future performance.

3. Control and update, if necessary, the information it holds.

8.3 The Persons Associated with the KBS

The preceding section has presented the ideal functions effected by the KBS. This section describes the interaction between the system, its developer, the expert and the user.

Figure 8.2 shows the concatenation of the roles of the people and the machine involved in the development and usage of the KBS, as individual units. The people are:

1. The expert who performs the task.

2. The developer of the KBS.

3. The user of the system who seeks advice from the expert through the system.

The expert, whose knowledge is to be built into the system, may not always be able to justify fully decisions that he makes. This creates a problem to be addressed by the developer of the KBS.

The developer, or the "*knowledge engineer*", has as his primary task the interview of the expert to elicit his knowledge. He must also be able to understand the logical processes used. He has then to convert this information into a form suitable for computer simulation.

The user of the system should be able to understand the problem without necessarily having the specific knowledge of the expert. This, in a well arranged system, will be provided to him through the advice of the KBS itself. The system should be able to generate advice for its user and most importantly communicate with him.

In the work to date the roles and experience of the knowledge engineer and the expert have been determined from a study of case histories reported in the literature.

8.4 Concluding Summary

In order to build the KBS it was felt advisable to develop a reduced scale prototype version. For this reason, in this chapter the required operations performed by an ideal system were described and explained, together with the definition of the roles of the persons associated with the KBS as both the above guided the design of the programmed system.

FIGURES

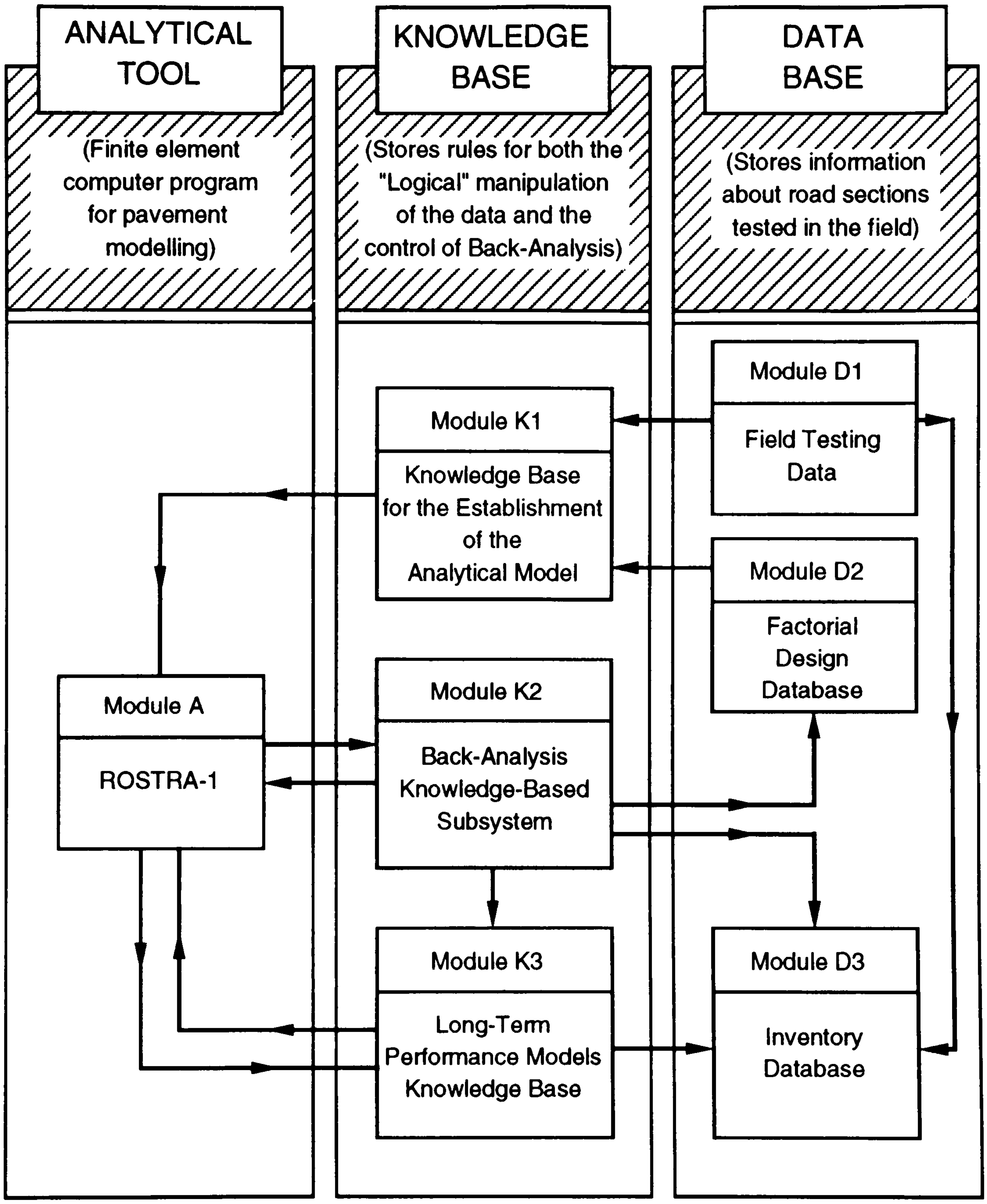

Figure 8.1: The Structure of the Ideal KBS.

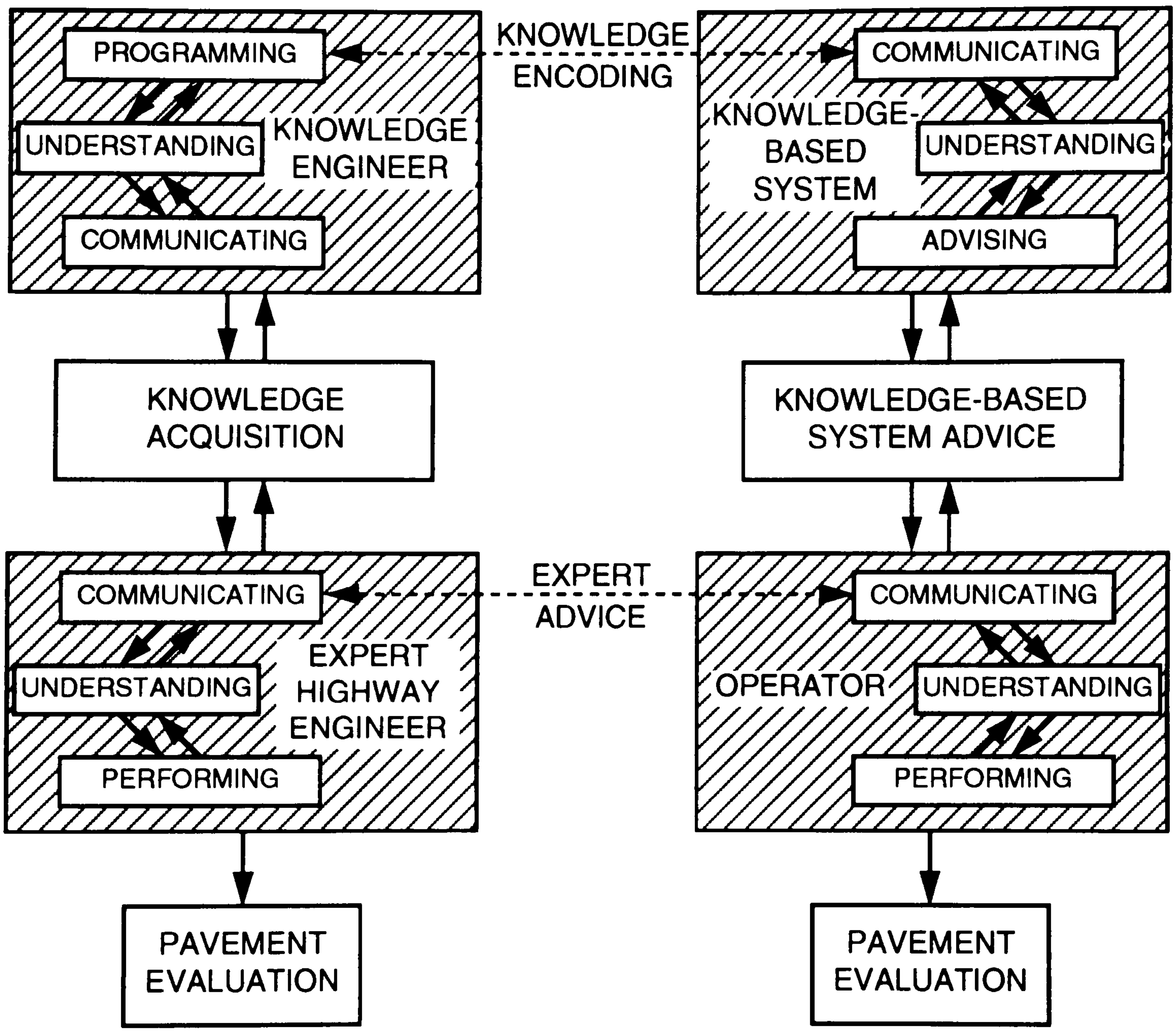

Figure 8.2: The Interactive Role of the KBS.

Chapter 9

PROGRAMMING THE KNOWLEDGE-BASED SYSTEM

This chapter reports the developments made in the prototype KBS for pavement analysis and focuses on a number of practical issues that have been encountered; namely:

1. The Selection of the Development Tool.

2. The Selection of Prolog.

3. The Selection of POPLOG-Prolog.

4. Programming in Prolog.

5. Implementation of the System.

6. Future Developments.

9.1 The Selection of the Development Tool

KBS have been written in a variety of programming languages [Salvo, 1989]. Consequently the selection of the appropriate tool for developing a specific system is a difficult task. In order to select the most suitable tool for a particular application, the following items should be considered [Waterman, 1986]:

1. Development constraints such as time, money, personnel and hardware.

2. Support facilities such as debugging mechanisms and built-in editors.

3. Reliability.

4. Maintainability.

5. Task Characteristics.

The prospective developer has to make a decision whether to use either a programming language or a shell. Shells are complete applications development environments which contain one or more programming languages, an editor, debugging tools, software utilities and a large library of functions that the developer may require [Salvo, 1989].

Programming languages such as *Lisp* and *Prolog* provide flexibility and the result may therefore fit more closely the needs of the problem. However, they require the developer to design the structure of the KBS (i.e. the type of the knowledge representation and the reasoning mechanisms).

Conversely, development using a shell is easier and faster but the result may be a system less effective or efficient than that written in a programming language.

Evaluating the above factors, it was felt that the KBS should be developed in a programming language rather than a shell. It was considered that the flexibility this approach offered would lead to an integrated system which should perform adequately and provide the required functions described in section 8.2.

9.2 The Selection of Prolog

Prolog and Lisp are the most popular symbolic languages for the development of KBS. Much debate has been conducted on the benefits of using Prolog over Lisp and vice versa. Each language has certain advantages and shortcomings. It has been said [Bratko, 1990] that from a broad point of view a knowledge of both languages is essential for the Artificial Intelligence scientist. A discussion about them may be found elsewhere [Harmon *et al.*, 1988]. However the selection of Prolog by the Japanese "Fifth Generation Project" [Rada, 1989] has stimulated interest in it and increased its popularity.

Prolog has its roots in *propositional* or *binary* logic [Kowalski, 1979] and as stated by Clocksin *et al.*, [1984] it

> " can be seen as a first step towards the ultimate goal of
> <u>Pro</u>gramming in <u>Log</u>ic."

It provides a uniform data structure, called the *term*, out of which all data as well as Prolog programs, are built. A Prolog program consists of a set of *clauses* (see also Section 9.4). Each clause is either a *fact* about the given information or a *rule* about how the solution may relate to, or be inferred from, the given facts [Clocksin *et al.*, 1984].

However, Prolog is neither able to formulate any definition containing more than one "*If*" statement nor to express any negative conclusion. Another unhelpful characteristic of Prolog is that although the programming structures it manipulates are similar to those used by other specialist Artificial Intelligence languages like Lisp, its behaviour

"is a bit clumsy" [Sloman, 1987].

It has been said that Prolog's true flexibility is its ability to infer facts from other facts [Harmon *et al.*, 1988]. In addition it has its own inference and search mechanisms and also it is relatively easy to devise a user-friendly interface so that the resultant system behaves in a similar manner to a shell [Sterling *et al.*, 1986]. Generally, it has been suggested [Gooley *et al.*, 1989] that a KBS written in Prolog requires less code than those written in other languages.

Therefore, it was concluded from the above, that the expressiveness of Prolog taken in conjunction with its own inference mechanisms make it the appropriate tool for the task covered by this research programme.

9.3 The Selection of POPLOG-Prolog

A variety of Prolog versions have been developed from the standard version described originally by Clocksin and Mellish [1984]. In order to create the KBS required by this work it was decided that the POPLOG variant of the software [POPLOG 14.1, 1991] would be used as it appeared to be well suited both to the task in hand and to the available hardware, a VAXstation 3100 operating under VAX/VMS system.

POPLOG is an interactive program development environment. It supports incremental compilers for the following languages:

1. POP-11.

2. Prolog.

3. Common Lisp.

4. Standard ML.

In addition it includes a built-in editor, called VED, and furthermore has the ability to build solutions in a mixture of languages supported by POPLOG and indeed externally compiled languages [POPLOG 14.1, 1991].

Figure 9.1 is a schematic representation of the architecture of POPLOG. It can be seen that the four compilers supported by POPLOG generate code from the same virtual machine (VM) instruction set. The VM code is translated into machine code. At this level, programs developed in POPLOG can communicate with other programs written in FORTRAN or C. Thus,

> "POPLOG gives the application builder the opportunity to choose languages that are appropriate not just to the particular application but to each part of the application." [POPLOG 14.1, 1991]

This is particularly useful in the development of the system under consideration, since it is desirable that the system should communicate smoothly with the analytical tool as described in section 8.2.

In conclusion it may be stated that the POPLOG-Prolog development environment appeared to be a promising tool for the required KBS. It was felt that its in-built capabilities should enable the development of the required system in a versatile form.

9.4 Programming in Prolog

This section presents the programming characteristics of the computer language Prolog. This presentation should not be regarded as a brief introduction to the programming techniques and capabilities of Prolog as these are explicitly described in specialized books [Bratko, 1990; Sterling *et al.*, 1986; Clocksin *et al.*, 1984].

Prolog is a programming language which may be viewed as ideal for symbolic and non-numeric computations. The problems that lend themselves to resolution by Prolog are usually made up of a number of *facts* which consist of objects and relationships which link them. For example, the expression

```
material_type('Subgrade soil with known CBR').
```

may be interpreted as the fact that "*The type of the material is a subgrade soil with known CBR* ". A set of such facts makes up the *Prolog database.*

Another programming characteristic is that Prolog is able to infer new relations from given facts if an appropriate *rule* is defined. An example of such a rule is given below to enable the determination of the Poisson's ratio of a cohesive soil:

```
poisson_ratio('0.50') :- type_of_soil(cohesive).
```

This expression can be interpreted as "*If the type of soil is cohesive then its Poisson's ratio is 0.50* ".

In addition, *queries* may be carried out about the facts held in the database. The conversation between the Prolog database and the operator may be as follows:

Actual Code	**Explanation**
`?- material_type(X).`	(Query to Prolog typed by the user.)
`X = Subgrade soil with known CBR ? ;`	(Prolog's response. The symbol ";" is typed by the user and may be interpreted as "*Are there any other solutions ?*")
`no`	(Prolog's response.)

Obviously, Prolog is unable to "generate" answers to the questions posed. Rather, a procedure is provided which enables the operator to obtain from the database the information which is relevant to the query. This procedure is based on the manner in which both *facts* and *rules* are connected together within a Prolog program and may be graphically represented as an *OR-Tree* (see Figure 9.2). From this Figure it may be seen that whilst a program is running, the Prolog interpreter may follow all the paths which are linked with the query made, until a solution is found. As a consequence, the user may obtain not only one but also all the possible answers. Although this practice enables a certain degree of flexibility, it may result in a lack of programming efficiency.

Facts, rules and queries are special cases of the Prolog *clause*. A clause has the general form:

```
head :- goal_1, goal_2, ..., goal_n.
```

The clause is a conjunction of premises (goals) that imply a single conclusion (head), and may be considered as a *Horn* clause [Thayse, 1988]. It may be interpreted with either a declarative or procedural meaning:

1. Declarative meaning.

   "The `head` holds, If `goal_1` and `goal_2` and all the goals through to `goal_n` hold."

2. Procedural meaning.

   "To do the tasks indicated by `head`, do `goal_1` and `goal_2` and all the goals through to `goal_n`."

In conclusion it may be stated that the representational schemes and mechanisms provided by Prolog enable the formulation of problem solving techniques that can be described with a series of logical relationships expressed as Horn clauses. The following sections present the implementation of the prototype KBS for pavement analysis effected by this technique.

9.5 Implementation of the System

This section describes the individual modules of the prototype system programmed during this study. The architecture of the prototype system, shown in Figure 9.3, has been inferred from the requirements for an ideal KBS for pavement analysis which was schematically represented in Figure 8.1. Thus, the prototype system consists of the following items:

1. The Finite Element program ROSTRA-1, written in FORTRAN (Module A).

2. The Database program which contains the moduli and Poisson's ratio of various pavement materials and is written in POPLOG-Prolog (Module K_1).

3. The Back-Analysis programs, written in POPLOG-Prolog (Module K_2).

4. Control facilities.

5. The linking interface of the above items programmed in the VAX/VMS DIGITAL Command Language (DCL) [DIGITAL^{TM}, 1982].

In addition, two other programs have been written which are not linked with the above modules. These are:

1. An elementary Prolog-based knowledge base to demonstrate the feasibility of such an approach to an evaluation of pavements based on data collected during relatively superficial surveys (see section 4.2). This knowledge base could be included within Module K_1.

2. A small database (to act as a pilot) to facilitate the factorial design processes (Module D_2) (see Appendix C).

9.5.1 The Finite Element Program ROSTRA-1

As stated in Chapter 5, the finite element program ROSTRA-1 was used in the KBS for the simulation of the response of road structures to traffic loading. Thus, to enable the program (Module A) to conform with the communication requirements shown in Figure 8.1 it was necessary to alter the format of the output file of ROSTRA-1. As a result, this file contains only the values which are necessary to feed the Back-Analysis module. These are the number of layers, the moduli of the layers and the computed surface deflections. No change has been made to the format of the input file. Rather, it was considered that the Prolog Database (see next subsection) should create the suitable format of the input file together with the selection of the appropriate values of the data.

9.5.2 The Prolog Database

The Prolog programming techniques, presented in section 9.4, enabled the development of the subsystem known as Module K_1 (see Figures 8.1 and 9.3) which performs, within the overall KBS, the following tasks:

1. The initial selection of the appropriate values of modulus and Poisson's ratio for the materials of the pavement constituent layers.

2. The formulation of the ROSTRA-1 input file.

This subsystem is a database in which the data are organized in a hierarchical manner that may be considered as rule-based knowledge representation. The information stored in the database is displayed by means of menus. The menus enable the operator to select appropriate values of modulus and Poisson's ratio for a variety of paving materials, by providing a number of attributes which can influence the properties of each of these materials. These programming techniques were very helpful because they both met the criteria of rule selection mentioned in section 6.4.2 (i.e. recency, specificity and refraction) and also increased the efficiency of the system.

9.5.3 The Back Analysis System

The Back Analysis subsystem (Module K_2) should be considered as the core of the KBS. In addition it is the most demanding in terms of computational techniques for the following reasons:

1. In order that the system may adjust the moduli of the various layers, it is desirable that it should initially use logical inferences based on the observations acquired during field testing and also, to a lesser extent, arithmetic procedures.

2. The system should enable the use of any combination of modelling techniques to cope with the variety of cases which are to be analyzed.

3. The system should enable efficient manipulation of data to ensure reasonable accuracy.

4. The system should converge quickly to a unique solution.

Considerable effort has been put into the development of appropriate programming procedures which sought to provide an effective means for back-analysis. The present system includes only heuristic methods. These methods are based on deflection considerations with respect to the radial distances at which the deflections are measured. It will be appreciated that certain unlikely combinations of materials found in the field will not result in a good solution as the system is essentially empirical.

9.5.4 The VAX/VMS Interface

The necessity for combining together the capabilities of two computer languages which are considerably different from each other such as Prolog (for the simulation of the logical processes required by the back analysis technique) and FORTRAN (for ROSTRA-1), may create difficulties. Consequently, the ability of POPLOG-Prolog to communicate smoothly with code externally compiled in FORTRAN was investigated prior to the development of the two Prolog-based subsystems (Modules K_1 and K_2). The results of this may be briefly summarized as follows:

1. In theory, it is possible that any variable may be interchanged between Prolog and FORTRAN through POP-11, the language in which the POPLOG environment is programmed.

2. It would appear that only executable FORTRAN code can communicate with POP-11 and subsequently with Prolog.

3. Executable Prolog code cannot be generated. Rather, "saved images" of programs are loaded to the computer memory together with the POPLOG system.

4. Since the POPLOG-Prolog implementation is essentially a standard version of Prolog, the mathematical functions provided are limited to the basic four (+, -, *, /) and the remainder of integer division, consequently the accuracy of the arithmetic computations achieved is relatively low.

From the above it may be seen that there is considerable incompatibility between POPLOG-Prolog and FORTRAN. Such behaviour has been the subject of extensive debate between computer scientists [Sloman, 1992] who decided that an interface should be built to enhance the compatibility. Therefore it was felt that in order to join together POPLOG-Prolog and FORTRAN code, a simple program should be written in the command language of the operating system of the available hardware (VAXstation 3100). This was done as part of this research and its listing may be found in Appendix D.

9.6 Future Developments

Comparing Figure 8.1 with Figure 9.3, it may be seen that the present prototype system does not incorporate the following useful modules:

1. A knowledge base for the interpretation of information collected in the field by means other than the FWD.

2. A database that would enable automatic storage and subsequent use of the field testing data (Module D_1).

3. A knowledge base that would estimate the prediction of long-term pavement performance and would assist the selection of the required remedial treatments (Module K_3).

4. A database for the automation of the factorial design functions and furthermore the storage of the previously analyzed cases (Module D_2).

5. An inventory database which would allow an overall organization of both the collected and analyzed data in a form useful to the end-user (Module D_3).

A discussion about the development and the usefulness of these items may be found in Chapters 10 and 11. The following subsections present two small programs which seek to facilitate items 1. and 4. of the above list pending their full introduction in the post prototype system. These programs are not linked with the KBS automatically.

9.6.1 A Small Knowledge Base for Functional Evaluation

To demonstrate the feasibility of building a knowledge base for the functional evaluation of pavement structures, a small program was written. A sample of its output is given in Appendix F. The program incorporates the information given in Table 4.1. The user feeds the program with information about the cracking and rutting state of a tested road section. In response, the program evaluates the pavement condition and decides whether the pavement is at a sound, critical or failed level. This small knowledge base may be further expanded and then incorporated in Module K_1 (see Figure 9.3).

9.6.2 Programming the Factorial Design

As stated in section 8.2 it is felt that the factorial design given in Appendix C is particularly useful in the absence of either an adequate amount or quality of field testing data. Thus, to automate the procedure of estimating pavement material properties, given the approximate layer thicknesses and the measured FWD deflection bowl of the pavement tested, a small database has been written in FORTRAN. In its present state this database (see Module D_2 of Figure 9.3) could be used for three-layer modelled pavement structures, and may subsequently be extended to cope with multi-layer models. The database consists of two parts:

1. The data file which contains the relevant structural details (i.e. number of layers, thickness of layers, moduli of the layers, and deflection data).

2. The searching mechanism program DATABANK.

Extracts from both the database and the program may be found in Appendix E.

9.7 Summary

This chapter has focused on the practical issues involved in the development of the KBS. The factors that influence the selection of the appropriate programming environment were given and also a justification for the use of the Prolog programming language was presented. Subsequently, the features of the development tool, the POPLOG version of Prolog, were described to enable a proper understanding of the KBS's behaviour. The constituent subsystems of the programmed prototype KBS have also been presented together with their characteristics.

FIGURES

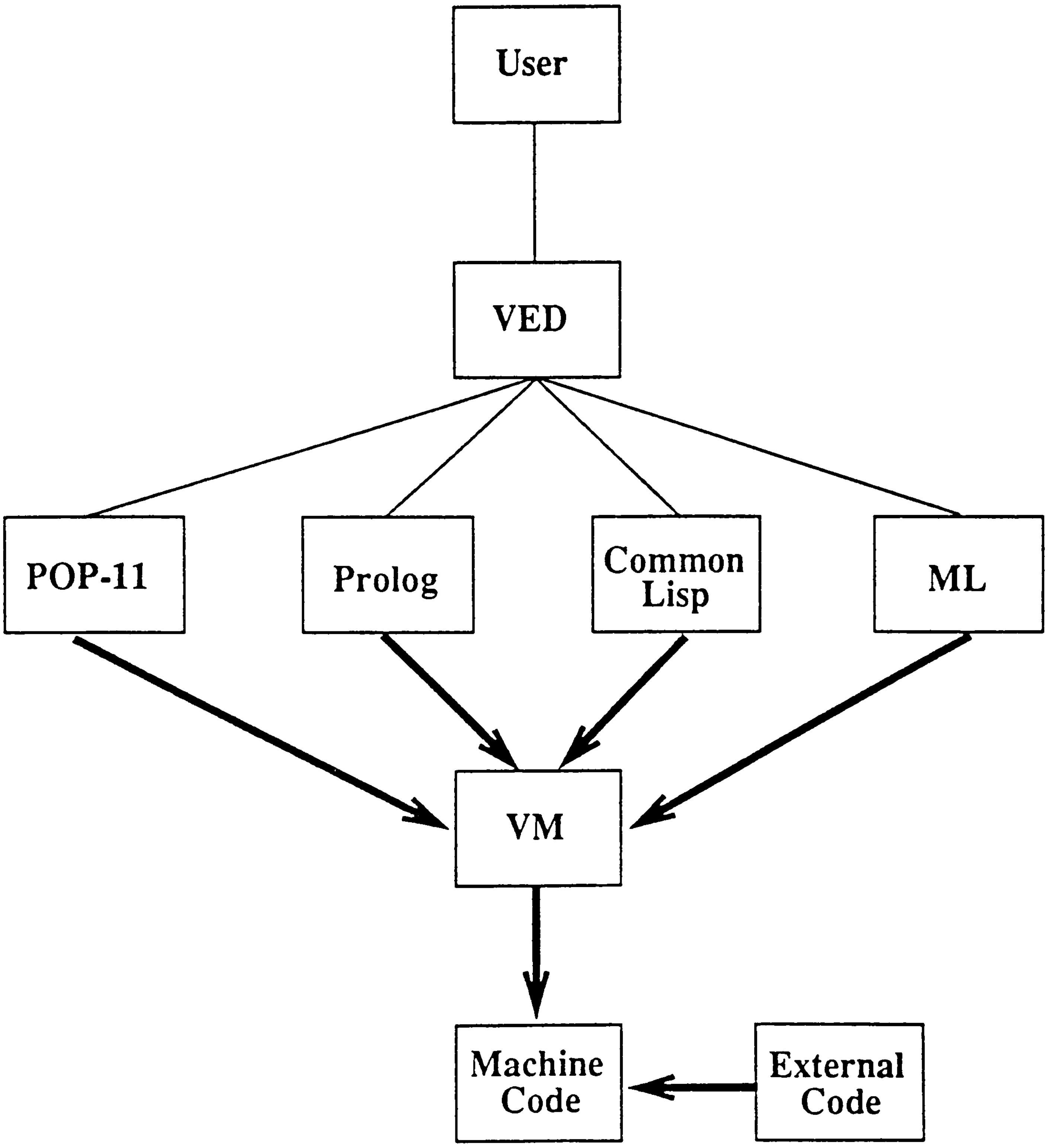

Figure 9.1: POPLOG-System Architecture [After POPLOG, 1991].

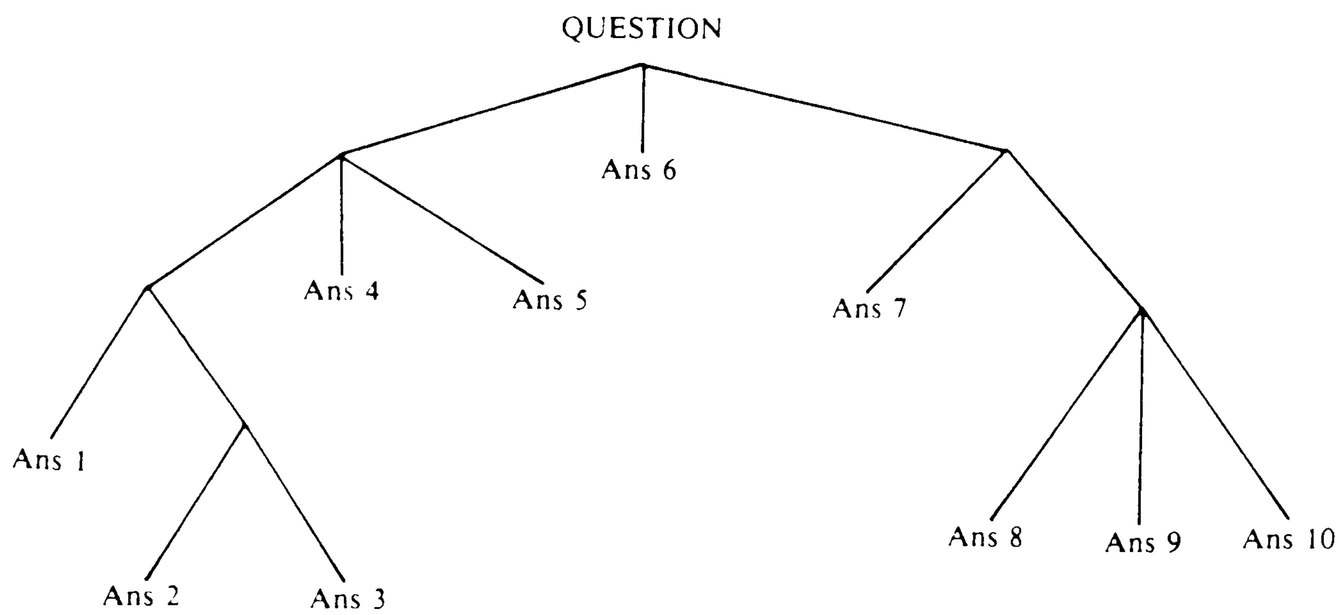

Figure 9.2: An OR-Tree [After Sloman, 1987].

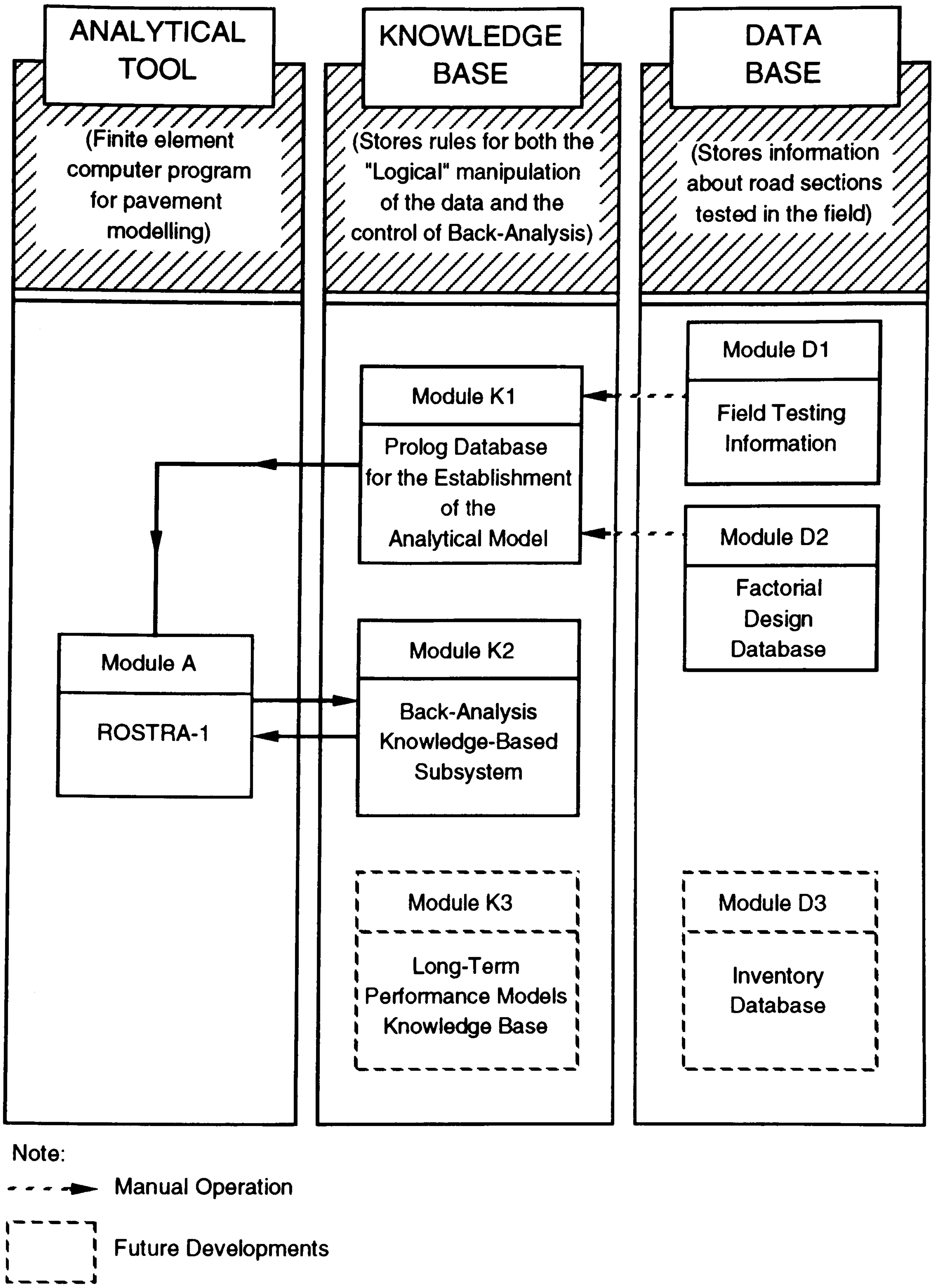

Figure 9.3: The Modules of the Prolog KBS.

Chapter 10

SYSTEM PROOF-OF-CONCEPT PROTOTYPE

10.1 Introduction

In this study the prototype of the back analysis system has been tested using a full-scale example. The available data have been processed both manually and automatically by the prototype to enable direct comparisons. This chapter presents the work which seeks to determine the behaviour of the KBS and to suggest solutions to those areas in which operation was not felt to be at the optimum level.

In order to analyze the field data, the procedure showed in Figure 8.1 was followed. Initially the system was operated manually using the computer only to run the analytical program ROSTRA-1. In this mode the user has full control on the process and the likelihood of achieving the usage of the most appropriate logic required with consequent accuracy of the estimation of the pavement material moduli is high. Following this the data were analyzed by the full KBS operating without intervention of the user (i.e. automatically). In each case two approaches were considered. The system was run both with and without recourse to that part of the knowledge base concerned with the acquisition of experience. The former was intended to simulate operation which included learning mechanisms.

10.2 System Input Data

To demonstrate the basic functions of the KBS, a suitable set of field data was selected. Deflection measurements, made by a FWD on behalf of TRL during a comparative study of the performance of various FWDs [Ferne, 1992], were used. The deflections were measured at four test sites (known as A, B, C and D) on a flexible pavement at a U.K. motorway site in 1990. The deflection data, surface condition and layer thicknesses of the pavement at the test sites are given in Tables 10.1 and 10.2.

The estimations of the back-calculated moduli from these measurements for both a two-layer (i.e. bound and unbound) and a more comprehensive model, were required. In addition the horizontal tensile strain at the bottom of the bituminous layer and the vertical compressive strain at the top of the subgrade were to be calculated.

10.3 System Usage

10.3.1 Manual Operation

The deflection data given in Tables 10.1 and 10.2 may be considered to be stored in the database. These data were then "normalized" to that associated with an applied stress of 700 kPa (cf. Section 4.6). The results of the process are given in Table 10.3.

As the database does not hold information on the materials from the tested pavement, the set of factorial pavement models given in Appendix C have been used to provide initial estimates of the layer moduli from a simple deflection bowl fitting process.

Thus, for each test site the measured deflection bowl was compared with those of the factorial pavements. The central deflection provided an indication of the overall strength of the tested pavement whilst the outer deflections suggested the modulus of the subgrades. As the thicknesses of the construction layers were known, the estimation of the initial moduli to be back-calculated was easier. As a result it seemed likely that for the test sites A, B, C and D the modulus of the bituminous material was 2000 MPa (see curve D, Factorial 7 in Appendix C). For the subgrade it appeared that the modulus in all cases was the same with a value above 120 MPa. These moduli were used as initial values only for the two-layer model. For the multi-layer model the first estimations were taken from the knowledge base itself (see Table 7.4 and 7.8).

The details of the two-layer models are given in Table 10.4 and those of the multi-layer model in Table 10.5. The Poisson's ratio were taken from Table 7.13.

In order to back-analyze the pavement models it was considered that the outer deflections were indicative of the moduli of the granular layers and subgrade soil whilst the moduli of the bituminous material primarily influenced the deflections at or near the loaded area. Hence during the back-analysis process the modulus of the pavement foundation was adjusted first, until a close agreement (within ±5%) was achieved between the measured and the calculated deflections at distances greater than 600 mm. Second the modulus of the bituminous layer was tuned to achieve the required fit for the central deflection.

Since the pavements at the four test sites behaved similarly, the back analysis of each succeeding case became easier under the manual system.

10.3.2 Automatic Operation

The procedure described above was then repeated using the system in its automatic mode, involving the process of the KBS (see Section 9.5 and Figure 9.3). A log of the dialogue between user and the system is provided in Appendix G which presents the output of the analysis carried out for one of the two-layer models developed for Test Site A.

From this example it may be seen that initially the system is operated as an advisory tool. The user inputs the loading characteristics of the pavement model (i.e. radius and value of the uniformly distributed circular load) together with the structural details of the model (i.e. number of layers, type of finite element grid and layer thicknesses). Thereafter the system tries to identify a suitable modulus and Poisson's ratio for each of the pavement constituent layers on the basis of information supplied by the operator. The system employs a menu mechanism which presents attributes given to a variety of pavement materials. Thus the user is driven by the system to select a value for each of these attributes.

After the completion of this phase, a theoretical solution is provided by the program ROSTRA-1 for the deflections of the model formed. These deflections are presented together with the measured ones which are provided by the user. Subsequently, the system compares these two deflection sets and either confirms the suitability of the initially selected material properties or adjusts the moduli so that a better agreement may be achieved. After each iteration a table is provided to the operator of the system who is able to see both the computed and calculated deflections as well as their difference both as an absolute number and as a percentage. In addition, the adjusted moduli are presented. When the desired convergence level is achieved, the layer moduli are printed.

In this work several attempts have been made to produce a KBS able to give consistent results independent of the initial conditions of the analysis (i.e. complexity of pavement model and accuracy of initial moduli estimation). As a result a system has been derived which, albeit in a limited way, is able to cope with the field testing data currently available. Its characteristics may be summarized as follows:

1. The system is able to provide data on the properties of a wide range of materials and to back analyze pavement models consisting of up to five layers.

2. The accuracy which may be achieved with respect to convergence between measured and computed deflection bowls is:

   (a) One-layer models:
   $\pm 5\%$ for the central deflection (d_1).

   (b) Two-layer models:
   $\pm 5\%$ for the central deflection (d_1) and $\pm 15\%$ for the deflection (d_i) measured at up to 0.60 m.

   (c) Other models:
   $\pm 10\%$ for the central deflection (d_1) and $\pm 15\%$ for the deflections (d_i) measured at 0.30, 0.60 and 0.90 m.

3. If the computed deflections do not conform to the above tolerances, then the moduli of the layers are adjusted according to the following heuristic methods:

   (a) One-layer models: $E_{1\ \text{revised}} = E_{1\ \text{old}}\ \frac{\text{computed } d_1}{\text{measured } d_1}$.

   (b) Multi-layer models.
   In order to test the system a few empirical rules were formulated and used for the convergence between the measured and computed deflection bowl. As with the one-layer model, the modulus of the top layer is usually adjusted with respect to the central deflection, whilst the other moduli are tuned as functions of the deflections measured at radial distances of up to 0.90 m. In addition, the modular ratio technique may be used between the moduli of the subgrade and the overlying layer.

Furthermore, the ability of the system to carry out the analysis with the assistance of data from previous analyses, was investigated. In the absence of such a programmed procedure, the system was used conventionally but the selection of the initial layer moduli was controlled and based on the previously analyzed models and the experience thus gained. This operation was felt to demonstrate the advantage that might be gained from the incorporation of a self-learning mechanism into the system.

Tables 10.6 to 10.9 present both the initially estimated and back-analyzed moduli for the two-layer and the multi-layer models of the pavements tested. (The results of the manual operation are also presented). Distinction has been made between the results from automatic operation and those when the simulation of self learning mechanisms has also been incorporated.

10.4 Results and Discussion

Table 10.1 shows that, as the deflection levels at the test sites A and B are higher than those at the sites C and D, the overall strength of the pavements at the test sites A and B are lower than that at the sites C and D. Additionally it may be seen that the overall strength of the four test sites in declining order is B, A, D and C. Consequently, the calibrated models derived from the analysis processes should comply with the deflection (deformation) criteria reported herein. Tables 10.10 to 10.12 demonstrate the convergence achieved between the measured deflection bowls and those calculated under a variety of modelling conditions. (The critical strains generated by a standard 40 kN wheel load on these models are also given in Tables 10.13 to 10.15).

10.4.1 Manual Operation

Two-layer Model

It appears that the moduli derived from the back-analysis process with the two-layer model are in good agreement with the overall structural behaviour of the pavement at the four different test sites (see Table 10.7).

The moduli assigned to the granular layers are consistent with the deflection levels recorded at each radial distance. As the deflections decrease according to $d_{iB} > d_{iA} > d_{iD} > d_{iC}$ (where d_{iB}, d_{iA}, d_{iD} and d_{iC} are the deflections at the test sites B, A, D and C respectively), the moduli increase as $E_{gB} < E_{gA} < E_{gD} < E_{gC}$ (where E_{gB}, E_{gA}, E_{gD} and E_{gC} are the moduli assigned to the granular layer at the test sites B, A, D and C respectively). In addition it may be seen that the findings for the moduli assigned to the bituminous materials follow the same trend with the exception of test site A. This may be attributed to the fact that the overall pavement response is controlled by the modulus of the pavement foundation as stated by Ullidtz [1987]. It should be noted that this will however occur, to some extent, when insufficient pavement structure is used to overcome the effects of the subgrade in the overall pavement performance.

Multi-layer Model

When the deflection data were analyzed with a multi-layer model, the predicted moduli of the pavement layers were lower than those of the two-layer model (see Tables 10.7 and 10.9). However they were in reasonable agreement with those reported by other researchers (see Table 7.4 and 7.8), and followed the same trend with respect to the overall pavement strength. The reason for such behaviour could be attributed to the difference in the number of layers modelled. When a two-layer model was used, the moduli of the constituent layers represented the resultant effect of either the bituminous or granular materials. The moduli assigned to the multi-layer models may be considered as more representative of the individual pavement layer materials. In addition, the factors that influence the values of the moduli (such as the influence of the thicknesses of both the overlying and underlying layers), as stated in Section 3.2, should also be taken into account.

The variation of the moduli used in simulating the pavement response to loading, has a considerable effect on the strains computed. Thus, the horizontal tensile strains at the bottom of the bituminous layer predicted by the multi-layer model were generally higher than those of the two-layer model. Conversely the vertical compressive strains at the top of the pavement foundation were lower in the multi-layer model than those computed by the two-layer model.

Furthermore, the deflections calculated by the multi-layer model at distances greater than 0.90 m are not in good agreement with those measured at the respective locations (see Table 10.10). However, it appears unlikely that any model employed for routine analysis could cater accurately for the full deflection bowl of the site. Various researchers have tried to overcome this difficulty by utilizing simplified procedures such as that of "Surface Modulus" developed by Ullidtz [1987], and that of "Surface Curvature Index" [Dohmen, 1992]. In this study, it was hoped that the rationale for the selection of the appropriate modulus implemented by the KBS could provide an alternative means for solving the problems encountered.

10.4.2 Automatic Operation

When the system was operated automatically, the back analyzed moduli for both the two-layer and the multi-layer models followed the same trends as those derived from the manual operation. However their values, in some cases, differed significantly from those found by the manual system. The results of the analysis carried out by the programmed KBS are presented in Tables 10.11, 10.12, 10.14 and 10.15 as follows:

1. Tables 10.11 and 10.14 show respectively the deflections and strains computed by the calibrated models.

2. Tables 10.12 and 10.15 present the respective results of the "simulated full knowledge" analyses.

   As a result of this it is possible to deduce the following for:

1. The Standard System Analysis.

   (a) Two-layer Model.

      i. The computed deflections are in good agreement with those measured at distances up to 0.90 m (see Table 10.11).

      ii. The moduli assigned to the bituminous layer are consistent with the strength of the pavements indicated by the deflection levels.

iii. The moduli assigned to the granular layers follow the same trend as those of the bituminous layers, except for Test Site D (see Table 10.14). This discrepancy could be caused by the high value of modulus assigned to the bituminous layer, of Test Site D.

iv. The back-analyzed moduli of the Test Sites C and D are significantly different from those found during the manual operation of the KBS with consequent differences in the computed strains (see Table 10.14).

(b) Multi-layer Model.

i. Reasonable convergence between measured and computed deflections can be achieved at distances up to 0.90 m (see Table 10.11).

ii. The values of the back analyzed moduli of the granular layers and subgrade soil appear to be low compared with those moduli found manually (see Tables 10.8 and 10.9).

iii. The resultant moduli of the bituminous layers appear to be satisfactory for the Test Sites A, C and D.

iv. The values of the moduli of the bituminous layers found by the automated KBS are higher than those derived during the manual operation. By contrast, the moduli of the granular layers are lower than those back-analyzed manually.

2. The Simulated Full Knowledge Base Usage (i.e. Standard operation with access to the knowledge base concerned with the aquisition of experience).

(a) Two-layer Model.

i. The usage of previous knowledge has a significant effect on the back-analyzed moduli. This is clearly indicated by the models formed for the Test Sites C and D (see Table 10.14 and 10.15).

ii. The computed deflections are not markedly influenced by such a usage.

(b) Multi-layer Model.

i. There exists some variation between the moduli of the bituminous layers derived from the two types of automated usage. This is most evident in the moduli deduced for the unbound layers of the pavement.

10.5 Conclusions

An investigation of the prototype of the KBS behaviour was carried out. Despite the limited amount of data provided for testing the system's behaviour, significant variation was observed in the results of the different analyses. Although the use of a particular program, in this case ROSTRA-1, will affect the solution, it is judged that the behaviour of the system is primarily influenced by the following factors:

1. The conditions which lead to the initial estimation of the layers' moduli (e.g. use of a factorial design database).

2. The rules of the back analysis knowledge base and indeed mechanisms which take advantage of the experience gained from the use of the analysis system.

3. The architecture of the KBS and also both the nature and the capabilities of the individual building blocks of the system.

However, the prototype exercise is felt to be useful because:

1. It confirmed the feasibility for a KBS approach to pavement analysis.

2. It provided the basis for the validation process of the KBS.

3. It demonstrated the usefulness of the fundamental functions required by the KBS as outlined in Section 8.2.

4. It enabled a clarification of both the functional and design specifications for such a working system.

TABLES

Table 10.1: System Prototype Test Data: Deflection Measurements.

Test Site	Loading Pressure (KPa)	Deflections in microns at radius in mm — Offset Distances						
		0	300	600	900	1200	1500	2100
A	739	254	194	147	109	88	65	38
B	748	274	216	166	124	95	70	41
C	762	170	132	110	88	71	51	33
D	737	189	156	127	94	75	56	33

Table 10.2: System Prototype Test Data: Construction and Condition Information.

<table>
<tr><th rowspan="2">Test Site</th><th rowspan="2">Surface Condition</th><th colspan="5">Thickness of bituminous material (mm)</th></tr>
<tr><th>Layer 1
Wc</th><th>Layer 2
Bc</th><th>Layer 3
Rb1</th><th>Layer 4
Rb 2</th><th>Total</th></tr>
<tr><td>A</td><td>Cracked</td><td>38</td><td>69</td><td>115</td><td>100</td><td>322</td></tr>
<tr><td>B</td><td>Cracked</td><td colspan="2">90</td><td colspan="2">208</td><td>298</td></tr>
<tr><td>C</td><td>Uncracked</td><td colspan="2">104</td><td colspan="2">203</td><td>307</td></tr>
<tr><td>D</td><td>Uncracked</td><td colspan="2">100</td><td>100</td><td>110</td><td>310</td></tr>
<tr><td colspan="7">Nominal granular subbase thickness is 330 mm.</td></tr>
<tr><td colspan="7">Wc ⟶ Wearing course
Bc ⟶ Base course
Rb1 ⟶ Road base 1
Rb2 ⟶ Road base 2</td></tr>
</table>

Table 10.3: Deflection Measurements Normalized to a Reference Applied Stress of 700 kPa.

Test Site	Reference Stress (kPa)	Deflections in microns at radius in mm						
		Offset Distances						
		0	300	600	900	1200	1500	2100
A	700	241	184	139	103	83	62	36
B	700	256	202	155	116	89	66	38
C	700	156	121	101	81	65	47	30
D	700	180	148	121	89	71	53	31

Table 10.4: Initial Moduli and Poisson's Ratios for the Two-layer Model Found Manually.

Layer No.	Material Type	Young's Modulus (MPa)	Poisson's ratio
1	Bituminous	2000	0.35
2	Granular	120	0.35

Table 10.5: Initial Moduli and Poisson's Ratios for the Multi-layer Model Found Manually.

Layer No.	Material Type	Young's Modulus (MPa)	Poisson's ratio
1	Bituminous (uncracked)	3500	0.35
1	Bituminous (cracked)	2000	0.35
2	Bituminous Rb (uncracked)	2500	0.35
2	Bituminous Rb (cracked)	1000	0.35
3	Granular	500	0.30
4	Subgrade	120	0.40

Table 10.6: Initially Estimated Moduli for the Two-Layer Models Under Manual, Automatic and Simulated Knowledge Operations.

Test Site	Layer No.	Mode of Operation		
		Manual	Automatic	Simulated Knowledge
		Modulus (MPa)	Modulus (MPa)	Modulus (MPa)
A	1	2000	3000	3100
	2	120	200	200
B	1	2000	3000	3100
	2	120	200	200
C	1	2000	8000	3100
	2	120	200	200
D	1	2000	8000	3100
	2	120	200	200

Table 10.7: Back-Analyzed Moduli for the Two-Layer Models Under Manual, Automatic and Simulated Knowledge Operations.

Test Site	Layer No.	Mode of Operation		
		Manual	Automatic	Simulated Knowledge
		Modulus (MPa)	Modulus (MPa)	Modulus (MPa)
A	1	2300	2711	2675
	2	170	177	176
B	1	3000	2623	2675
	2	140	166	164
C	1	3500	7281	4346
	2	300	187	265
D	1	3000	6274	3941
	2	275	156	217

Table 10.8: Initially Estimated Moduli for the Multi-Layer Models Under Manual, Automatic and Simulated Knowledge Operations.

Test Site	Layer No.	Mode of Operation		
		Manual	Automatic	Simulated Knowledge
		Modulus (MPa)	Modulus (MPa)	Modulus (MPa)
A	1	2000	2200	2200
	2	1000	3000	3000
	3	500	200	200
	4	120	40	120
B	1	2000	2200	2200
	2	1000	3000	3000
	3	500	200	200
	4	120	40	120
C	1	3500	7000	7000
	2	2500	8000	8000
	3	500	200	200
	4	120	40	120
D	1	3500	7000	7000
	2	2500	7000	8000
	3	500	200	200
	4	120	40	120

Table 10.9: Back-Analyzed Moduli for the Multi-Layer Models Under Manual, Automatic and Simulated Knowledge Operations.

Test Site	Layer No.	Mode of Operation		
		Manual	Automatic	Simulated Knowledge
		Modulus (MPa)	Modulus (MPa)	Modulus (MPa)
A	1	1500	2845	2200
	2	1000	3844	3000
	3	500	126	200
	4	150	50	120
B	1	2000	3118	2195
	2	1000	4060	2848
	3	500	121	241
	4	150	48	96
C	1	3500	6195	5615
	2	3100	7047	6345
	3	500	79	173
	4	150	32	69
D	1	3100	5589	4799
	2	2400	5410	5283
	3	500	56	136
	4	150	23	55

Table 10.10: Measured, Normalized and Computed deflections for the Four Test Sites. Manual Operation of the System.

	DEFLECTIONS (microns)							
	Test Site A				Test Site B			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	254	241	253	242	274	256	260	253
0.30	194	184	174	116	216	202	192	121
0.60	147	139	131	71	166	155	146	71
0.90	109	103	100	45	124	116	110	42
1.20	88	83	78	26	95	89	84	21
1.50	65	62	67	13	70	66	67	6
2.10	38	36	58	0	41	38	51	0

	DEFLECTIONS (microns)							
	Test Site C				Test Site D			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	170	156	155	146	189	180	173	175
0.30	132	121	102	84	156	148	113	111
0.60	110	101	74	50	127	121	81	77
0.90	88	81	55	35	94	89	60	53
1.20	71	65	42	16	75	71	46	35
1.50	51	47	35	5	56	53	38	22
2.10	33	30	31	0	33	31	33	8

Table 10.11: Measured, Normalized and Computed deflections for the Four Test Sites. Programmed Operation of the System Using Prolog Under VAX/VMS. System's Knowledge Only.

	DEFLECTIONS (microns)							
	Test Site A				Test Site B			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	254	241	244	265	274	256	264	262
0.30	194	184	178	201	216	202	192	198
0.60	147	139	139	148	166	155	147	139
0.90	109	103	111	99	124	116	114	85
1.20	88	83	90	58	95	89	91	42
1.50	65	62	77	26	70	66	75	12
2.10	38	36	67	3	41	38	65	6

	DEFLECTIONS (microns)							
	Test Site C				Test Site D			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	170	156	154	163	189	180	180	195
0.30	132	121	126	126	156	148	147	150
0.60	110	101	103	87	127	121	120	103
0.90	88	81	83	52	94	89	98	60
1.20	71	65	67	23	75	71	79	25
1.50	51	47	54	3	56	53	64	2
2.10	33	30	44	0	33	31	52	0

Table 10.12: Measured, Normalized and Computed deflections for the Four Test Sites. Programmed Operation of the System Using Prolog Under VAX/VMS. Simulated Full Knowledge.

	DEFLECTIONS (microns)							
	Test Site A				Test Site B			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	254	241	243	245	274	256	264	267
0.30	194	184	179	172	216	202	193	189
0.60	147	139	140	128	166	155	148	137
0.90	109	103	111	92	124	116	115	95
1.20	88	83	91	64	95	89	91	61
1.50	65	62	77	42	70	66	76	34
2.10	38	36	67	25	41	38	66	15

	DEFLECTIONS (microns)							
	Test Site C				Test Site D			
Offset Distances (m)	Measured	Normalized	Two-layer Model	Multi-layer Model	Measured	Normalized	Two-layer Model	Multi-layer Model
0.00	170	156	161	161	189	180	180	191
0.30	132	121	119	123	156	148	140	145
0.60	110	101	92	87	127	121	110	103
0.90	88	81	72	55	94	89	87	64
1.20	71	65	58	28	75	71	71	32
1.50	51	47	49	9	56	53	59	10
2.10	33	30	43	0	33	31	51	0

Table 10.13: Back-Analyzed Moduli, Poisson's Ratios and Critical Strains found by the Knowledge-Based System. Manual Operation of the System.

Test Site	TWO-LAYER MODEL			MULTI-LAYER MODEL		
	Moduli (MPa) E_1 and E_2	Poisson's ratio ν_i	micro-strain ε_t and ε_c	Moduli (MPa) E_i	Poisson's ratio ν_i	micro-strain ε_t and ε_c
A	2300	0.35	62	1500 (Wc+Bc)	0.35	
				1000 (Rb1+Rb2)	0.35	92
	170	0.35	-210	500 (Subbase)	0.30	
				150 (Subgrade)	0.40	-133
B	3000	0.35	59	1500 (Wc+Bc)	0.35	
				1000 (Rb1+Rb2)	0.35	101
	140	0.35	-225	500 (Subbase)	0.30	
				150 (Subgrade)	0.40	-143
C	3500	0.35	41	3500 (Wc+Bc)	0.35	
				3100 (Rb1+Rb2)	0.35	55
	300	0.35	-139	500 (Subbase)	0.30	
				150 (Subgrade)	0.40	-105
D	3000	0.35	47	3100 (Wc+Bc)	0.35	
				2400 (Rb1+Rb2)	0.35	61
	275	0.35	-160	500 (Subbase)	0.30	
				150 (Subgrade)	0.40	-110

Table 10.14: Back-Analyzed Moduli, Poisson's Ratios and Critical Strains found by the Knowledge-Based System. Programmed Operation of the System Using Prolog Under VAX/VMS. System's Knowledge Only.

Test Site	TWO-LAYER MODEL Moduli (MPa) E_1 and E_2	Poisson's ratio ν_i	micro-strain ε_t and ε_c	MULTI-LAYER MODEL Moduli (MPa) E_i	Poisson's ratio ν_i	micro-strain ε_t and ε_c
A	2711	0.35	65	2845 (Wc+Bc)	0.35	74
				3844 (Rb1+Rb2)	0.35	
	177	0.30	-206	126 (Subbase)	0.30	-176
				50 (Subgrade)	0.40	
B	2623	0.35	75	3118 (Wc+Bc)	0.35	79
				4060 (Rb1+Rb2)	0.35	
	166	0.30	-248	121 (Subbase)	0.30	-186
				48 (Subgrade)	0.40	
C	7281	0.35	32	6195 (Wc+Bc)	0.35	52
				7047 (Rb1+Rb2)	0.35	
	187	0.30	-126	79 (Subbase)	0.30	-120
				32 (Subgrade)	0.40	
D	6274	0.35	37	5589 (Wc+Bc)	0.35	64
				5410 (Rb1+Rb2)	0.35	
	156	0.30	-145	56 (Subbase)	0.30	-142
				23 (Subgrade)	0.40	

Table 10.15: Back-Analyzed Moduli, Poisson's Ratios and Critical Strains found by the Knowledge-Based System. Programmed Operation of the System Using Prolog Under VAX/VMS. Simulated Full Knowledge.

Test Site	TWO-LAYER MODEL			MULTI-LAYER MODEL			
	Moduli (MPa) E_1 and E_2	Poisson's ratio ν_i	micro-strain ε_t and ε_c	Moduli (MPa) E_i		Poisson's ratio ν_i	micro-strain ε_t and ε_c
A	2675	0.35	66	2200	(Wc+Bc)	0.35	95
				3000	(Rb1+Rb2)	0.35	
	176	0.30	-208	200	(Subbase)	0.30	-130
				120	(Subgrade)	0.40	
B	2675	0.35	74	2195	(Wc+Bc)	0.35	86
				2848	(Rb1+Rb2)	0.35	
	164	0.30	-247	241	(Subbase)	0.30	-164
				96	(Subgrade)	0.40	
C	4346	0.35	44	5615	(Wc+Bc)	0.35	50
				6345	(Rb1+Rb2)	0.35	
	265	0.30	-144	173	(Subbase)	0.30	-113
				69	(Subgrade)	0.40	
D	3941	0.35	49	4799	(Wc+Bc)	0.35	59
				5283	(Rb1+Rb2)	0.35	
	217	0.30	-164	136	(Subbase)	0.30	-134
				55	(Subgrade)	0.40	

Chapter 11

DISCUSSION

11.1 Introduction

Highway pavements may be viewed as complex structures subjected to a variety of traffic and environmental loadings. Material characterization, pavement performance and their interrelationships are complex and a unified working framework for the solution of pavement deterioration is needed.

This chapter discusses the progress made in the development of a prototype KBS, as illustrated in Section 8.1, under the following headings:

1. Requirement Analysis.

2. Knowledge Acquisition.

3. Programming the System.

4. Evaluation of the System.

11.2 Requirement Analysis

11.2.1 General

This was the first phase in the development of the KBS. During this phase the pavement structural evaluation methodologies currently used were investigated. As a result, it was possible to select those kinds of information which are appropriate for the KBS. This information may be categorized into the following groups:

1. Information collected during field testing; that is:
   (a) FWD Deflection data.
   (b) Measurements of pavement cracking, rutting and temperature (during deflection testing).
   (c) Measurements of unbound material properties by means of CBR testing the DCP and the Clegg hammer.
   (d) Historical data from structural records.
2. Information about the characteristics, the usefulness and the usage of the currently available techniques to be used for the analysis of the above data.

From these the weaknesses of the constituent parts of the current processes were identified and the desirable characteristics and functions of the system under development were defined (see Section 8.2). Thereafter the optimum tools and assumptions were selected to enable the development of an effective system. Thus, decisions were made on:

1. The selection of the appropriate computer program to be used in the back-analysis of the deflection data.
2. The selection of the optimum programming tool for building the desirable KBS.

These decisions have been shown to be vital in the development of the system. The characteristics of both the analytical program and the KBS development tool controlled the overall performance of the system and indeed were principally responsible for the success of the prototyping process.

11.2.2 The Selection of ROSTRA-1

As stated in section 5.1.1, the analytical models available to simulate pavement response to loadings and performance in time were shown not to be sufficiently satisfactory. Simple models such as those based on the M.E.T. have the advantage of short running time whereas those based on the F.E.M. have a longer running time but appear to provide more accurate solutions. However, the main point of issue is the level of complexity of the pavement model to be used in the back-analysis process when balancing accuracy and time of computation.

In this thesis, an extensive study of three examples of M.E.T. and F.E.M. programs (i.e. DEFMET, and both DEFPAV and PAFEC respectively) was conducted to determine which exhibited the most suitable characteristics for the KBS. Thus, the three programs tested may be arranged in increasing order of both complexity in simulation and length of running time as follows; DEFMET, DEFPAV and PAFEC. Although it was desirable to use DEFMET, further consideration of the modelling technique it uses led to the exclusion of this program from the development of the KBS. The primary reason for this decision was that DEFMET, like any other M.E.T. program, is limited to model pavement structures in which the moduli of the layers decrease with depth. This is not always helpful and particularly in cases such as when composite pavements (with bituminous overlays upon uncracked cement-concrete layers) are to be modelled. In addition it appears impossible to model constructions which include grid reinforcement.

All the above obstacles may be overcome when using DEFPAV and indeed its derivative ROSTRA-1, which was produced to cope with a larger number of elements, strain calculation output and two finite element grid configurations suitable for FWD-based back analysis.

Heretofore, engineers using DEFPAV (or ROSTRA-1) had to consider the running time for one cycle of analysis. However, such limitations are not now valid. On the computer used during this study (a VAXstation 3100), the newly extended version of the program runs for 90 seconds on average. This time should not be viewed as long in the light of new technology currently available in processors like Intel's Pentium and that of Digital's Alpha AXP (COMPUTER WEEKLY, 1993). Using these new hardware products, the performance of the program can be significantly enhanced and reach levels of about 50 times the current speed.

Such speed of computation might enable the use of a highly sophisticated program like PAFEC. However, it is felt that such an approach is not feasible. The reason is that the suitability of PAFEC should not be judged only with performance criteria but also with those regarding ease of use. PAFEC is a general purpose finite element program and as stated in Section 5.4.4, albeit powerful, is unsuitable for routine analysis. The input data files (see Appendix B) include voluminous information which should be carefully selected, from a number of different options, so that the computed solution may be reliable. To achieve this it is required that the operator of PAFEC has to have considerable experience both with the program itself and the method of finite elements.

Thus, from the above it was concluded that the program ROSTRA-1 provided a satisfactory accuracy with a reasonable run time and therefore it was selected as the analytical tool of the KBS.

11.2.3 The Selection of POPLOG-Prolog for Building the KBS

The knowledge embodied in problem solving, such as that required during the evaluation of deteriorated pavement structures, may be regarded as heterogeneous. That is, to enable the engineer to suggest a reliable solution to the problems encountered, he has to employ a variety of methods. These methods are associated with analytical, statistical and also empirical considerations not necessarily compatible with each other.

Furthermore, in order that a KBS may emulate reasoning based on such methodologies and in the absence of well understood design principles, it was appreciated at an early stage that a heterogeneous architecture would have to be adopted. Such a structure has to combine a number of programming techniques, which have been used individually for computations on either qualitative or quantitative parameters, such as:

1. Propositional Logic (see Sections 9.2 and 9.4) for symbolic representations (Such approaches may be seen as focusing on the logical integrity of the data with the ability through their contained knowledge to handle poor data sets).
2. Numerical simulations (for the representation of analytical methods).
3. Databases (where efficient management of data was required).

However, systems based on such a heterogeneous approach to software development appeared to be ineffective and indeed worked against the fundamentals of engineering which are clarity, precision, reliability, predictability in design [Gaines, 1990] and ease of use.

Furthermore, as suggested by Buchanan and Shortliffe [1984], the success of a KBS relies heavily on its flexibility which is a function of its simplicity and modularity. In addition, as claimed by Harandi *et al.*, [1990], the success of a KBS depends on the quality of the encoded knowledge rather than on the nature of its inference engine. To this end it appeared that a homogeneous approach should be used to address the requirements of those modules of the KBS in hand that involved data or knowledge manipulation. (However, the overall system should be regarded as quasi-homogeneous in conjunction with the analytical program which is written in FORTRAN). Prolog is a typical language of this type. It has the ability to express both specific information and knowledge abstraction but the efficiency of its inference mechanisms is restricted to small amounts of data. Several versions of Prolog are currently implemented. The POPLOG-Prolog version was selected because:

1. It met the requirements of the available hardware.
2. It has been developed using the standard syntax.
3. It seemed that the various in-built facilities provided, enabled the necessary flexibility in programming for the prototype exercise.

11.3 Knowledge Acquisition

The second phase of the development of the KBS was the acquisition of the knowledge to be encoded. Generally, there are two manners in which knowledge may be obtained:

1. From human experts (in this case the process is called *knowledge elicitation* [Gammack *et al.*, 1984]) or from documents.

2. It may be learned by the system itself by means of *Machine Learning* techniques.

The task of acquiring the knowledge to be stored in a particular KBS has been regarded as a major bottleneck in the development of such systems [Gaines, 1990]. The acquisition process consists of the following items [Naughton, 1989]:

1. Acquisition of the right kind of knowledge in the right amounts.
2. Mapping of this knowledge into a coherent organizational structure.
3. Encoding this structure of knowledge into an inference engine software.

With respect to the above items the knowledge acquisition process was implemented as follows:

1. Acquisition of knowledge.
   The knowledge included in the system was acquired by means of an extensive literature review. However it was necessary that some screening of the encoded knowledge be made so that the knowledge base could comply with consistency criteria. Although it is felt that such an approach may not be totally satisfactory, it was considered as the most suitable for the prototype development because it had two advantages; it was simple and also the information collected could be considered as validated by "experts" prior to inclusion. However it is clear that for a working system the knowledge base should be further refined by expert highway engineers so that its consistency may be ensured. An important issue which may arise is the manner in which the experts judge the findings of their research or the results from the techniques they use. Since the KBS seeks to behave in a similar manner to that of an expert, it might be argued that subjectivity is not entirely absent. Consequently, where the solution of the system could be significantly influenced by such a subjective expert knowledge, it is clearly advisable that the developer of the system should provide facilities that enable the

end-user to select between alternative solutions which have arisen due to the programmed knowledge of more than one expert.

2. Mapping of the collected knowledge.

   In this study, the collected information concerned:

   (a) The moduli of various pavement materials used previously in mechanistic analysis by researchers.

   (b) The Poisson's ratios of various materials previously used in analytical models.

   (c) The pavement performance models that have been used to predict future life.

   (d) The heuristics and empirical relationships used by domain experts to overcome various difficulties encountered in the analysis of deflection data.

   A factorial design of pavement structures analyzed by ROSTRA-1 was also constructed to assist the analysis for those cases where there were insufficient moduli data.

3. Encoding the knowledge.

   The information collected as described above was neither purely arithmetic nor symbolic. Yet, it may be argued that it was data which could be characterized by a number of attributes that gave to these data a physical meaning. These observations in relation to the features of the programming language Prolog enabled conclusions to be drawn about the form of the encoded knowledge within this prototype KBS. The most important finding of this development step was that the selection of the initial estimations for the moduli of the pavement layers ("seed" moduli) had to be addressed by database oriented techniques whereas the control of the back-analysis module required the use of logical procedures represented in a knowledge base.

When the knowledge acquisition process was completed it was clear that systematic knowledge acquisition is a difficult task which requires a combination of methodologies derived from Cognitive Psychology and Computer Science [Naughton, 1989]. However, such an approach is highly theoretical and may be considered to be impracticable for the present. Yet, it appears possible that in well-defined domains, models of *knowledge* may be built and used in computers both by KBS developers and operators. This may be achieved by recent developments in *data* processing which gives increased understanding and control of the functions that manipulate that *data* [Gaines, 1990] (cf. Section 6.1.1). This study may be regarded as such an attempt.

11.4 Programming the System

The next step in building the prototype KBS was the development of the system software using POPLOG-Prolog, FORTRAN and assembly language. Clearly, the system should be able to provide reasonable estimations of the pavement layer moduli for a given deflection bowl and ancillary field data. Furthermore it should enable estimations of the pavement future life together with a level of confidence for the solutions computed.

The development of any software package is usually effected in an incremental manner in which feedback enables validation or optimization of the processes programmed.

Whilst the system was being programmed, the theoretical differences between *data* and *knowledge* (cf. Section 6.1.1) were recognized which triggered an investigation of the distinctive characteristics of both data and knowledge bases. The reason for such an investigation was that it appeared that a database could provide a development environment similar to that of a knowledge base. It was felt that if the functions provided by a database were carefully selected and combined, then the database could also act as a knowledge base.

To this end, the main objectives of a Data Base System (DBS) were identified. These may be summarized as follows [see also Gardarin *et al.*, 1989]:

1. Separation of data description and manipulation.
2. Logical and physical data independence.
3. Procedural and non-procedural interfaces.
4. Efficiency in data processing.
5. Easy data administration and control.
6. Minimal redundancy and storage space.
7. Data integrity, sharing and security.

These objectives have been implemented and used successfully in a number of commercially available DBS and especially in those based on the *Relational Data Model* [Codd, 1979; 1970; Stonebraker *et al.*, 1986; 1984; 1976; Zaniolo, 1983, as quoted in Gardarin *et al.*, 1989; Ullman, 1989]. However, such a system does not provide reasoning capabilities for the stored data. If this is made, then the DBS becomes a *Deductive Database*, or a knowledge base, where both the reasoning capabilities and the consequent knowledge may be expressed as rules. Prolog follows such an approach seeking to use logic programming to manage both data and knowledge in a consistent and efficient manner. Therefore it was considered that Prolog would provide the means for the efficient implementation of the procedures of the KBS.

In addition, Prolog may be used for creating inference engines which are available to act upon data held within the system. However the most problematic but important issue, which has been the focal point of the current research, is the implementation and design of inference models which can work with practical applications [Gardarin *et al.*, 1984; Stonebraker *et al.*, 1986; Ullman, 1989].

Consequently, the complexity of establishing a suitable inference engine together with the necessary simplicity required by the system, indicated that the system had to be written in Prolog, at least for its prototype version. Hence, Prolog's inference engine and appropriate programming techniques enabled the development of two subsystems:

1. A deductive database for the selection of pavement layer material properties.

2. A back analysis subsystem.

However, during programming the prototype KBS, a number of weaknesses with Prolog became apparent which prevented the full implementation of the desired system. These weaknesses concerned both a lack of supporting facilities within the POPLOG development environment and the inability of the Prolog programming style to provide a user-friendly interface for both the formulation and use of the knowledge base rules.

Specifically these weaknesses include:

1. A lack of mathematical functions.
   In a technical domain, such as pavement analysis, where arithmetic operations are the rule rather than the exception, this characteristic should be considered as crucial.

2. The inability of the POPLOG system to generate Prolog code transferable and readily available to the end-user.

3. The inability of Prolog to communicate directly with FORTRAN code. This is a vital aspect not only for the prototype system but for any further development. In the present system this obstacle has been overcome by creating an assembly interface using the VAX/VMS operating system. However this solution is not ideal because it does not permit the consideration of alternative solutions to any set of information being processed. That is, when the conditions of a particular rule are satisfied, then a solution is given and the computations carried out within the knowledge base stop. An alternative method would be to call the FORTRAN code (i.e. the analytical program acting as a subroutine) directly by Prolog. However, the incompatibility between Prolog and FORTRAN codes mitigates against this. It will be seen, therefore, that considerable problems still exist due to the heterogeneous structure of the KBS in this domain.

Such problems reduce the ease of use of the KBS and it is clear that the Prolog-based approach can provide neither the desired clarity nor the ease of use for the formulation of the represented knowledge. An alternative is to use rule-based development environments (see Section 6.3.3). However there are many differences between the Prolog programming style and such environments. The latter have been developed on the grounds of a representational scheme which, unlike Prolog, satisfy the following requirements:

1. They enable the formulation of the rules in a simple and easy manner.
2. They enable a clear representation of, and consequently an insight into, the encoded knowledge.
3. They enable both the developer and the operator of the system to create their own rules.
4. They provide explanation mechanisms for the decisions of the system.

Although arguably effective shells for a rule-based approach capable for addressing the above requirements could be programmed in Prolog, it is not possible to implement a knowledge base with such characteristics relying exclusively on Prolog's inference structure. Somewhat more disturbing is that it appears unlikely that there is any other development tool available which is markedly more effective than Prolog. It is possible that the use of a shell could provide a more user-friendly and clarified rule-based development environment. However, it is much less likely that such a shell could provide satisfactory functions for both the internal computations and the external communications.

11.5 Evaluation of the System

In Computer Science the term "evaluation" of a particular piece of software encompasses a number of aspects which are carried out to test two distinguishable characteristics of any program; its optimization and its performance [Hayes-Roth *et al.*, 1983]. These characteristics include within those two terms the following items:

1. Optimization.
   (a) Efficiency.
   (b) Utility.
   (c) Robustness.
   (d) Cost.
   (e) Maintainability.
2. Performance.
   (a) Reliability.
   (b) Validity.
   (c) Certifiability.

(d) Competence.

In the case of a KBS the evaluation process should be extended to an investigation of both the knowledge and its representational forms that make up the knowledge base [Harrison, 1989].

In this study, the evaluation of the system was conducted in a more simple way because the system is in its prototype form. The optimization criteria were not considered because it was felt that these concern the evaluation of a working system. Thus the evaluation process was focused on the performance criteria. The reliability addresses the problem of whether the system behaves in the same way in the same circumstances. The validity is concerned about whether the system does what it is supposed to do. The certifiability ensures that the processes of the system are employed correctly both in manner and context of operation. The competence addresses the problem of whether the system demonstrates the expertise of the specific domain in a consistent manner.

With respect to the above criteria the following conclusions for the prototype KBS may be drawn:

1. The system is reliable and able to perform in the same fashion in the same circumstances. This is ensured by the relatively simple procedures implemented and the clarity in the programming style.

2. The validity of the system has been shown during the analysis of the four test sites data, as presented in Chapter 10.

3. The assessment of the certifiability of the system is more complicated. As far as the deductive mechanisms of the knowledge base used for the selection of the pavement material properties are concerned, it may be stated that the system works well in the programmed procedures and also gives rational results. However, for the back-analysis system it could be argued

that such criteria may not be applicable. The software weaknesses (see Section 11.4) covered the possible incompletenesses of the back-analysis techniques used. As a result, it was merely indicated that although the rules that control the adjustment processes are relatively simple, the solutions provided for the simplest models could achieve reasonable accuracy. However it became clear that it was not possible to address the complexity of multi-layer models with the present system because of the inability of the system to consider at the same time the alternative rules available.

4. Clearly, although a major step forward, this prototype KBS does not demonstrate the competence that it had been hoped to show. However, it may be stated that it enabled a clarification of the requirements of the objectives of a working system and it enabled a refinement of the definition of the overall problem addressed by such a KBS.

In addition, with respect both to the observations made in Chapter 10, about the performance of the system, and also to the facilities provided by the individual modules of the overall system, it may be concluded that:

1. The selection of the appropriate material properties as "seed" values for the back-analysis technique is essentially a problem of manipulating data. These data should be stored, accessed, updated and selected efficiently. Prolog may not be considered as the best tool for such operations. Rather, it is felt that a relational database system would perform more effectively.

2. The back analysis module requires both the efficient manipulation of data (e.g. deflections, moduli, number of layers) and also the consideration of the logical relationships which may be deduced from these data. The development environment to be used for this module should address such issues efficiently and clearly Prolog does not.

3. Integrating a database, a knowledge base and an analytical tool into a unified system demands full compatibility between the above individual

programs. Unfortunately it has been found that the software packages available for each of them are not always compatible. Consequently, any further attempt to create the final working system should take this into account.

11.6 Summary

KBSs, like many other computing developments, have been at the focal point of research carried out in a wide range of scientific and engineering domains. The expectations of what may be achieved through the use of KBS technology have been raised to an unreasonable high level. Although it seems that their potential uses may cover existing gaps in the commercially available software, their capabilities are limited due to a number of factors. The most important of these are the lack of a concrete theoretical background to cover the behavioural procedures concerned, and weaknesses in both software and hardware. Such factors have influenced the performance of the prototype KBS developed during this study. However, it is felt that the observations made will be helpful in the future development of a working system.

Chapter 12

LOGICAL DESIGN OF THE CONSEQUENT KBS

12.1 Introduction

This chapter describes the design of the constituent modules of a computer system to be used for the evaluation of road pavements at project level. The considerations made about its functions, its characteristics and its architecture were guided by the experience gained during the development of the prototype system presented in Chapters 7 to 10. This system design seeks to facilitate the automation of the computational processes required by a comprehensive evaluation tool or tools, by integrating the capabilities of DBS, KBS and analytical programs.

It has been suggested that in order to build such a system, three approaches may be considered. These are [Jarke *et al.*, 1984; Bocca *et al.*, 1986 as quoted in Gardarin *et al.*, 1989]:

1. *Loose Coupling.*
2. *Tight Coupling.*
3. *Integration.*

Loose Coupling is the architectural approach in which the main program, written in Prolog, has automatic facilities to invoke a relational database (e.g. dBase, Oracle, Ingres) from which new facts may be deduced and subsequently stored in the Prolog program. *Tight Coupling* is the software architecture in which a rule-based language interpreter is built as a further layer onto a relational database. *Integration* may be considered as a further extension of such techniques. Using this approach both a rule definition language, and an inference subsystem to answer queries and execute updates on deduced relations, are integrated. A schematic representation of all three architectures is given in Figure 12.1 [After Gardarin *et al.*, 1989]. Unlike *Loose Coupling*, both *Tight Coupling* and *Integration* appear to be efficient programming environments with which to cope with the requirements of handling the data.

However, to date, there does not exist a commercially available development environment effected by any of the above techniques. As a result, the design of a working system will have to be based on a combination of the commonly used software packages which will have to satisfy the following criteria:

1. They should enable ease of use.

2. They should be based on a modular architecture in which each individual module can smoothly communicate with another.

3. The modules of the overall system should be sufficiently flexible to anticipate future enhancements.

4. They should exploit both the capabilities and facilities provided by Relational Database Management Systems (e.g. Oracle).

5. They should provide access to statistical analysis packages, spreadsheets and graphical interfaces.

12.2 Description of the System

A schematic representation of the system foreseen is shown in Figure 12.2. The architecture of this system has been developed on the basis of both the functions required by an ideal KBS for pavement analysis, as noted in Section 8.2 and presented in Figure 8.1, and also the experience gained from the performance of the prototype system during the validation process (cf. Chapter 11).

Thus, the constituent subsystems of the overall working system should be organized into the three part structure of the analytical program, the knowledge base and the database. In addition, a self-learning module should ideally be inserted, associated with the knowledge base and the database linking functions, to enable reference to be made to previous detailed analyses of a variety of case histories. The resultant four systems should then be linked for operation on the basis of a specified user friendly interface that would enable an efficient insight into the constituent processes.

The knowledge base subsystem will be constituted by a number of smaller programs that would perform the following tasks:

1. A comparative evaluation of both the observed and the measured data, permanently stored in the database, to establish the model to be used in the overall analysis process.

2. The back analysis.

3. The prediction of the remaining life of the tested pavement.

4. An optimization process that would provide a selection of remedial treatment alternatives (if required). It is felt that in this stage the system could provide either an overlay design or make suggestions for appropriate non-overlay roadworks. An interesting further development would be

a program that would attempt an economic evaluation of the proposed solutions although it is more likely that this would be effected as part of a wider management system.

All the above subprograms should be developed using a shell supported by a reliable certainty model (see Section 6.4.3).

The database subsystem should consist of a number of interfaces acting upon the sum total of data from the particular road section under scrutiny. Thus, provisions should be made for sub-modules such as:

1. A deflection database with automatic input facilities.

2. A database for the storage of the material properties (e.g. moduli, Poisson's ratio, stress-strain characteristics) used in pavement structures.

3. A database for the storage of the factorial design data (see Section 9.6.2). This database should enable the storage of verified case histories through the learning module.

4. A database for the storage of data concerning functional characteristics collected by means other than the FWD.

5. A database interface that would provide the user of the system with an overall presentation of the data (both collected and analyzed) which concerns a particular road section. This database should be fed with the results of the optimization process for the selection of the remedial treatment alternatives. In addition this database should have an interface to enable network level systems access.

There is considerable debate about the structure of a learning module. Although it is an attractive concept because of its innovative nature, *Machine Learning* is a research area of Artificial Intelligence and therefore it is felt that progress on such development will be slow in the near future.

12.3 Summary

This chapter has presented a design for a KBS for pavement analysis at project level. The system seeks to provide a uniform structure for conducting the tasks required for an effective rehabilitation process based on non-destructive testing data. The overall system is effected by a combination of software environments such as an analytical program, databases, and knowledge bases. Emphasis has been given to the currently available databased techniques, although the advantages of using logical inferences on the collected data by means of knowledge-based technology have been appreciated and discussed.

FIGURES

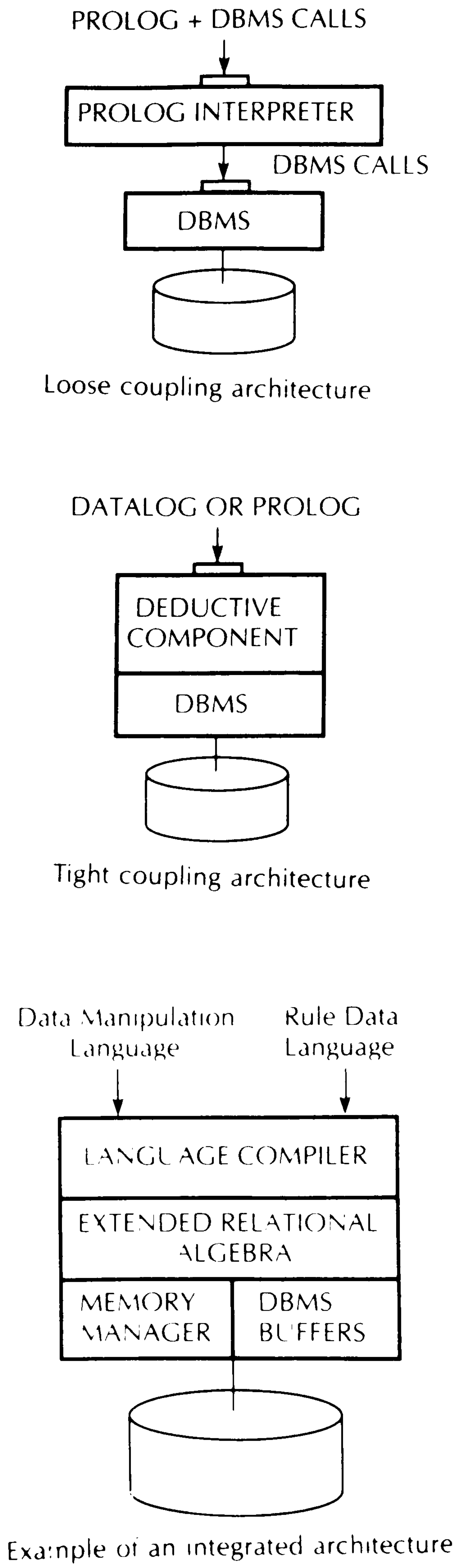

Figure 12.1: Types of Software Architectures for Integrating DBS with KBS

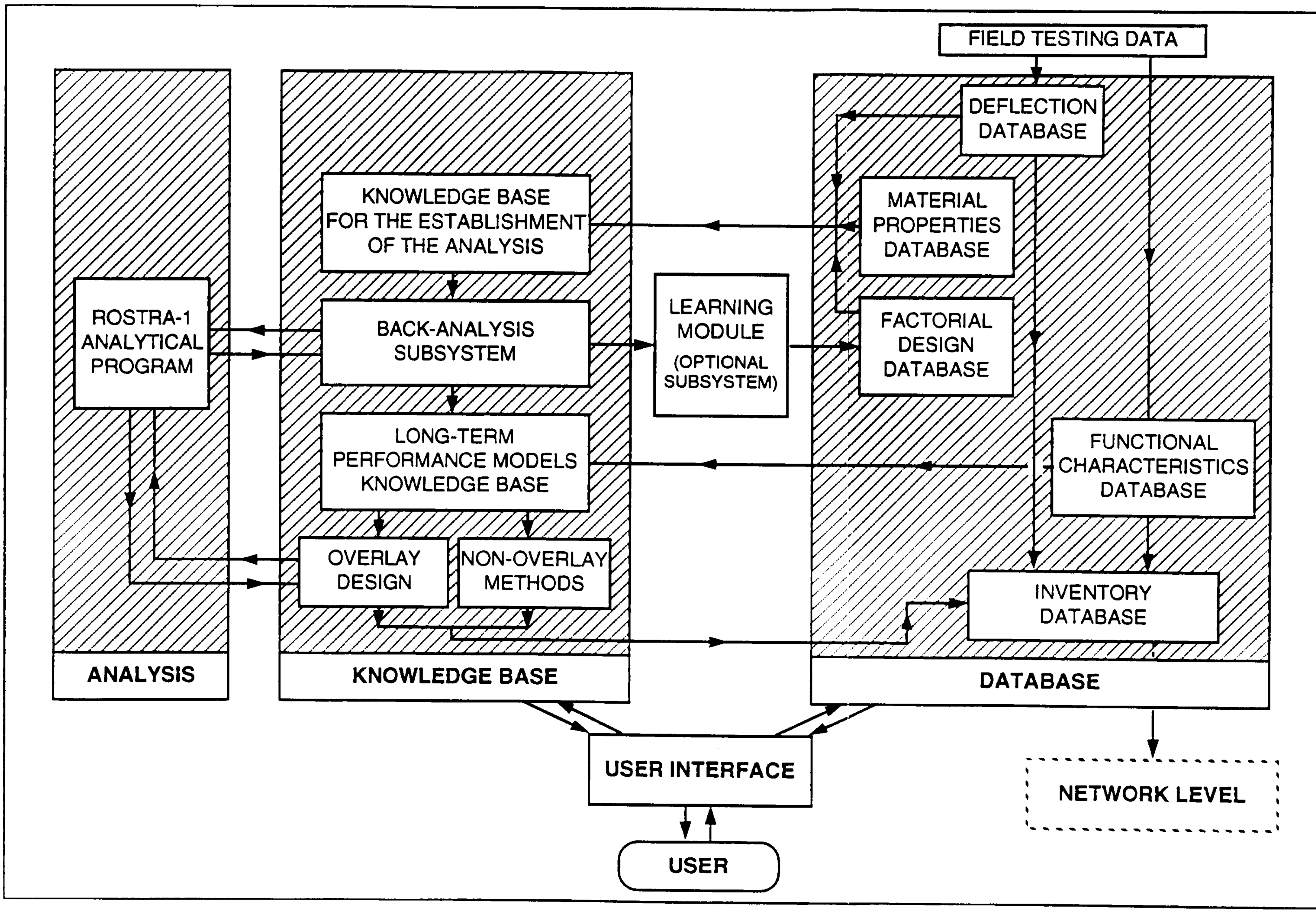

Figure 12.2: Logical Design of a KBS for Pavement Evaluation at Project Level.

Chapter 13

CONCLUSIONS

This work may be regarded as a systematic approach to the establishment of a knowledge-based system for use by a road maintenance engineer. The product of this research is the specification for a software package for use in the structural evaluation of flexible road pavements together with the production of a prototype which was used as a development tool for the former. The principal conclusions are given under the following headings:

1. The Establishment of the KBS.

2. Programming the Prototype KBS.

3. The Design of a Working KBS.

13.1 The Establishment of the KBS

1. It has been demonstrated that a KBS can be developed to "inject" engineering knowledge into conventional pavement structural evaluation techniques.

2. The functions required by an ideal KBS for the structural analysis of pavements at project level may be performed by means of a set of individual but interrelated modules. These are:

   (a) A database which holds the field testing data.

(b) A finite element computer program which conducts the structural analysis of the pavements tested with the FWD.

(c) A knowledge base which provides a tool for handling the data used by the system in a logical manner.

3. The extent of knowledge necessary for the operation of a KBS has been investigated and the following items are required:

   (a) Information about the pavement condition.

   (b) Likely moduli of a variety of pavement materials for use in the mechanistic analysis.

   (c) Likely Poisson's ratios of a number of material types.

   (d) Pavement performance models.

   (e) Heuristics and empirical relationships that may assist the analysis.

   (f) The results from a wide variety of typical pavements previously analyzed by the analytical program.

13.2 Programming the Prototype System

1. A prototype KBS has been designed and programmed which subsequently enabled a full demonstration of the performance characteristics of such a system and also a systematic assessment of the KBS based processes.

2. The prototype KBS system includes:

   (a) A deductive database for the establishment of the analytical model to be used in pavement simulation, written in Prolog.

   (b) The program ROSTRA-1, a derivative of the finite element program DEFPAV specially designed for the analysis of road structures, written in FORTRAN.

(c) A back analysis system, that is based on empirical rules rather than pure arithmetic procedures, written in Prolog.

(d) Control facilities written in DCL.

3. It was shown that the process may be enhanced by the use of a databased system (programmed in FORTRAN). The use of this indicated the advisability of developing a self-learning capacity within the overall process.

4. An elementary knowledge base has been programmed in Prolog to demonstrate how such systems may be used for the simulation of the assessment procedure carried out during field testing.

Conclusions Drawn

1. The prototype system fulfilled the designed functions and provided results that were generally consistent with known material characteristics. However, when inconsistencies were present, these were found to be due to a number of weaknesses in both the software used and the overall architecture of the system.

2. It is evident that the prototype system is not entirely satisfactory in the following respects:

   (a) Separation between the storage of the data and their manipulation by the knowledge base.

   (b) Security in the encoded knowledge base.

   (c) Easy administration and control of the programmed processes.

3. It is unlikely that any further enhancements could be made to the prototype system.

4. From both a research and practicing engineer's point of view, Prolog is not the ideal tool for developing a KBS.

5. The highway engineer requires a knowledge base development tool which addresses highly sophisticated processes. It appears that the current software technology does not provide such capabilities.

6. Feedback procedures, based on previously analyzed case histories, could enhance the performance of the system.

13.3 The Design of a Working KBS

1. The development of the knowledge base of a working KBS should be based on a rule-based shell environment with the ability to provide an audit trail of its logical processes to the user.

2. The ancillary software to be used should be well-established and should include items such as:

   (a) A relational database supported by a number of facilities such as a spreadsheet, a graphical interface and an extension to a statistical package.

   (b) Conventional programming languages such as FORTRAN.

3. In addition to the standard processes, provisions should be made to anticipate a number of future developments. These include:

   (a) A relational database system for the various types of data collected during a full diagnostic field testing process.

   (b) A knowledge base for the optimization of the selection of the remedial treatment required for a deteriorated road section, based on both engineering and economic considerations.

   (c) A self-learning module which will simulate experience acquisition procedures from the case studies earlier analyzed.

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Appendix A

ROSTRA-1 OUTPUT FILES

This Appendix contains extracts from the output of an analysis of a pavement model carried out by ROSTRA-1. The extracts show the characteristics of the new program; that is, the grid expansion, the calculation of the strains and the FWD-specific automatically generated grid.

```
                                    ****************************************
                                    *                                      *
                                    *               PROGRAM                *
                                    *     ROad STRuctural Analysis - 1     *
                                    *           ( ROSTRA -1 )              *
                                    *                                      *
                                    *     THE UNIVERSITY OF BIRMINGHAM     *
                                    *     SCHOOL OF CIVIL ENGINEERING      *
                                    *        HIGHWAYS RESEARCH GROUP       *
                                    *                                      *
                                    *                                      *
                                    *  M.S.SNAITH           H.T.EVDORIDES  *
                                    *                                      *
                                    *                          FEB 1993    *
                                    ****************************************
                   Hillsborough Test Site
OUSING GRID SPECIFICATION OPTION (GRID = 1)
 ******************************************
ONUMBER OF LAYERS:-   3
ONUMBER OF ROWS:-    25
ONUMBER OF COLUMNS:- 18

OTOTAL NUMBER OF NODES USED IN GRID = 494
OLAYER  1 HAS  4 ROWS
OLAYER  2 HAS  4 ROWS
OLAYER  3 HAS 17 ROWS
ORADIUS OF NODES IN EACH COLUMN:-

            0.000   0.025   0.050   0.075   0.100   0.130   0.160   0.200   0.300   0.600   0.900   1.200
            1.500   1.800   2.100   2.400   3.000   3.500   4.000
OVERTICAL ORDINATE OF NODES IN EACH ROW:-

            0.000   0.025   0.050   0.075   0.100   0.221   0.342   0.464   0.585   0.685   0.885   1.000
            1.500   2.000   2.500   3.000   3.500   4.000   4.500   5.000   5.500   6.000   6.500   7.000

            7.500   8.000
OLAYER  1
---------
OMODULUS CODE:-  0
OYOUNG'S MODULUS:-     2500.00
OPOISSON'S RATIO:-        0.40

OLAYER  2
---------
OMODULUS CODE:-  0
OYOUNG'S MODULUS:-       31.25
OPOISSON'S RATIO:-        0.30

OLAYER  3
---------
```

Figure A.1: ROSTRA-1 output extract showing the grid expansion.

```
OMODULUS CODE:-  0
OYOUNG'S MODULUS:-        12.50
OPOISSON'S RATIO:-         0.45


0 APPLIED LOADS -             TYPE ROW  COL  DIST/HOR  LOAD/VERT

                               1     1    1     0.130   590.000


0 OUTPUT OF DEFLECTIONS OF NODES AFTER COMPLETION OF CYCLE NUMBER 4
 =================================================================


0                   NODAL CHARACTERISTICS, CYCLE NUMBER  4.
                    ========================================

0                   CO-ORDINATES            INITIAL LOADS              DEFLECTIONS
    NODE NO.        ============            =============              ===========
    ========    R-ORDINATE Z-ORDINATE    HORIZONTAL    VERTICAL     HORIZONTAL    VERTICAL

0  ROW NUMBER  1
        1          0.000        0.000        0.000        0.386        0.0000       0.5906                           1
        2          0.025        0.000        0.000        2.317       -0.0123       0.5852                           3
        3          0.050        0.000        0.000        4.634       -0.0238       0.5731                           5
        4          0.075        0.000        0.000        6.951       -0.0341       0.5538                           7
        5          0.100        0.000        0.000       10.364       -0.0428       0.5280                           9
        6          0.130        0.000        0.000        6.673       -0.0506       0.4866                          11
        7          0.160        0.000        0.000        0.000       -0.0554       0.4422                          13
        8          0.200        0.000        0.000        0.000       -0.0575       0.3873                          15
        9          0.300        0.000        0.000        0.000       -0.0507       0.2609                          17
       10          0.600        0.000        0.000        0.000       -0.0253       0.0130                          19
       11          0.900        0.000        0.000        0.000        0.0004      -0.0530                          21
       12          1.200        0.000        0.000        0.000        0.0081      -0.0138                          23
       13          1.500        0.000        0.000        0.000        0.0020       0.0200                          25
       14          1.800        0.000        0.000        0.000       -0.0029       0.0105                          27
       15          2.100        0.000        0.000        0.000       -0.0009      -0.0056                          29
       16          2.400        0.000        0.000        0.000        0.0011      -0.0021                          31
       17          3.000        0.000        0.000        0.000       -0.0002       0.0045                          33
       18          3.500        0.000        0.000        0.000       -0.0001      -0.0020                          35
       19          4.000        0.000        0.000        0.000        0.0000       0.0012                          37

1   ELEMENT STRESSES.
    ================

                    RADIAL          HOOP          VERTICAL       SHEAR        MODULUS      NEW MODULUS    STRESS COMP.

OLAYER NO.  1  ROW NO.   1

         ELEMENT NO.  1    -1817.749     -1817.749      -535.435      -69.596      2500.000
```

Figure A.2: ROSTRA-1 output extract showing the grid expansion (*cont'ed*).

```
ELEMENT MICRO STRAIN      -350.590    -350.590    367.505     -77.947
        ELEMENT NO.  2   -1728.357   -1758.822   -530.791     -72.421    2500.000
ELEMENT MICRO STRAIN      -325.005    -342.065    345.632     -81.111
        ELEMENT NO.  3   -1608.082   -1676.337   -531.256    -102.850    2500.000
ELEMENT MICRO STRAIN      -290.018    -328.241    313.005    -115.192
        ELEMENT NO.  4   -1440.459   -1568.628   -544.197    -137.290    2500.000
ELEMENT MICRO STRAIN      -238.132    -309.906    263.775    -153.765
        ELEMENT NO.  5   -1153.460   -1333.919   -395.230    -240.322    2500.000
ELEMENT MICRO STRAIN      -184.720    -285.777    239.889    -269.161
        ELEMENT NO.  6    -777.509   -1001.057   -102.179    -229.208    2500.000
ELEMENT MICRO STRAIN      -134.486    -259.673    243.699    -256.712
        ELEMENT NO.  7    -435.090    -741.828     -4.069    -137.593    2500.000
ELEMENT MICRO STRAIN       -54.693    -226.466    186.679    -154.104
        ELEMENT NO.  8     -40.132    -397.740     40.923    -118.337    2500.000
ELEMENT MICRO STRAIN        41.038    -159.222     86.429    -132.537
        ELEMENT NO.  9     133.985     -90.503     33.437     -52.305    2500.000
ELEMENT MICRO STRAIN        62.725     -62.989      6.417     -58.581
        ELEMENT NO. 10     194.094      57.660     27.930      23.413    2500.000
ELEMENT MICRO STRAIN        63.943     -12.460    -29.109      26.222
        ELEMENT NO. 11      55.352      26.173     -8.653      39.926    2500.000
ELEMENT MICRO STRAIN        19.337       2.997    -16.505      44.717
        ELEMENT NO. 12     -53.491     -21.620    -18.113      13.896    2500.000
ELEMENT MICRO STRAIN       -15.039       2.809      4.773      15.563
        ELEMENT NO. 13     -39.561     -18.015     -4.337     -15.974    2500.000
ELEMENT MICRO STRAIN       -12.248      -0.182      7.477     -17.891
        ELEMENT NO. 14      20.352      10.350     10.030     -11.040    2500.000
ELEMENT MICRO STRAIN         4.880      -0.721     -0.900     -12.364
        ELEMENT NO. 15      16.814       7.926      2.785      10.242    2500.000
ELEMENT MICRO STRAIN         5.012       0.034     -2.844      11.471
        ELEMENT NO. 16      -7.463      -4.418     -4.408       2.810    2500.000
ELEMENT MICRO STRAIN        -1.573       0.132      0.138       3.147
        ELEMENT NO. 17       0.926       0.828      1.355      -7.909    2500.000
ELEMENT MICRO STRAIN         0.021      -0.034      0.261      -8.858
        ELEMENT NO. 18      -0.506      -0.903     -1.664       7.036    2500.000
ELEMENT MICRO STRAIN         0.208      -0.014     -0.440       7.880

                          ******************************************
                          *                                        *
                          *              PROGRAM                   *
                          *     ROad STRuctural Analysis - 1       *
                          *           ( ROSTRA -1 )                *
                          *                                        *
                          *    THE UNIVERSITY OF BIRMINGHAM        *
                          *    SCHOOL OF CIVIL ENGINEERING         *
                          *       HIGHWAYS RESEARCH GROUP          *
                          *                                        *
                          *                                        *
                          *  M.S.SNAITH            H.T.EVDORIDES   *
                          *                                        *
                          *                             FEB 1993   *
                          ******************************************
```

Figure A.3: ROSTRA-1 output extract showing the grid expansion (*cont'ed*).

```
                          *******************************************
                          *                                         *
                          *              PROGRAM                    *
                          *     ROad STRuctural Analysis - 1        *
                          *           ( ROSTRA -1 )                 *
                          *                                         *
                          *     THE UNIVERSITY OF BIRMINGHAM        *
                          *     SCHOOL OF CIVIL ENGINEERING         *
                          *       HIGHWAYS RESEARCH GROUP           *
                          *                                         *
                          *                                         *
                          *  M.S.SNAITH            H.T.EVDORIDES    *
                          *                                         *
                          *                              FEB 1993   *
                          *******************************************
                   Demostration Example Showing FWD-Specific Grid Generation and Grid Expansion
0 USING AUTOMATIC GRID OPTION SPECIFIED FOR FWD DEFLECTION BOWL BACK ANALYSIS ( GRID=2 )
 **************************************************************************************
0NUMBER OF LAYERS:-   7
0NUMBER OF COLUMNS:- 15

0RADIUS OF NODES IN EACH COLUMN:-

            0.000    0.050    0.100    0.150    0.200    0.300    0.600    0.900    1.200    1.500    1.800    2.100
            2.400    2.700    3.000    3.300
0GRID GENERATED HAS 3 ROWS PER LAYER FOR ALL LAYERS EXCEPT SUBGRADE,LAYER   7

 SPECIFIED LAYER THICKNESSES IN ORDER FROM TOP LAYER,BUT EXCLUDING BOTTOM (SUBGRADE) LAYER:-

            0.100    0.100    0.150    0.150    0.150    0.150
0NUMBER OF NODES AVAILABLE FOR SUBGRADE = NOLEFT =   95
0LAYER   7 HAS   5 ROWS
0VERTICAL ORDINATE OF NODES IN EACH ROW:-

            0.000    0.030    0.058    0.100    0.130    0.158    0.200    0.244    0.287    0.350    0.394    0.437
            0.500    0.544    0.587    0.650    0.694    0.737    0.800    0.900    1.238    2.038    3.600    6.300

0NUMBER OF ELEMENT ROWS IN GRID = 23
0TOTAL NUMBER OF NODES USED IN GRID = 384
0LAYER  1
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-     8000.00
0POISSON'S RATIO:-        0.40

0LAYER  2
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-     5000.00
0POISSON'S RATIO:-        0.40
```

Figure A.4: ROSTRA-1 output extract showing the FWD-specific grid generation together with the expanded size grid and the calculation of the strains.

```
0LAYER  3
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-       500.00
0POISSON'S RATIO:-         0.30

0LAYER  4
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-       195.00
0POISSON'S RATIO:-         0.30

0LAYER  5
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-        78.00
0POISSON'S RATIO:-         0.30

0LAYER  6
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-        31.25
0POISSON'S RATIO:-         0.30

0LAYER  7
---------
0MODULUS CODE:-  0
0YOUNG'S MODULUS:-        12.50
0POISSON'S RATIO:-         0.45

0 LOAD DATA INITIALISED TO ZERO.


0 APPLIED LOADS -            TYPE ROW  COL  DIST/HOR  LOAD/VERT

                               1    1    1     0.150   700.000
0 BOUNDARY CONDITIONS INITIALISED.

0 OUTPUT OF DEFLECTIONS OF NODES AFTER COMPLETION OF CYCLE NUMBER 4
 ===============================================================


0                   NODAL CHARACTERISTICS, CYCLE NUMBER  4.
                    =======================================

0                   CO-ORDINATES              INITIAL LOADS             DEFLECTIONS
    NODE NO.        ============              =============             ===========
    ========    R-ORDINATE Z-ORDINATE     HORIZONTAL    VERTICAL     HORIZONTAL    VERTICAL
```

Figure A.5: ROSTRA-1 output extract showing the FWD-specific grid generation together with the expanded size grid and the calculation of the strains (*cont'ed*).

0 ROW NUMBER 1

1	0.000	0.000	0.000	1.833	0.0000	0.1569	1
2	0.050	0.000	0.000	10.996	-0.0048	0.1539	3
3	0.100	0.000	0.000	21.991	-0.0089	0.1473	5
4	0.150	0.000	0.000	14.661	-0.0120	0.1351	7
5	0.200	0.000	0.000	0.000	-0.0140	0.1223	9
6	0.300	0.000	0.000	0.000	-0.0159	0.1010	11
7	0.600	0.000	0.000	0.000	-0.0144	0.0438	13
8	0.900	0.000	0.000	0.000	-0.0086	0.0050	15
9	1.200	0.000	0.000	0.000	-0.0024	-0.0120	17
10	1.500	0.000	0.000	0.000	0.0016	-0.0113	19
11	1.800	0.000	0.000	0.000	0.0023	-0.0031	21
12	2.100	0.000	0.000	0.000	0.0009	0.0027	23
13	2.400	0.000	0.000	0.000	-0.0005	0.0025	25
14	2.700	0.000	0.000	0.000	-0.0008	-0.0008	27
15	3.000	0.000	0.000	0.000	-0.0002	-0.0025	29
16	3.300	0.000	0.000	0.000	0.0000	-0.0019	31

1 ELEMENT STRESSES.
================

0LAYER NO. 1 ROW NO. 1

	RADIAL	HOOP	VERTICAL	SHEAR	MODULUS	NEW MODULUS	STRESS COMP.
ELEMENT NO. 1	-1409.239	-1409.289	-676.146	-56.821	8000.000		
ELEMENT MICRO STRAIN	-71.889	-71.889	56.411	-19.888			
ELEMENT NO. 2	-1274.886	-1323.618	-681.655	-51.706	8000.000		
ELEMENT MICRO STRAIN	-59.097	-67.625	44.718	-18.097			
ELEMENT NO. 3	-1041.519	-1116.310	-504.828	-164.158	8000.000		
ELEMENT MICRO STRAIN	-49.133	-62.221	44.788	-57.455			
ELEMENT NO. 4	-685.213	-785.688	-136.822	-144.037	8000.000		
ELEMENT MICRO STRAIN	-39.526	-57.109	56.442	-50.413			
ELEMENT NO. 5	-370.731	-532.510	-3.875	-47.830	8000.000		
ELEMENT MICRO STRAIN	-19.522	-47.833	44.678	-16.741			
ELEMENT NO. 6	-57.860	-233.970	27.037	-37.567	8000.000		
ELEMENT MICRO STRAIN	3.114	-27.705	17.971	-13.149			
ELEMENT NO. 7	121.625	-42.341	29.060	-13.053	8000.000		
ELEMENT MICRO STRAIN	15.867	-12.827	-0.332	-4.568			
ELEMENT NO. 8	156.784	32.847	13.929	1.104	8000.000		
ELEMENT MICRO STRAIN	17.259	-4.430	-7.740	0.386			
ELEMENT NO. 9	106.557	41.246	2.356	11.830	8000.000		
ELEMENT MICRO STRAIN	11.139	-0.290	-7.096	4.141			
ELEMENT NO. 10	19.578	12.278	-8.498	13.397	8000.000		
ELEMENT MICRO STRAIN	2.258	0.981	-2.655	4.689			
ELEMENT NO. 11	-41.491	-15.584	-11.656	5.653	8000.000		
ELEMENT MICRO STRAIN	-3.824	0.709	1.397	1.979			
ELEMENT NO. 12	-42.985	-18.893	-5.936	-4.003	8000.000		
ELEMENT MICRO STRAIN	-4.132	0.084	2.352	-1.401			
ELEMENT NO. 13	-6.389	-3.552	1.713	-6.594	8000.000		

Figure A.6: ROSTRA-1 output extract showing the FWD-specific grid generation together with the expanded size grid and the calculation of the strains.

```
ELEMENT MICRO STRAIN       -0.707      -0.210      0.711      -2.308
       ELEMENT NO. 14      18.304       8.177      4.923      -1.586      8000.000
ELEMENT MICRO STRAIN        1.633      -0.1 9     -0.709      -0.555
       ELEMENT NO. 15       0.945      -2.088     -5.682       6.722      8000.000
ELEMENT MICRO STRAIN        0.507      -0.024     -0.653       2.353
                                    *****************************************
                                    *                                       *
                                    *              PROGRAM                  *
                                    *      ROad STRuctural Analysis - 1     *
                                    *            ( ROSTRA -1 )              *
                                    *                                       *
                                    *      THE UNIVERSITY OF BIRMINGHAM     *
                                    *      SCHOOL OF CIVIL ENGINEERING      *
                                    *        HIGHWAYS RESEARCH GROUP        *
                                    *                                       *
                                    *                                       *
                                    *  M.S.SNAITH            H.T.EVDORIDES  *
                                    *                                       *
                                    *                            FEB 1993   *
                                    *****************************************
```

Figure A.7: ROSTRA-1 output extract showing the FWD-specific grid generation together with the expanded size grid and the calculation of the strains (*cont'ed*).

Appendix B

PAFEC INPUT FILES

The capabilities of the computer program PAFEC together with a critical discussion of them have already been presented in Chapter 5. In this appendix a basic input file of an axisymmetric representation of a pavement is given. In addition five other input files which may be useful to the user of the program are presented. The first one enables the calculation of plastic strains and equivalent stresses in an axisymmetric model. The second model could be used in order that the dynamic response of an axisymmetrically modelled pavement may be found. The third and the forth model simulate the pavement as a slab which is supported by springs. These springs may be considered as a representation of a Winkler foundation. It is felt that this simulation may be useful if a rigid pavement is to be analysed. The encoding of a creep law equation is also presented.

Further explanations of the preparation of these files may be found elsewhere [PAFEC, 1984].

B.1 Typical Axisymmetric Pavement Model

```
TITLE  *** PAVEMENT ANALYSIS ***   Run by H. T. EVDORIDES
CONTROL
AXISYMMETRIC
STRESS
CONTROL.END
NODES
NODE.NUMBER,X,Y
1,5.585,0
2,5.585,0.13
3,5.585,0.5
4,5.585,3
5,5.485,0
6,5.485,0.13
7,5.485,0.5
8,5.485,3
9,5.323,0
10,5.323,0.13
11,5.323,0.5
12,5.323,3
13,5.161,0
14,5.161,0.13
15,5.161,0.5
16,5.161,3
17,5,0
18,5,0.13
19,5,0.5
20,5,3
```

```
21,0,0
22,0,0.13
23,0,0.5
24,0,3
PAFBLOCKS
TYPE=1
ELEMENT.TYPE=36210
BLOCK.NUMBER GROUP.NUMBER PROPERTIES  N1 N2   TOPOLOGY
     1             1            1      4  4   1 2 5 6
     2             2            1      12 4   3 6 7
     3             3            1      24 2   4 7 8
     4             4            2      4  4   5 6 9 10
     5             5            2      6  2   6 7 10 11
     6             6            2      24 2   7 8 11 12
     7             7            3      4  4   9 10 13 14
     8             8            3      6  2   10 11 14 15
     9             8            3      24 2   11 12 15 16
     10            10           4      4  4   13 14 17 18
     11            11           4      6  2   14 15 18 19
     12            12           4      24 2   15 16 19 20
     13            13           5      2  30  17 18 21 22
     14            14           5      2  30  18 19 22 23
     15            15           5      12 30  19 20 23 24
MESH
REFERENCE SPACING.LIST
     2          2
     4          4
     6          6
     12         12
```

```
    24          24
    30          30
PLATES.AND.SHELLS
PLATE.NUMBER MATERIAL
    1           11
    2           12
    3           13
    4           14
    5           15
PRESSURE
LOAD.CASE PRESSURE.VALUE LIST.OF.NODES
   1          590E3         1 2
RESTRAINTS
AXIS.NUMBER=1
NODE PLANE DIRECTION
 21    1       1
 24    1       1
 24    2       2
MATERIAL
MATERIAL.NUMBER      E         NU
      11           3000E6      0.4
      12            390E6      0.3
      13            156E6      0.3
      14             63E6      0.3
      15             25E6      0.45
IN.DRAW
DRAWING.NUMBER TYPE.NUMBER INFORMATION.NUMBER
       1            3              5
OUT.DRAW
```

```
PLOT.TYPE
    1
GRAPH
TYPE.NUMBER  LIST.OF.NODES
     1            1 4
END.OF.DATA
```

B.2 Plastic Analysis Model

```
TITLE  *** PAVEMENT PLASTIC ANALYSIS ***   run by   H. T. EVDORIDES
CONTROL
PLASTIC
FULL.CONTROL
PHASE=1
REDUCED.OUTPUT
PHASE=2
REDUCED.OUTPUT
PHASE=3
PHASE=4
REDUCED.OUTPUT
PHASE=6
PHASE=7
CLEAR.FILES
PHASE=8
PHASE=9
PHASE=10
CLEAR.FILES
AXISYMMETRIC
STRESS
CONTROL.END
STRAIN.ENERGY.DENSITY
START FINISH STEP
  1    1000    1
NODES
NODE.NUMBER,X,Y
1,2.585,0
```

```
2,2.585,0.13
3,2.585,0.5
4,2.585,1.5
5,2.485,0
6,2.485,0.13
7,2.485,0.5
8,2.485,1.5
9,2.323,0
10,2.323,0.13
11,2.323,0.5
12,2.323,1.5
13,2.161,0
14,2.161,0.13
15,2.161,0.5
16,2.161,1.5
17,2,0
18,2,0.13
19,2,0.5
20,2,1.5
21,0,0
22,0,0.13
23,0,0.5
24,0,1.5
PAFBLOCKS
TYPE=1
BLOCK.NUMBER GROUP.NUMBER ELEMENT.TYPE PROPERTIES N1 N2  TOPOLOGY
     1             1          36110          1      4  4    1 2 5 6
     2             2          36210          1      12 4    2 3 6 7
     3             3          36210          1      12 2    3 4 7 8
```

```
    4          4       36210      2    4  4    5 6 9 10
    5          5       36210      2    6  2    6 7 10 11
    6          6       36210      2    6  1    7 8 11 12
    7          7       36210      3    4  4    9 10 13 14
    8          8       36210      3    6  2    10 11 14 15
    9          9       36210      3    6  1    11 12 15 16
    10         10      36210      4    4  4    13 14 17 18
    11         11      36210      4    6  2    14 15 18 19
    12         12      36210      4    6  1    15 16 19 20
    13         13      36210      5    2  12   17 18 21 22
    14         14      36210      5    2  3    18 19 22 23
    15         15      36210      5    2  3    19 20 23 24
MESH
REFERENCE SPACING.LIST
    1        1
    2        2
    3        3
    4        4
    5        5
    6        6
    8        8
    10       10
    12       12
    16       16
    20       20
    24       24
    32       32
    48       48
    96       96
```

```
PLATES.AND.SHELLS
PLATE.NUMBER MATERIAL
     1          11
     2          12
     3          13
     4          14
     5          15
PRESSURE
LOAD.CASE PRESSURE.VALUE LIST.OF.NODES
   1         590E3          1 2
RESTRAINTS
AXIS.NUMBER=1
NODE PLANE DIRECTION
 21    1       1
 24    1       1
 24    2       2
MATERIAL
MATERIAL.NUMBER      E          NU     RO
      11           3750E6       0.4    2200
      12          31.25E6       0.3    2000
      13          31.25E6       0.3    2000
      14          31.25E6       0.3    2000
      15           12.5E6       0.45   1800
PLASTIC.MATERIAL
PLASTIC.MATERIAL.NUMBER TYPE.OF.PLASTIC.MATERIAL PROPERTY.LIST
            1                     2                35E3 2.549E-4
*70E3 4.028E-4 105E3 5.102E-4 140E3 5.833E-4
            2                     2                20E3 6.667E-4
*30E3 1.176E-3 40E3 1.905E-3 50E3 3.03E-3 60E3 5E-3
```

```
YIELDING.ELEMENTS
PLASTIC.MATERIAL.NUMBER    GROUP.ELEMENT
            1                  5
            1                  6
            1                  7
            1                  8
            1                  9
            1                  10
            1                  11
            1                  12
            2                  13
            2                  14
            2                  15
INCREMENTAL
GAUSS.POINT.PRINT DISPLACEMENT.PRINT NODAL.STRESS.PRINT STEP.LIST
       1                     1                  1         100
IN.DRAW
TYPE.NUMBER INFORMATION.NUMBER  GROUPS
    3             0                0
OUT.DRAW
PLOT.TYPE
    1
    51
    31
GRAPH
TYPE.NUMBER LIST.OF.NODES
     1          1 4
END.OF.DATA
```

B.3 Dynamic Analysis Model

```
TITLE DYNAMIC AXISYMMETRIC PAVEMENT ANALYSIS  run by   H. T. EVDORIDES
CONTROL
FULL.CONTROL
PHASE=1
PHASE=2
PHASE=3
PHASE=4
PHASE=5
PHASE=6
PHASE=7
PHASE=8
PHASE=9
PHASE=10
CLEAR.FILES
AXISYMMETRIC
STRESS
CONTROL.END
NODES
NODE.NUMBER,X,Y
1,5.585,0
2,5.585,0.15
3,5.585,0.5
4,5.585,3
5,5.485,0
6,5.485,0.15
7,5.485,0.5
8,5.485,3
```

```
9,5.323,0
10,5.323,0.15
11,5.323,0.5
12,5.323,3
13,5.161,0
14,5.161,0.15
15,5.161,0.5
16,5.161,3
17,5,0
18,5,0.15
19,5,0.5
20,5,3
21,0,0
22,0,0.15
23,0,0.5
24,0,3
PAFBLOCKS
TYPE=1
BLOCK.NUMBER GROUP.NUMBER ELEMENT.TYPE PROPERTIES N1 N2 TOPOLOGY
     1             1            36210         1     4  4  1 2 5 6
     2             2            36210         1     12 4  2 3 6 7
     3             3            36210         1     24 2  3 4 7 8
     4             4            36210         2     4  4  5 6 9 10
     5             5            36210         2     6  2  6 7 10 11
     6             6            36210         2     24 2  7 8 11 12
     7             7            36210         3     4  4  9 10 13 14
     8             8            36210         3     6  2  10 11 14 15
     9             8            36210         3     24 2  11 12 15 16
     10            10           36210         4     4  4  13 14 17 18
```

```
    11        11        36210       4     6  2   14 15 18 19
    12        12        36210       4    24  2   15 16 19 20
    13        13        36210       5     2  3   17 18 21 22
    14        14        36210       5     2  3   18 19 22 23
    15        15        36210       5    12 30   19 20 23 24
MESH
REFERENCE SPACING.LIST
    1         1
    2         2
    3         3
    4         4
    5         5
    6         6
    8         8
    10        10
    12        6
    16        16
    18        18
    24        12
    30        15
    36        36
PLATES.AND.SHELLS
PLATE.NUMBER MATERIAL
    1         11
    2         12
    3         13
    4         14
    5         15
RESTRAINTS
```

```
AXIS.NUMBER=1
NODE PLANE DIRECTION
 21     1         1
MATERIAL
MATERIAL.NUMBER        E           NU      RO
      11            3500E6        0.35    2300
      12             390E6        0.3     2200
      13             165E6        0.3     2200
      14              63E6        0.3     2200
      15              25E6        0.45    1800
MODES.AND.FREQUENCIES
AUTO MODES
 20     0
MASTERS
NODE DIRE
 1     1
 2     1
 3     1
 4     1
RESPONSE
TYPE
 1
FREQUENCIES.FOR.ANALYSIS
TYPE START FINISH STEP
 1      0     100      2
FORCING
TIME    LIST.OF.NODES.DIRECTIONS.AND.VALUES
 0.0           1           1           0.0
 0.0           2           1           0.0
```

```
 125E-4       1           1           -25E3
 125E-4       2           1           -25E3
 25E-3        1           1            0.0
 25E-3        2           1            0.0
DAMPING
FREQUENCY  DAMPING.RATIO
    0           0.05
   40           0.05
SINE.LOADING
NODE.NUMBER DIRECTION.OF.LOAD TABLE.NUMBER
     1             1               1
     2             1               1
TABLE.OF.APPLIED.FORCES
TABLE BASIS.VALUE VALUE.LIST
  1         0         0   0
  1        40       -25E3 0
SINUSOIDAL.OUTPUT
NODE DIRECTION
 1       1
 2       1
 3       1
 4       1
IN.DRAW
DRAWING.NUMBER TYPE.NUMBER INFORMATION.NUMBER
       1             3            5
OUT.DRAW
PLOT.TYPE
    1
GRAPH
```

```
TYPE.NUMBER  LIST.OF.NODES
     1            1 4
DYNAMICS.GRAPH
NODE DIRECTION
 1       1
 2       1
 3       1
 4       1
FULL.DYNAMICS.OUTPUT
TYPE START FINISH STEP
  2    1     0     1
END.OF.DATA
```

B.4 Static Analysis of Cement Concrete Slab

```
C CEMENT CONCRETE SLAB  4 X 4
C    STATIC ANALYSIS
C LOADED AT THE EDGE
CONTROL
STRESS
PHASE=9
CLEAR.FILES
CONTROL.END
NODES
NODE  X  Y
1     0  0
2     4  0
3     0  4
4     4  4
65    2  2
66    1  1
67    3  1
68    1  3
69    3  3
70    1  2
71    3  2
72    2  1
73    2  3
74    0  2
75    0.5 2
76    1.5 2
77    1.5 1.5
```

```
78     0.5 0.5
79     2  0
80     2  4
81     4  2
LINE.NODES
LIST.OF.NODES.ON.LINE
 1 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 2
 1 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 3
 2 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 4
 3 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 4
SPRINGS
C      THE SLAB IS ON A LAYER WITH ~500MPa E
NUMBER.OF.SPRING    KZ
       1            25E6
ELEMENTS
PROPERTIES=1
ELEMENT.TYPE=30100
 TOPOLOGY
   1 0
   2 0
   3 0
   4 0
   5 0
   6 0
   7 0
   8 0
   9 0
  10 0
  11 0
```

```
12 0
13 0
14 0
15 0
16 0
17 0
18 0
19 0
20 0
21 0
22 0
23 0
24 0
25 0
26 0
27 0
28 0
29 0
30 0
31 0
32 0
33 0
34 0
35 0
36 0
37 0
38 0
39 0
40 0
```

```
41 0
42 0
43 0
44 0
45 0
46 0
47 0
48 0
49 0
50 0
51 0
52 0
53 0
54 0
55 0
56 0
57 0
58 0
59 0
60 0
61 0
62 0
63 0
64 0
65 0
66 0
67 0
68 0
69 0
```

```
  70  0
  71  0
  72  0
  73  0
  74  0
  79  0
  80  0
  81  0
PAFBLOCKS
TYPE=1
ELEMENT.TYPE=44210
PROPERTIES=1
N1=1
N2=1
TOPOLOGY
 1  2  3  4
MESH
REFERENCE SPACING
   1          16
PLATES.AND.SHELLS
PLATE MATERIAL THICKNESS
  1        10       0.1
C
C  IF THE NODE NUMBER IS 65 THEN THE SLAB IS LOADED AT ITS CENTRE
C
LOADS
CASE.OF.LOAD   NODE.NUMBER  DIRECTIONS.OF.LOAD  VALUE.OF.LOAD
     1              79                3               -120E3
IN.DRAW
```

```
TYPE.NUMBER
   2
OUT.DRAW
PLOT.TYPE
   1
   20
   21
   22
END.OF.DATA
```

B.5 Dynamic Analysis of Cement Concrete Slab

```
C                SLAB OF "INFINITE" LENGTH (=16M) & WIDTH=4M
C DYNAMIC ANALYSIS
C THE SLAB RESTS ON A SYSTEM OF SPRINGS
CONTROL
PHASE=7
CLEAR.FILES
STRESS
CONTROL.END
NODES
NODE   X  Y
1      0  0
2     16  0
3      0  4
4     16  4
65     8  2
66     4  1
67    12  1
68     4  3
69    12  3
70     4  2
71    12  2
72     8  1
73     8  3
74     0  2
75     2  2
76     6  2
77     6  1.5
```

```
78      2  0.5
79      8  0
80      8  4
81     16  2
LINE.NODES
LIST.OF.NODES.ON.LINE
 1 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 2
 1 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 3
 2 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 4
 3 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 4
SPRINGS
NUMBER.OF.SPRING    KZ
       1            25E6
ELEMENTS
PROPERTIES=1
ELEMENT.TYPE=30100
 TOPOLOGY
   1 0
   2 0
   3 0
   4 0
   5 0
   6 0
   7 0
   8 0
   9 0
  10 0
  11 0
  12 0
```

```
13 0
14 0
15 0
16 0
17 0
18 0
19 0
20 0
21 0
22 0
23 0
24 0
25 0
26 0
27 0
28 0
29 0
30 0
31 0
32 0
33 0
34 0
35 0
36 0
37 0
38 0
39 0
40 0
41 0
```

```
42 0
43 0
44 0
45 0
46 0
47 0
48 0
49 0
50 0
51 0
52 0
53 0
54 0
55 0
56 0
57 0
58 0
59 0
60 0
61 0
62 0
63 0
64 0
65 0
66 0
67 0
68 0
69 0
70 0
```

```
  71 0
  72 0
  73 0
  74 0
  79 0
  80 0
  81 0
PAFBLOCKS
TYPE=1
ELEMENT.TYPE=44210
PROPERTIES=1
N1=1
N2=1
TOPOLOGY
 1 2 3 4
MESH
REFERENCE SPACING
   1         16
PLATES.AND.SHELLS
PLATE MATERIAL THICKNESS
  1        11        0.1
MODES.AND.FREQUENCIES
 AUTO MODES
  20      0
MASTERS
NODE DIRE
   1        3
   78       3
   66       3
```

```
   77      3
   65      3
   74      3
   75      3
   70      3
   76      3
RESPONSE
 TYPE
  1
DAMPING
FREQUENCY DAMPING.RATIO
     0          0.05
     40         0.05
FREQUENCIES.FOR.ANALYSIS
TYPE START FINISH STEP
  1    0    100    5
SINE.LOADING
NODE.NUMBER DIRECTION.OF.LOAD TABLE.NUMBER
    65                3               1
TABLE.OF.APPLIED.FORCES
TABLE BASIS.VALUE VALUE.LIST
    1        0       -50E3 0
SINUSOIDAL.OUTPUT
 NODE DIRECTION
   1       3
   78      3
   66      3
   77      3
   65      3
```

```
   74      3
   75      3
   70      3
   76      3
IN.DRAW
TYPE.NUMBER
   2
OUT.DRAW
PLOT.TYPE
   1
DYNAMICS.GRAPH
 NODE DIRECTION
   1       3
   78      3
   66      3
   77      3
   65      3
   74      3
   75      3
   70      3
   76      3
FULL.DYNAMICS.OUTPUT
TYPE START FINISH STEP
 2     1     0      1
END.OF.DATA
```

B.6 Extract from an Input File for Creep Analysis

```
TITLE  CREEP ANALYSIS      run by   H. T. EVDORIDES
C
C
C  Note: this extract is for demostration only.
C
C
CONTROL
SNAKES
CREEP
FULL.CONTROL
PHASE=1
PHASE=2
PHASE=3
PHASE=4
PHASE=5
PHASE=6
PHASE=7
PHASE=8
PHASE=9
INCLUDE:
      SUBROUTINE CRPLAW(TIME, SIGEQ, CRST, ICRP, IOPT)
      INTEGER    ICRP, IOPT
      REAL       TIME, SIGEQ, CRST
      IOPT=2
C
      CRST=((0.00015*((ALOG10(TIME))**1.9)*SIGEQ)**1.75)*100
```

```
C
       RETURN
       END
END.OF.INCLUDE
NON.LINEAR.TOL=2
PHASE=10
CLEAR.FILES
AXISYMMETRIC
STRESS
CONTROL.END
```

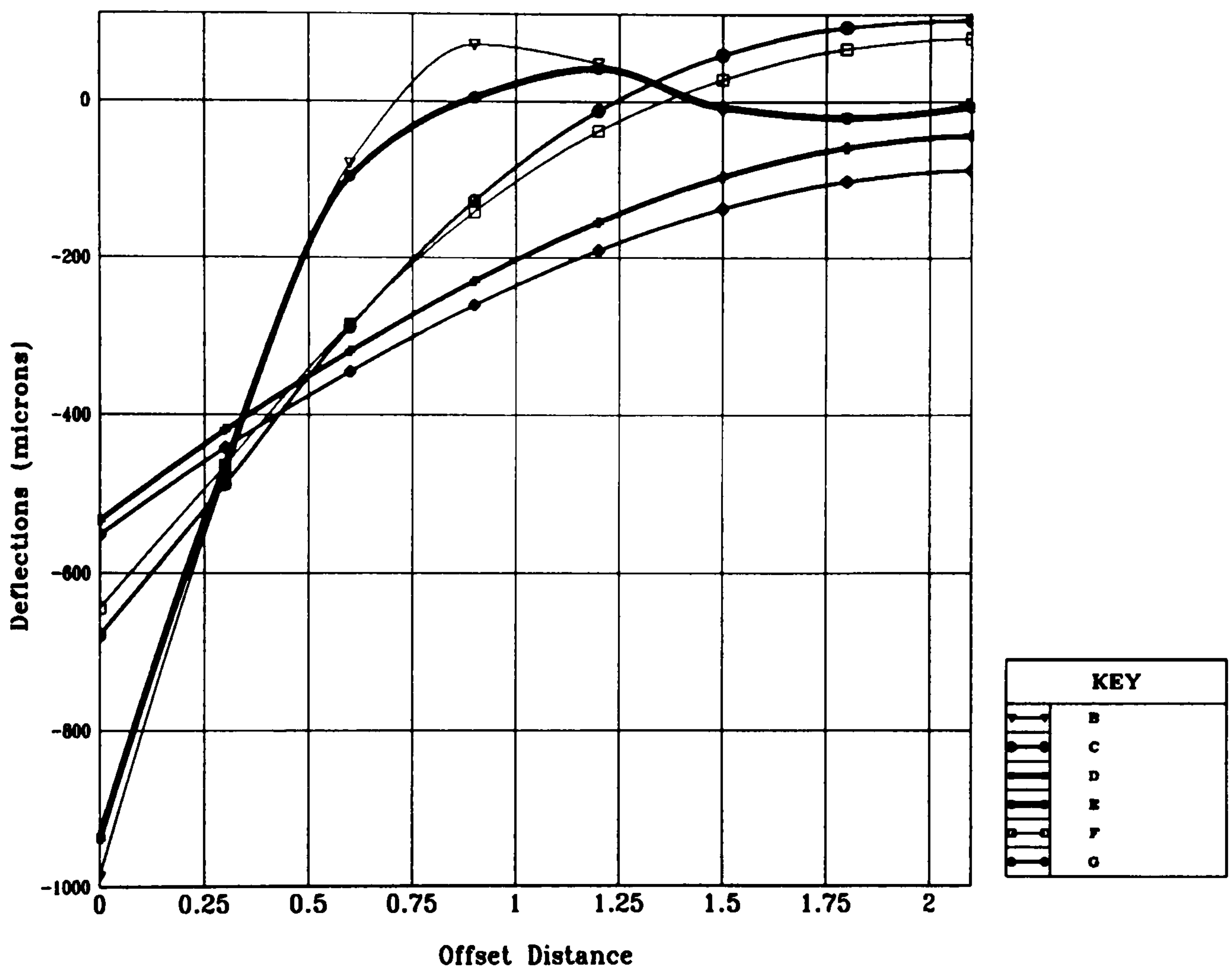
Appendix C

FACTORIAL DESIGN

A set of factorial pavement models have been used to provide initial estimates of the layer moduli in the Back-Analysis process in the absence of initial layer moduli estimates. The factorial design is given in Figures C.1 to C.9. It includes 54 three-layer pavement models.

The first layer represents a bituminous material. The moduli assigned to this layer are 2000, 5000 and 7500 MPa. This moduli may correspond to materials with low, medium and high strength. The thicknesses t_1 were 100, 200 and 300 mm.

The second layer represents granular roadbase materials and the third the subgrade soil. A constant modular ratio of 2.5 was maintained between the granular layer and the subgrade to reduce the number of cases. Thus the moduli assigned to the granular materials were 75, 150 and 300 MPa whilst those of the subgrade were 30, 60 and 120 respectively. The moduli assigned to the subgrade may correspond to soils with low, medium and high strength characterized by CBRs 3%, 6% and 12% (see section 7.3). The possible alternative thicknesses t_2 of the roadbase were 250 and 500 mm.



STRUCTURAL CHARACTERISTICS:

$E_1 = 2000$ MPa $E_2 = 75$ MPa and $E_3 = 30$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

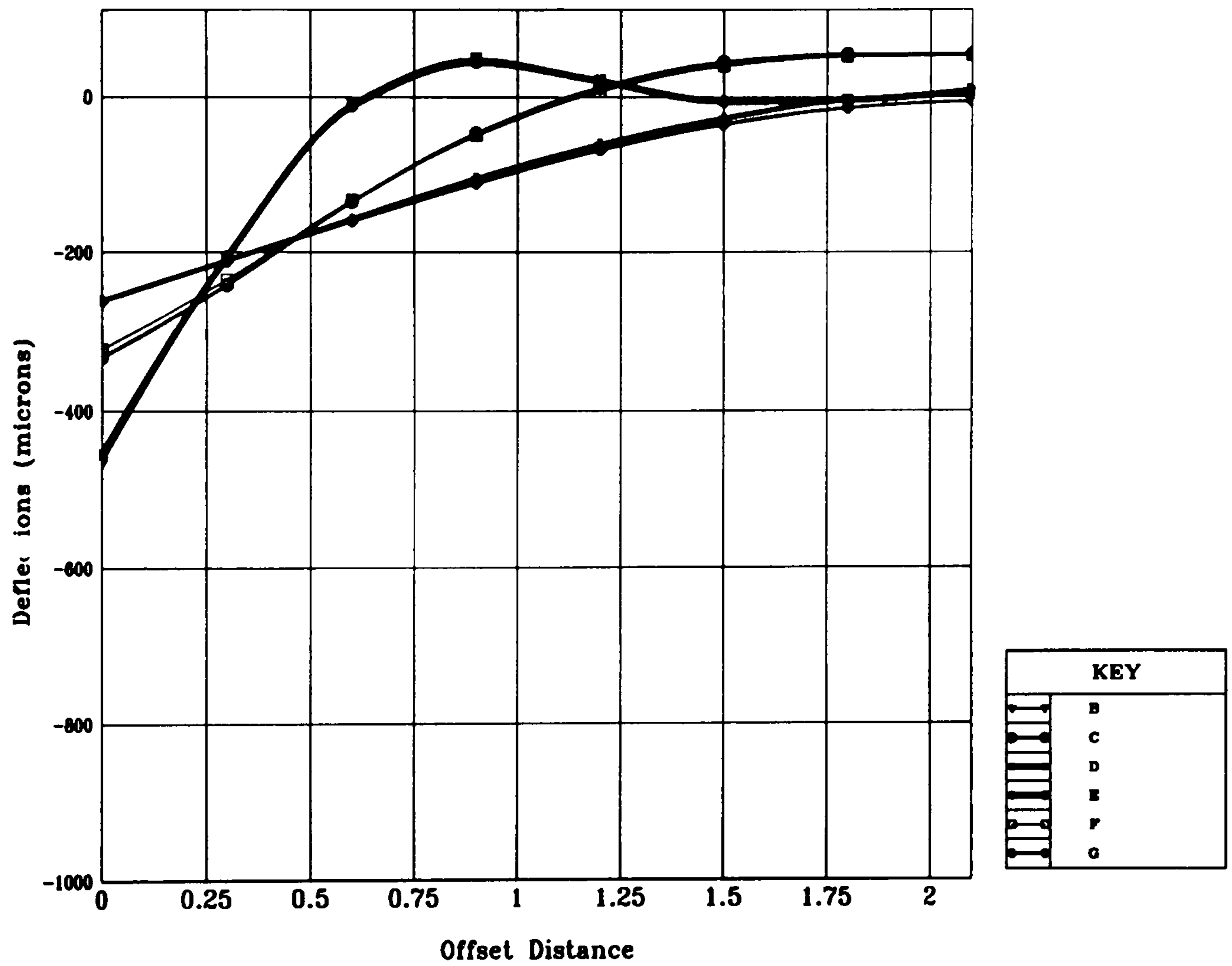
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.1: Factorial Design 1.



STRUCTURAL CHARACTERISTICS:

$E_1 = 5000$ MPa $E_2 = 75$ MPa and $E_3 = 30$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

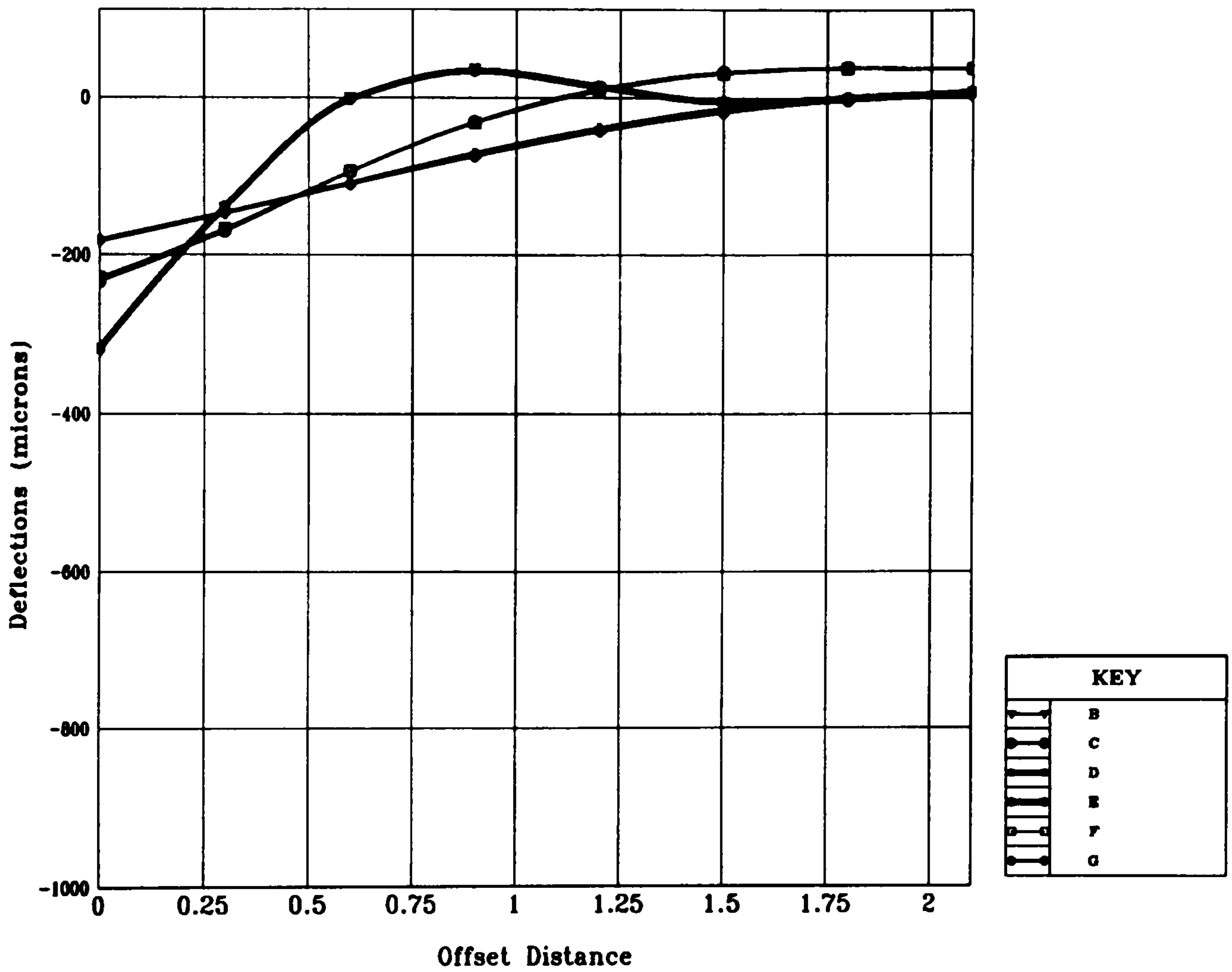
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.2: Factorial Design 2.



STRUCTURAL CHARACTERISTICS:

$E_1 = 7500$ MPa $E_2 = 75$ MPa and $E_3 = 30$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

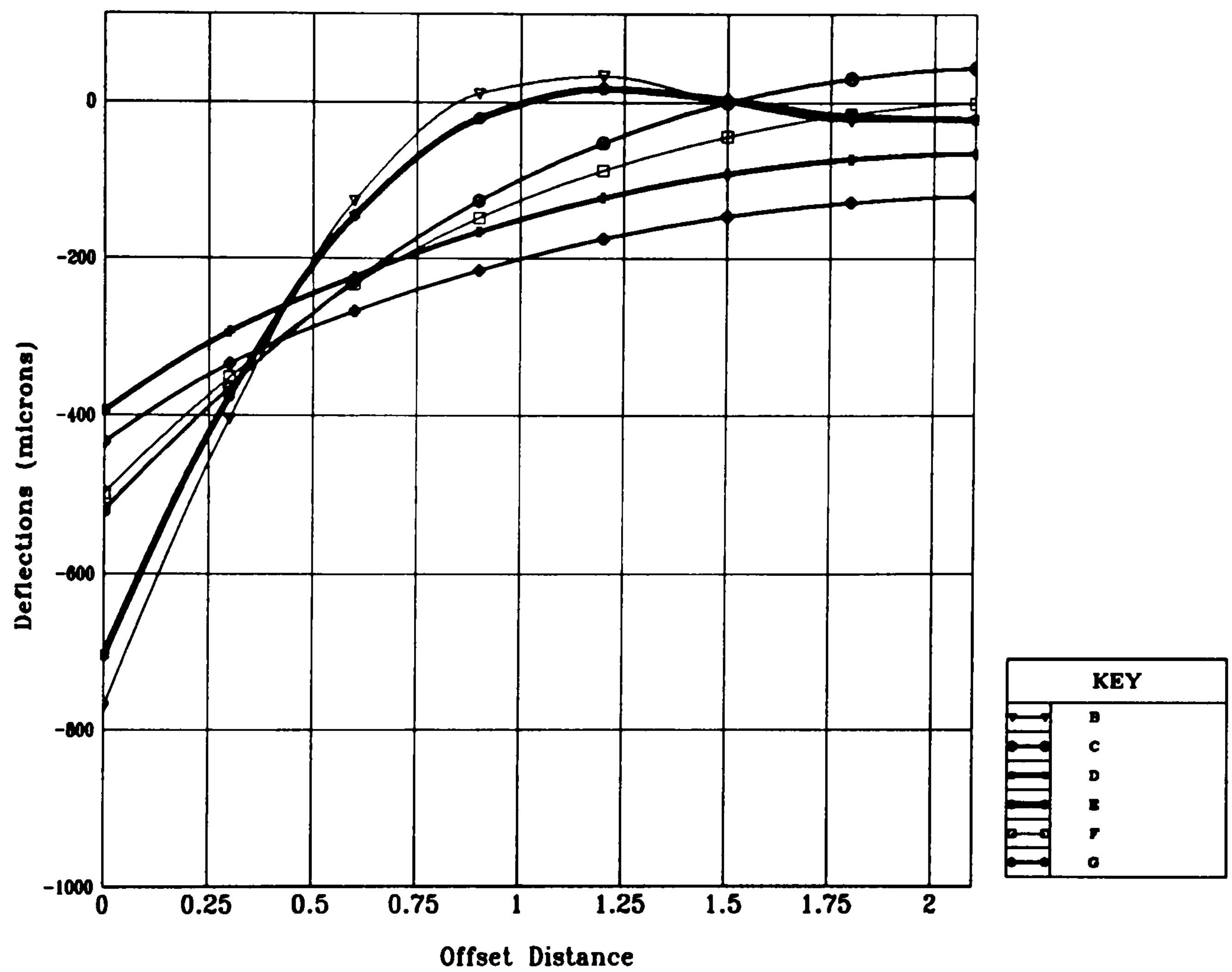
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.3: Factorial Design 3.



STRUCTURAL CHARACTERISTICS:

$E_1 = 2000$ MPa $E_2 = 150$ MPa and $E_3 = 60$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

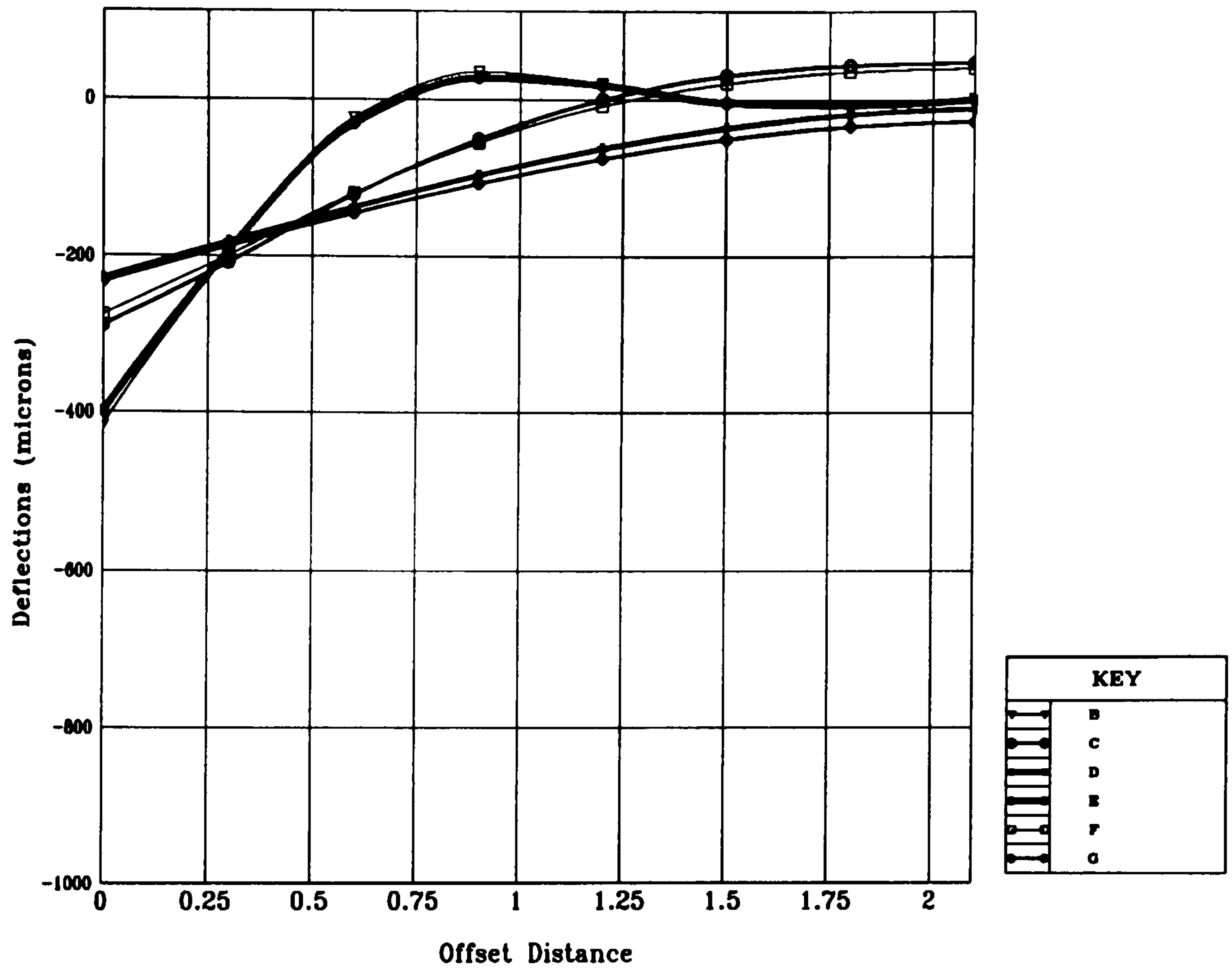
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.4: Factorial Design 4.



STRUCTURAL CHARACTERISTICS:

$E_1 = 5000$ MPa $E_2 = 150$ MPa and $E_3 = 60$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

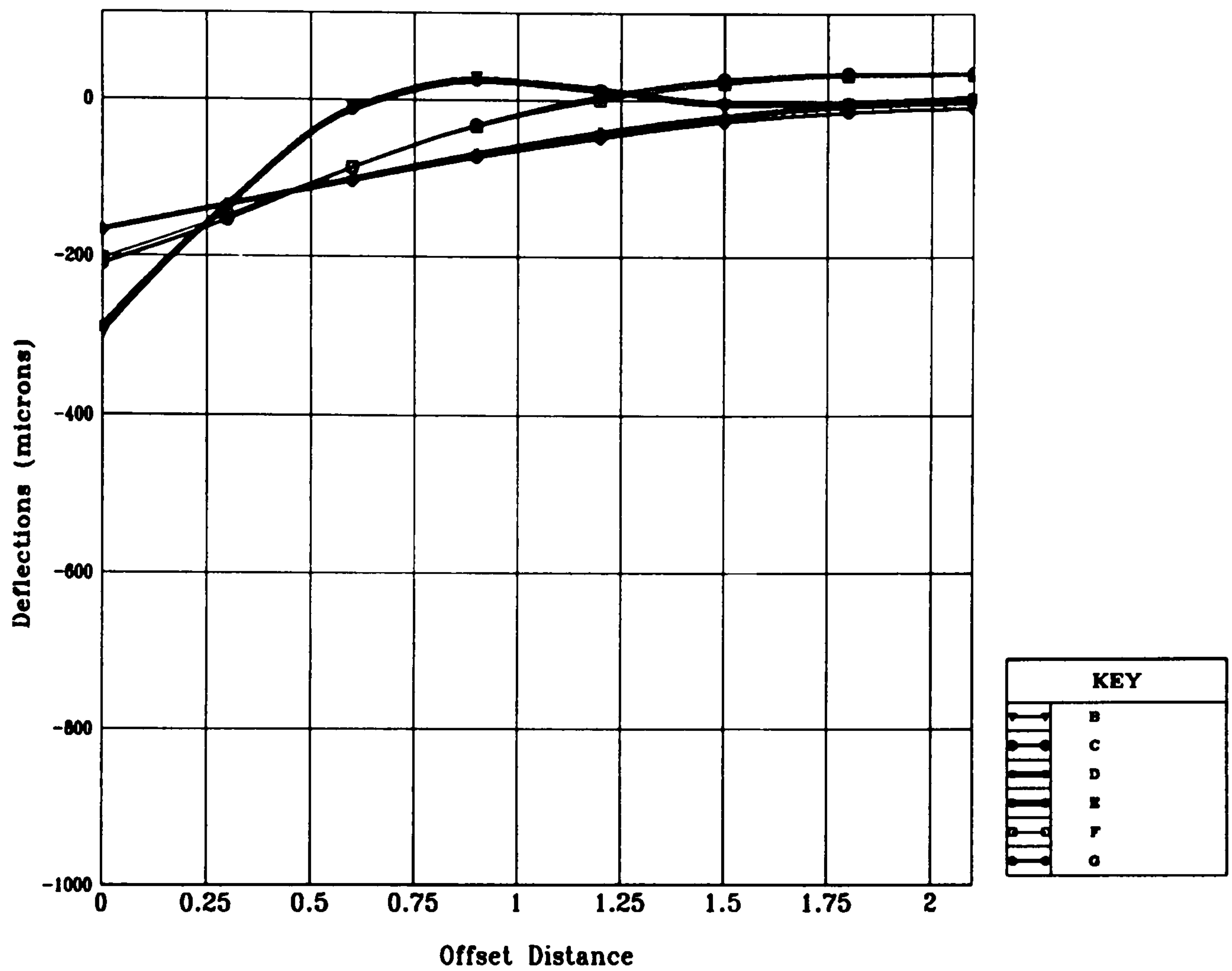
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.5: Factorial Design 5.



STRUCTURAL CHARACTERISTICS:

$E_1 = 7500$ MPa $E_2 = 150$ MPa and $E_3 = 60$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

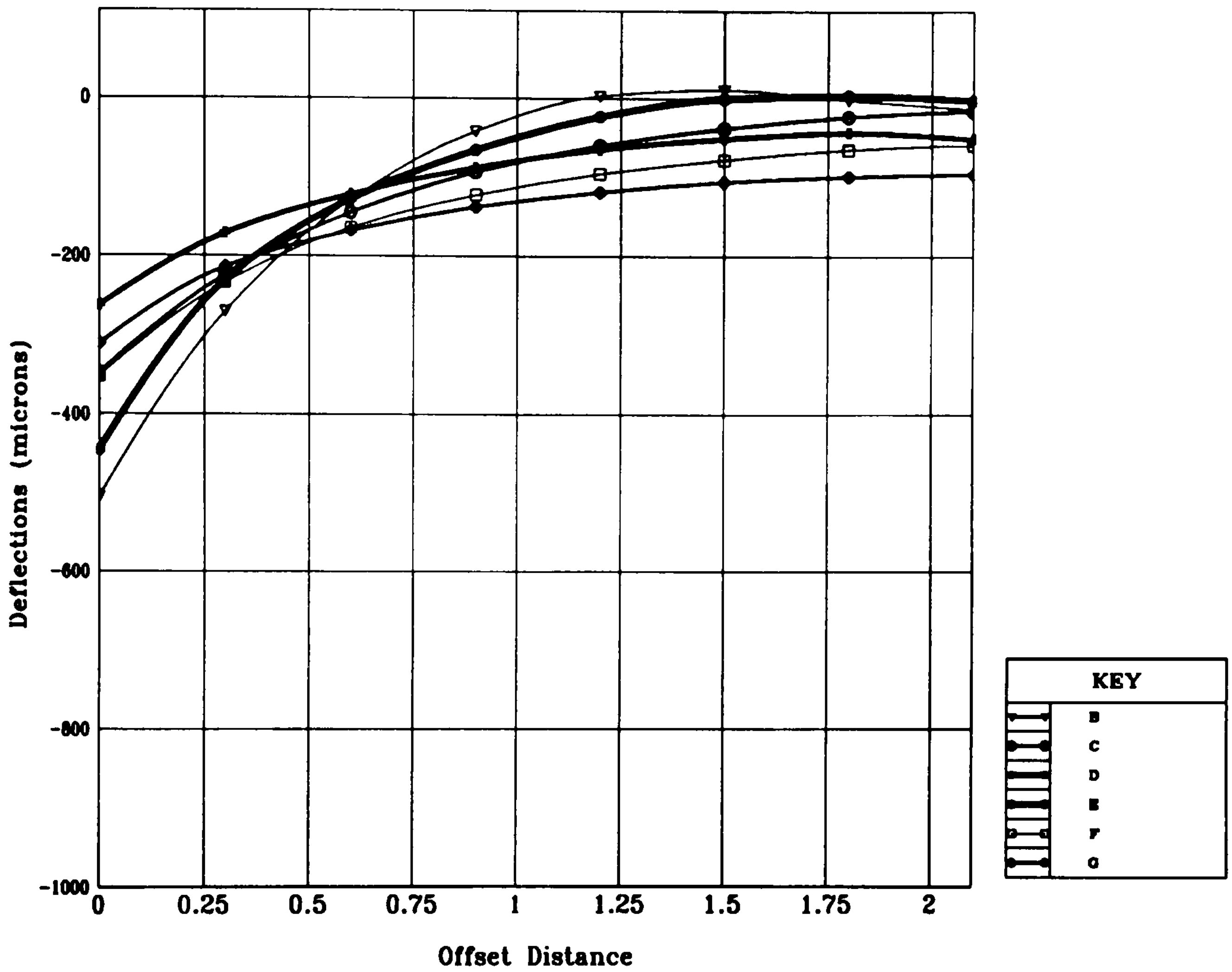
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.6: Factorial Design 6.



STRUCTURAL CHARACTERISTICS:

$E_1 = 2000$ MPa $E_2 = 300$ MPa and $E_3 = 120$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

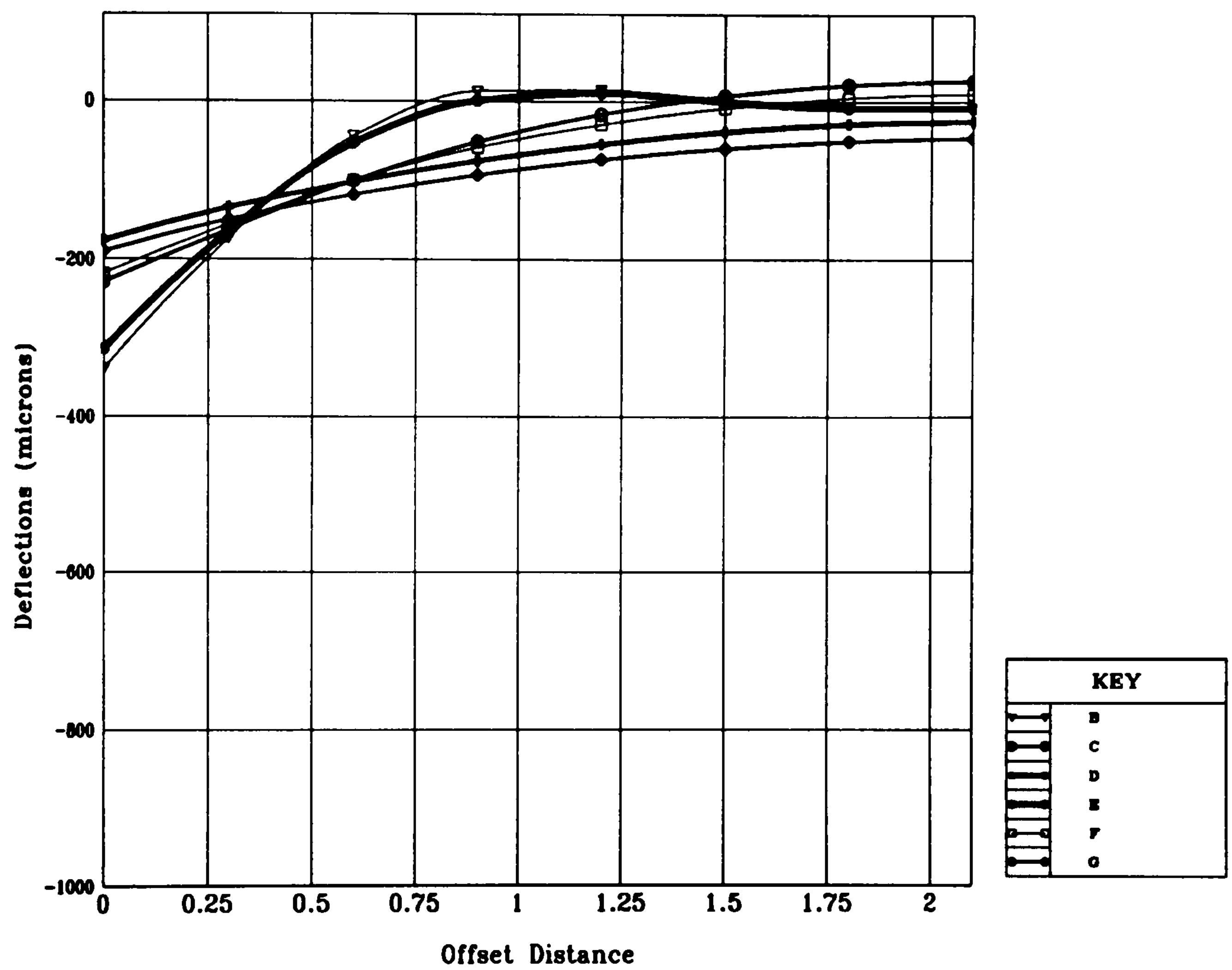
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.7: Factorial Design 7.



STRUCTURAL CHARACTERISTICS:

$E_1 = 5000$ MPa $E_2 = 300$ MPa and $E_3 = 120$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

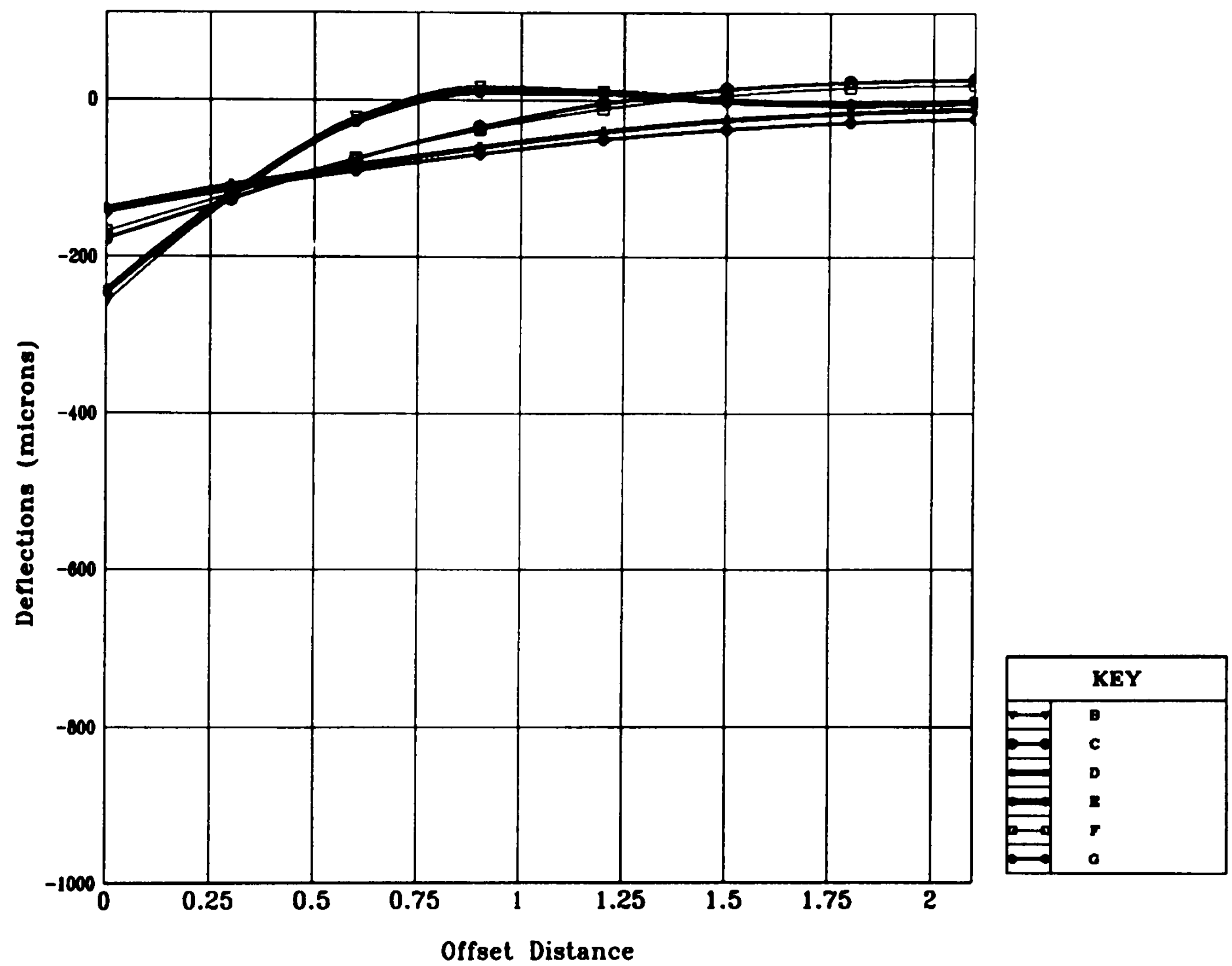
Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.8: Factorial Design 8.



STRUCTURAL CHARACTERISTICS:

$E_1 = 7500$ MPa $E_2 = 300$ MPa and $E_3 = 120$ MPa.

$\nu_1 = \nu_2 = \nu_3 = 0.35$

Curve B : $t_1 = 100$ mm and $t_2 = 250$ mm.

Curve C : $t_1 = 200$ mm and $t_2 = 250$ mm.

Curve D : $t_1 = 300$ mm and $t_2 = 250$ mm.

Curve E : $t_1 = 100$ mm and $t_2 = 500$ mm.

Curve F : $t_1 = 200$ mm and $t_2 = 500$ mm.

Curve G : $t_1 = 300$ mm and $t_2 = 500$ mm.

Figure C.9: Factorial Design 9.

Appendix D

THE VAX/VMS INTERFACE OF THE KBS

An extract from the command file used for creating the VAX/VMS operating system interface between the constituent programs of the KBS is given below:

```
$ define sys$input sys$command
$ prolog +MPdatabase
$ define/user for005 i.dat
$ define/user for006 first_result.dat
$ run rostra-1
$ type cont.dat
$ prolog +ba
$ open in control.dat
$ read in code
$ close in
$ if code .eqs. "OK" then goto label1
$ if code .eqs. "CONTINUE" then goto label2
$ label2:
```

```
$ define/user for005 i.dat
$ define/user for006 further_result.dat
$ run rostra-1
$ type further_back_analysis.dat
$ prolog +continue_ba
$ open in control.dat
$ read in message
$ close in
$ if message .eqs. "OK" then goto label1
$ if message .eqs. "CONTINUE" then goto label2
$ label1:
$ exit
```

Appendix E

AUTOMATING THE FACTORIAL DESIGN

This Appendix presents both the data included in the Factorial Design given in Appendix C and an extract of the listing of the FORTRAN code, which automates the searching procedure.

E.1 The Factorial Design Data

The factorial design database consists of 54 sets of data. Each set of data consists of four lines and the information included is organized as follows:

Line 1:	
`3`	Number of layers N (Integer).
Line 2:	
`0.1000.250`	Thicknesses of layers ((N-1)F5.3).
Line 3:	
`2000.  75.  30.`	Moduli of layers (NF5.0).
Line 4:	
`987 477 79 0 0 0 0`	Deflections in microns at 0.0, 0.30, 0.60, 0.90, 1.20, 1.50, 1.80 m (F5.0).

Data sets

```
3
0.1000.250
2000.  75.  30.
  987  477   79    0    0    0    0
3
0.2000.250
2000.  75.  30.
  678  487  288  127   12    0    0
3
0.3000.250
2000.  75.  30.
  533  419  319  229  154   96   59
3
```

```
0.1000.500
2000.  75.  30.
  937  463   96    0    0    0    0
3
0.2000.500
2000.  75.  30.
  644  463  284  141   38    0    0
3
0.3000.500
2000.  75.  30.
  552  441  345  260  190  137  102
3
0.1000.250
5000.  75.  30.
  466  207    7    0    0    0    0
3
0.2000.250
5000.  75.  30.
  332  241  135   47    0    0    0
3
0.3000.250
5000.  75.  30.
  261  210  157  105   61   27    4
3
0.1000.500
5000.  75.  30.
  455  205   12    0    0    0    0
3
0.2000.500
```

```
5000.  75.  30.
  322  234  133   50    0    0    0
3
0.3000.500
5000.  75.  30.
  262  211  160  111   68   35   14
3
0.1000.250
7500.  75.  30.
  323  140    0    0    0    0    0
3
0.2000.250
7500.  75.  30.
  233  170   94   31    0    0    0
3
0.3000.250
7500.  75.  30.
  182  147  109   71   39   14    0
3
0.1000.500
7500.  75.  30.
  318  139    2    0    0    0    0
3
0.2000.500
7500.  75.  30.
  228  166   93   32    0    0    0
3
0.3000.500
7500.  75.  30.
```

```
  182  147  110   74   42   18    3
3
0.1000.250
2000. 150.  60.
  771  404  125    0    0    0    0
3
0.2000.250
2000. 150.  60.
  520  364  228  125   51    0    0
3
0.3000.250
2000. 150.  60.
  394  293  223  165  121   90   71
3
0.1000.500
2000. 150.  60.
  705  375  144   20    0    0    0
3
0.2000.500
2000. 150.  60.
  499  351  233  147   86   43   14
3
0.3000.500
2000. 150.  60.
  434  334  267  215  174  145  127
3
0.1000.250
5000. 150.  60.
  416  196   23    0    0    0    0
```

```
3
0.2000.250
5000. 150.  60.
  289  208  121   50    0    0    0
3
0.3000.250
5000. 150.  60.
  228  181  137   96   62   36   19
3
0.1000.500
5000. 150.  60.
  399  192   31    0    0    0    0
3
0.2000.500
5000. 150.  60.
  275  199  119   55    8    0    0
3
0.3000.500
5000. 150.  60.
  233  187  145  107   75   50   34
3
0.1000.250
7500. 150.  60.
  299  136    8    0    0    0    0
3
0.2000.250
7500. 150.  60.
  210  153   86   32    0    0    0
3
```

```
0.3000.250
7500. 150.  60.
  166  133  100   68   41   20    7
3
0.1000.500
7500. 150.  60.
  290  134   12    0    0    0    0
3
0.2000.500
7500. 150.  60.
  203  147   85   34    0    0    0
3
0.3000.500
7500. 150.  60.
  167  135  103   73   48   27   15
3
0.1000.250
2000. 300. 120.
  505  269  129   42    0    0    0
3
0.2000.250
2000. 300. 120.
  347  223  145   94   60   38   23
3
0.3000.250
2000. 300. 120.
  262  171  122   88   65   51   43
3
0.1000.500
```

```
2000. 300. 120.
  445  230  128   66   23    0    0
3
0.2000.500
2000. 300. 120.
  351  233  164  123   96   78   65
3
0.3000.500
2000. 300.  120.
  310  213  168  138  119  106   99
3
0.1000.250
2000. 300. 120.
  339  173   44    0    0    0    0
3
0.2000.250
2000. 300. 120.
  229  162  100   51   16    0    0
3
0.3000.250
2000. 300. 120.
  176  134  102   75   54   38   28
3
0.1000.500
2000. 300. 120.
  314  164   53    0    0    0    0
3
0.2000.500
2000. 300. 120.
```

```
  218  155  100   58   29    8    0
3
0.3000.500
2000. 300.  120.
  190  149  118   93   73   59   50
3
0.1000.250
7500. 300. 120.
  258  126   21    0    0    0    0
3
0.2000.250
7500. 300. 120.
  177  127   75   34    4    0    0
3
0.3000.250
7500. 300. 120.
  139  109   83   60   40   25   16
3
0.1000.500
7500. 300. 120.
  244  221   27    0    0    0    0
3
0.2000.500
7500. 300. 120.
  168  120   74   38   11    0    0
3
0.3000.500
7500. 300.  120.
  144  115   90   69   50   37   28
```

E.2 Listing of the Program DATABANK

```
   PROGRAM DATABANK
REAL MODULUS(1000),POISSON(10),MEASURED_DEFLECTIONS(7),
1 THICKNESS(10),THICK(1000),MOD(1000,1000),DEF(1000),
1 NEWTHICK(1000,1000),A(1000),Y(1000),SUM(1000),MIN_SUM, DI(1000)
INTEGER LAYERS,NUMBER_OF_LAYERS,COUNTER
OPEN (
     1        UNIT=8,
     1        FILE = 'RESULT.TXT' ,
     1        STATUS = 'NEW')
C
C
C READ DATA FROM TERMINAL
C
C
WRITE(*,6)
6   FORMAT(' What is the number of layers ?')
READ(*,1)LAYERS
1 FORMAT(I1)
DO 2 I=1,LAYERS-1
           WRITE(*,7) I
7          FORMAT(' What is the thickness of layer ',I1,' ?')
    READ(*,3) THICKNESS(I)
3     FORMAT (F5.3)
2     CONTINUE
DO 4 I=1,7
           J = I-1
    D = 0.30 * J
```

```
            WRITE(*,5)D
5     FORMAT (' What is the deflection (in microns) at ' , F5.3, ' m
?')
    READ(*,8) MEASURED_DEFLECTIONS(I)
8           FORMAT(F3.0)
4     CONTINUE
C
C
C SET A COUNTER FOR THE RECORDS
            COUNTER = 1
            SUM(0)= 0
            NEWTHICK(1,0)= 1.
            NEWTHICK(2,0)= 1.
            NEWTHICK(3,0)= 1.
            NEWTHICK(4,0)= 1.
            NEWTHICK(5,0)= 1.
            MOD(1,0) = 1.
            MOD(2,0) = 1.
            MOD(3,0) = 1.
            MOD(4,0) = 1.
            MOD(5,0) = 1.
C
C
C READ DATA FROM FILE ''THREE_LAYER_MODEL_DATA.DAT''
C

IF ( LAYERS .NE. 3) GOTO 10
OPEN (
     1         UNIT=7,
```

```
     1         FILE = 'THREE_LAYER_MODEL_DATA.DAT' ,
     1         STATUS = 'OLD')
28      READ(7,11) NUMBER_OF_LAYERS
11      FORMAT(I2)
C
C -1 IS A CONTROL CHARACTER TO END THE PROGRAM
C
IF( NUMBER_OF_LAYERS  .EQ. -1)  GOTO 32
        WRITE (8,25) NUMBER_OF_LAYERS
25      FORMAT (' NUMBER OF THE LAYERS IN THE FACTORIAL MODEL ', I1)
READ(7,13) (THICK(I), I=1,NUMBER_OF_LAYERS-1)
13      FORMAT(10F5.3)
   DO 12 I=1,NUMBER_OF_LAYERS-1
                WRITE(8,26) I,THICK(I)
26              FORMAT('  LAYER THICKNESS(',I1,') IS ', F5.3)
12 CONTINUE
READ(7,15) ( MOD(I,COUNTER), I=1,NUMBER_OF_LAYERS )
15 FORMAT(10F5.0)
           DO 14 I=1, NUMBER_OF_LAYERS
                WRITE(8,27) I, MOD(I,COUNTER)
27 FORMAT('  MODULUS OF LAYER(',I1,') IS ', F5.0)
14 CONTINUE
READ(7,17) (DEF(I), I=1,7)
17 FORMAT(10F5.0)
            IF ( THICKNESS(1) .LT. 0.150 ) THEN
        NEWTHICK(1,COUNTER) = 0.100
    ELSE IF ( ( THICKNESS(1) ) .LT. 0.250 ) THEN
        NEWTHICK(1,COUNTER) = 0.200
    ELSE
```

```
                NEWTHICK(1,COUNTER) = 0.300
    END IF
    IF ( THICKNESS(2) .LT. 0.375 ) THEN
        NEWTHICK(2,COUNTER) = 0.250
            ELSE
                NEWTHICK(2,COUNTER) = 0.500
            END IF
DO 43 I=1,LAYERS-1
    IF (NEWTHICK(I,COUNTER) .NE. THICK(I)) GO TO 28
43     CONTINUE
        WRITE(8, 29) COUNTER
29      FORMAT('  RECORD NUMBER ', I3,
     1      /, '**************************************')
        WRITE (8,18)NEWTHICK(1,COUNTER),NEWTHICK(2,COUNTER)
18      FORMAT(/,'  ROUNDED THICKNESSES FOUND IN THE DATABANK'
     1      /      '       THICKNESS(1)   THICKNESS(2) ',
     1      /      '       ============   ============ ',
     1      /  5X, F10.3, 5X, F10.3,/)
C
C CHECK THE MINIMUM SUM OF THE DIFFERENCES OF THE DEFLECTIONS
C
SUM(COUNTER) = 0
DO 19 I=1,7
Y(I) = ABS((MEASURED_DEFLECTIONS(I) - DEF(I))/MEASURED_DEFLECTIONS(I))
WRITE(8,45) I,Y(I)
45 FORMAT('  DIF(',I1,')= ', F10.5)
IF ( Y(1) .LE. 0.25 ) THEN
SUM(COUNTER) = SUM(COUNTER) + Y(I)
        ELSE
```

```
        GOTO 28
END IF
19      CONTINUE
C
C
C
WRITE(8,24)
24 FORMAT(
     1 '  MEASURED DEFLECTIONS   DATABANK DEFLECTIONS     DIFFERENCE',
     1 /
     1 '  ====================   ====================     =========')
DO 22 I=1,7
    WRITE (8,23) MEASURED_DEFLECTIONS(I),DEF(I),
     1      MEASURED_DEFLECTIONS(I)-DEF(I)
23     FORMAT(F10.0, 15X, F10.0, 12X, F10.0)
22     CONTINUE
39      FORMAT(/)
        DO 37 I=1, NUMBER_OF_LAYERS
                WRITE(8,41) I, MOD(I,COUNTER)
41 FORMAT('  MODULUS OF LAYER(',I1,') IS ', F5.0)
37 CONTINUE
C
C
C
C
81      WRITE(8,39)
WRITE (8,20) SUM(COUNTER),SUM(COUNTER-1)
20      FORMAT('  SUM OF THE PERCENTAGE OF THE DEFLECTION DIFFERENCES',
     1  /, '       PRESENT = ',F10.6 ,'  PREVIOUS = ', F10.6,
```

```
    1  //, '          ***    ***    ***')
C
C
C
10 CONTINUE
WRITE (8,21)
WRITE (*,21)
21 FORMAT('  PROBLEM WITH THE DATA')
32 CONTINUE
        DO 83 I=1,COUNTER-1
WRITE(8,85) I,SUM(I)
85 FORMAT(' COUNTER = ', I3, '  SUM = ', F10.6)
        DO 87 J=1,LAYERS
        WRITE(8,89) J, MOD(J,I)
89 FORMAT(' MOD(',I1') = ',F10.3)
87 CONTINUE
83      CONTINUE
C
C FIND THE MINIMUM
C
MIN_SUM  = 1000
  DO 91 I=1,COUNTER-1
MIN_SUM = AMIN1(SUM(I),SUM(I-1))
91      CONTINUE
        WRITE(8,*)MIN_SUM
47      WRITE(8,33)
C
DO 93 I=1,COUNTER-1
        DI(I)= MIN_SUM - SUM(I)
```

```
WRITE(8,*)DI(I)
93 CONTINUE
DO 95 I=1,COUNTER-1
        IF ( DI(I) .EQ. 0.00 ) THEN
51      WRITE (*,35)
    WRITE (8,35)
35      FORMAT(' BASED ON THE DEFLECTION DATA IT WAS FOUND THAT : ',/)
             DO 31 J=1,LAYERS
             WRITE(*,30)J, MOD(J,I)
             WRITE(8,30)J, MOD(J,I)
30           FORMAT(' FIRST GUESS FOR THE MODULUS OF LAYER ', I1,
     1       ' IS ', F5.0)
31      CONTINUE
ELSE
        WRITE(8,97)
97 FORMAT('  ')
END IF
95  CONTINUE
94 CONTINUE
C
C
33       FORMAT(' END OF SEARCHING')
CLOSE(UNIT=8, STATUS = 'KEEP')
CLOSE(UNIT=7, STATUS = 'KEEP')
STOP
END
```

Appendix F

FUNCTIONAL EVALUATION KNOWLEDGE BASE

A Prolog based knowledge base which seeks to simulate a functional evaluation process relying on parameters such as cracking and rutting may be relatively easily built. The example given below is the output of such a simple program which is presented for demonstration reasons.

After having loaded both the POPLOG-Prolog interpreter and the saved image of the program the user types the following predicate:

```
?- detect.
```

The system then responds by giving the following menu.

```
What is the the state of cracking ?
1     :  No cracking
2     :  Single crack
3     :  Multiple cracking
Enter the number of choice  |: 2.
```

The user selects the answer by typing the number of his choice after the Prolog prompt "| :".

A similar menu is provided for rutting. That is:

```
What is the the state of rutting ?
1     :  < 5 mm
2     :  5-9 mm
3     :  10-19 mm
4     :  =< 19 mm
5     :  >= 20 mm
Enter the number of choice  |: 4.
```

Finally the system gives its advice with respect to the information entered as follows:

```
The pavement is at a critical stage with probability 90% .
Therefore, determine material properties to calculate
the remaining life.
*** Risk of reflection cracking. ***
High weakness of the subgrade soil.
Apply overlay design so that new pavement life may be achieved.
```

Appendix G

SYSTEM USAGE

This Appendix presents a full example of the usage of the KBS. The output has been slightly edited for presentation reasons.

```
CEVAX5> @expav'

************************************************************************

************************************************************************

************************************************************************

                           E X P A V


               Expert System for Pavement Analysis



                                            MSS and HTE
                                   The University of Birmingham
                                    School of Civil Engineering
```

```
                                              and
                          Science and Engineering Reasearch Council
************************************************************************

Please, type ''consult.'' to start the consultation.

************************************************************************
************************************************************************
************************************************************************

?- consult.
This is the first phase of the program.
Information concerning the pavement model is required.
The program provides the initial moduli of the
constituent layers of the pavement model together with the
Poisson's ratio. A number of questions lead to the first
estimation of the moduli.
Please, be as accurate as possible.


Please, input the radius of the loaded area after the prompt.
The units must be in metres and typed as a decimal number
with five digits, e.g., 0.150. Include the input data between single
quotes if it has five digits or the last digit is zero; e.g. ' 0.15'.
|: '0.150'.

OK, the radius of the loaded area has been set to 0.150 metres.

Please, input the applied stress after the prompt.
```

```
The units must be in kPa and typed as a decimal number
with five digits, i.e., 700.0.
|: 700.0.
OK, the magnitude of the applied stress has been set to 700.0 MPa.

Please, input the number of the pavement layers after the
prompt. The maximum number is limited to five (5).
|: 2.
OK, the number of the layers of the pavement model has been set to 2.



Please, specify the grid option to be used by the finite element
program ''ROSTRA-1''.

What is the the required grid option ?
1    :  GRID=0 (Option for Benkelman beam or Deflectograph bowl analysis)
2    :  GRID=2 (Option for FWD; d(i) at 0.0, 0.30, 0.60,..., 2.10m)
Enter the number of choice
|: 2.

Please, enter the thicknesses of the pavement layers except for
that of the subgrade after the prompt. The input data should be
included between single quotes and the units should be in metres.
A full-stop should be typed at the end of each input data;
(e.g., '0.100'.).
What is the thickness of layer 1 ?
|: '0.322'.
```

```
OK, the thickness of layer 1 is 0.322 metres.


Please, answer the questions provided
which lead to the determination of the moduli
and Poisson's ratio of the constituent layers of the pavement
model. Select one of the available options provided in menus.
A full-stop is always necessary at the end of each answer.

Material characteristics of layer 1

What is the material ?
1     :  Bituminous with known Modulus
2     :  DBM
3     :  HRA
4     :  Asphaltic Concrete
5     :  Dense bitumen concrete
6     :  Stone filled sand sheet
7     :  Base course asphalt concrete
8     :  Porous asphalt
9     :  Lean bituminous macadam
10     :  Bitumen sand
11     :  Bituminous mortar
12     :  Full-depth Asphaltic Concrete
13     :  Granular with known Modulus
14     :  Granular with known CBR
15     :  Granular with unknown CBR
16     :  Cement bound
17     :  Subgrade soil with known Modulus
```

```
18    :  Subgrade soil with known CBR
19    :  Subgrade soil with unknown CBR
Enter the number of choice
|: 1.

What is the Modulus of the bituminous material in MPa ?
|: 3000.

What is the temperature ?
1    :  -30
2    :  -20
3    :  -10
4    :  -5
5    :  0
6    :  5
7    :  10
8    :  20
9    :  25
10    :  30
11    :  40
12    :  ultra low   (        T < -5 degrees Celsius )
13    :  very  low   ( -5 =< T <  5 degrees Celsius )
14    :        low   (  5 =< T < 15 degrees Celsius )
15    :     normal   ( 15 =< T < 26 degrees Celsius )
16    :       high   ( 26 =< T < 36 degrees Celsius )
17    :  very high   (        T > 36 degrees Celsius )
Enter the number of choice
|: 15.
```

```
The modulus of the layer 1 is 3000 MPa
and the Poisson's ratio is 0.35 .


Material characteristics of layer 2

What is the material ?
1    :  Bituminous with known Modulus
2    :  DBM
3    :  HRA
4    :  Asphaltic Concrete
5    :  Dense bitumen concrete
6    :  Stone filled sand sheet
7    :  Base course asphalt concrete
8    :  Porous asphalt
9    :  Lean bituminous macadam
10    :  Bitumen sand
11    :  Bituminous mortar
12    :  Full-depth Asphaltic Concrete
13    :  Granular with known Modulus
14    :  Granular with known CBR
15    :  Granular with unknown CBR
16    :  Cement bound
17    :  Subgrade soil with known Modulus
18    :  Subgrade soil with known CBR
19    :  Subgrade soil with unknown CBR
Enter the number of choice
|: 13.
```

```
What is the Modulus of the granular material in MPa ?
|: 200.

What is the type of granular material ?
1    :  crushed stone
2    :  unprocessed rounded gravel or sands
3    :  capping layer
4    :  wet-mix roadbase
5    :  unknown material
Enter the number of choice
|: 5.

The modulus of the layer 2 is 200 MPa
and the Poisson's ratio is  0.35 .


Program terminated. Please, wait.

The finite element program ROSTRA-1 is now analyzing the pavement.


                        *****   *****   *****
                        *****   *****   *****


Please type ``back_analyze.'' to start the back analysis.
```

```
***** ***** *****
***** ***** *****

?- back_analyze.
Please, enter the measured deflections at the required locations, in
mm;
i.e., ''0.340.''.

  Offset distance          Deflection
  ===============          ==========
Centre of the load          |: 0.241.

0.30 m                      |: 0.184.

0.60 m                      |: 0.139.

0.90 m                      |: 0.103.

1.20 m                      |: 0.083.

1.50 m                      |: 0.062.

1.80 m                      |: 0.049.


   Radial      Measured       Computed       Difference       %
  distances   deflections    deflections
```

===========	=============	=============	============	=========
0.00 m	0.241	0.217808	0.023192	9.62324
0.30 m	0.184	0.15855	0.02545	13.8315
0.60 m	0.139	0.123765	0.015235	10.9604
0.90 m	0.103	0.098285	0.004715	4.57767
1.20 m	0.083	0.080235	0.002765	3.33133
1.50 m	0.062	0.06793	-0.00593	-9.56452
1.80 m	0.049	0.059674	-0.010674	-21.7837

```
The Modulus of the first layer has been set to       2711.3 MPa,
and the Modulus of the second layer has been set to  177.349 MPa.
Please wait. The back analysis is going on.

                        ***** ***** *****
                        ***** ***** *****

Please type ``carry_on.'' to continue the back analysis.

                        ***** ***** *****
                        ***** ***** *****

?- carry_on.
```

Radial distances	Measured deflections	Computed deflections	Difference	%
0.00 m	0.241	0.243781	-0.002781	-1.15394
0.30 m	0.184	0.178053	0.005947	3.23206
0.60 m	0.139	0.139232	-0.000232	-0.166907
0.90 m	0.103	0.110686	-0.007686	-7.46214
1.20 m	0.083	0.090398	-0.007398	-8.91325
1.50 m	0.062	0.076527	-0.014527	-23.4306
1.80 m	0.049	0.067198	-0.018198	-37.1388

The Modulus of the first layer is 2711 MPa,

and the Modulus of the second layer is 177 MPa.

Appendix H

PUBLICATION

This Appendix contains the publication which has been accepted for the *4th International Conference on Bearing Capacity of Roads and Airfields*, to be held July 17-21, 1994 in Minneapolis, Minnesota, U.S.A. and which is based on the work reported in this Thesis.

A Systematic Knowledge-Based Approach to the Structural Analysis of Pavements

M.S. Snaith* H.T. Evdorides†

March 1993

Abstract

Project level structural maintenance of highways relies increasingly on the back analysis of computer models of pavements from which surface deflections and standard loads, such as that of the Falling Weight Deflectometer, are available. The procedures tend to be mechanistic with the best results obtained when used by experienced maintenance engineers.

In order to reduce direct reliance on such skills, a knowledge-based system has been developed to "inject" engineering knowledge into the conventional techniques. The system consists of three parts: a) a finite element computer program, b) a knowledge base, and c) a database. The analytical program carries out the analysis of the pavements tested in the field. The knowledge base encodes engineering knowledge, and, using artificial intelligence techniques, it drives the back analysis procedure to select a modulus set for the pavement layers that satisfies two criteria: Convergence of the model pavement deflection to that of the field and compliance with engineering judgement for the known materials and apparent condition of the pavement. The database holds the characteristics of various pavement materials which are used as input data to the analytical model by the user working with the knowledge base of the system.

To build this prototype system, the POPLOG-Prolog computer language operating under VAX/VMS was selected. Preliminary operation of the system has indicated that the knowledge included within the system, together with appropriate feedback procedures, provides an effective evaluation scheme. Examples will be given of its operation, together with an analysis of the system operation. It is already believed that the current software environment is not suitable for the more complex developments envisaged for the knowledge base in the next stage of the work. This will be discussed.

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A Systematic Knowledge-based Approach to the Structural Analysis of Pavements

by M S Snaith and H T Evdorides

1. Introduction

The assessment of remaining life and the selection of the thickness of structural overlays for major highways constructed with bituminous surfacings is now widely effected using deflection based techniques. These may be empirical, theoreticial or indeed a combination of the two. However, with increased accountability and reduced infrastructure budgets the need for greater precision in those processes has increased. This requires that the maintenance process should include an extensive "diagnostics" (1) package which will determine the condition of the individual layers of the pavement and seek out the cause for any weakness present to enable the selection of an appropriate treatment (eg rectification of drainage, overlaying, deep patching). Whilst trial pits are advisable to check these findings, for those road sections where major works are planned, they are expensive and should only be used following a full diagnostic process based on non-destructive testing and observation.

The non-destructive test which is gaining increasing credibility for structural assessment is the Falling Weight Deflectometer (2,3). In this study the Falling Weight Deflectometer has been used but the techniques discussed are equally applicable to the analysis of load induced elastic surface deflections produced by other testing apparatus.

In "conventional" structural evaluation of road pavements Koole (4) has suggested that there are three distinct but complementary elements to condition assessment:

1. An appropriate non-destructive testing technique.
2. An analytical procedure capable of determining key design parameters using a computer simulation of the pavement tested in the field
3. A design process relying on the above.

A variant of a well-established finite element program DEFPAV (5) is used for the computer modelling for the second, and a design process for overlay thickness selection, when required, is relatively easily added such as that contrived by McMullen et al (6).

However, it has become clear that solutions based largely on a mechanistic "back analysis" of Falling Weight Deflectometer data have not been particularly successful except when moderated by the judgement provided by experienced highway engineers. In general terms, the more extensive the knowledge and experience of the "expert", the better the solution. Consequently it was felt advisable to investigate the possibility of designing a Knowledge-Based System (KBS) which would effect the fault diagnosis together with the mechanistic analysis in a similar way to an "expert" by populating the knowledge base with the information typically held by such experts. A KBS is merely one area of Artificial Intelligence in which computer programs address problems that were previously felt to require human intelligence in order to find a solution (7).

2. Previous work

Some work has been done in this area previously such as the development of a prototype system, SCEPTRE, by Ritchie et al (8) for the evaluation of surface distress in pavements which was subsequently enhanced with the view of providing an overlay design system based on the Asphalt Institute Method.

Using the system development software EXSYS (9), Hajek et al (10) developed a process for the assessment of need for crack sealing based on the work of Chong et al for the Ontario Ministry of Transportation and Communications (11). Most recently, work has been effected by Schwartz et al (12) to produce a databased technique which seeks to act as a KBS for the management of airfield pavements. Interestingly the system uses the simple programming tools Quick Basic and Fortran together with assembly language rather than purpose created software such as EXSYS.

3. The Knowledge Based System Operation

Typically a KBS consists of three modules (13):

1. A Knowledge Base.
2. An Inference Engine.
3. A User Interface.

A Knowledge Base contains knowledge, usually in the form of rules, which is specific to the task or application set for it, together with a set of procedures which control the use of this knowledge in a formal way. The Inference Engine is the mechanism which uses the knowledge to arrive at a solution and the User Interface provides smooth communication between the system and its operator. When the Inference Engine is "packaged" with the User Interface and provided with tools to assist in the development of the overall system, it may be known as a "Shell". A representation of this may be seen in Fig 1. Obviously this simple structure may be enhanced by other assorted modules which provide subsystems for specific tasks (eg a database or a statistical analysis).

Fig 2 gives the structure of the KBS ultimately envisaged for pavement analysis. The core of the system is the Knowledge Base which performs those "expert" tasks more normally associated with the road engineer. The Database holds data collected from the field together with past solutions and recommendations provided by the system. The analytical program carries out the mechanistic analysis of the pavement structure under scrutiny.

With this system the data provided, by the use of the Falling Weight Deflectometer on the concerned road section, is stored in the Database (module D_1). In addition to the deflection data, other allied information such as temperature, in situ CBR, layer thicknesses may also be stored if available. Furthermore surface condition indicators such as rutting or cracking may also be supplied to, and refined by, this module to enhance the diagnostic process.

This information is accessed by the Knowledge Base (module K_1). At this stage the rules contained within the Knowledge Base cause the wider Database (Module D_3 - which contains information on previously analysed structures) to be searched for a road pavement structure which most clearly matches that under observation. As a result the system is able to provide "seed" values for Elastic Modulus and Poisson's ratio for entry to the analytical model. Where the Knowledge Base is unable to find a similar pavement from the case histories within Module D_3 in order to obtain "seed" values an extra process is required. The Knowledge Base directs itself to the results of a set of imaginary pavement structures covering a wider variety of materials, thicknesses and conditions which have been previously analysed to determine their deflection behaviour, which are stored within a separate Database (module D_2).

With this preliminary model of the pavement, the system carries out the Back Analysis within Module K_2 by calling a derivative of DEFPAV (5), ROSTRA-1 contained within Module A, to calculate its deflection under a Falling Weight Deflectometer loading. This computation is done repetitively with the Knowledge Base, adjusting the layer moduli until there is an acceptable correlation between the observed and modelled deflection data.

The above has largely been done in the prototype but it is clear that further modules are required to complete the rehabilitation advice process. The calculation of remaining life will be effected in Module K_3 by computing the magnitude of the failure parameters felt to be significant (eg horizontal tensile strain at the base of the bituminous layer to control fatigue cracking) together with an appropriate performance model following the processes used widely elsewhere (eg McMullen et al, 6). This information would also be sent to Module D_3 to enhance that Database as previously noted, effectively providing a "self-learning" component in the overall system.

4. The Prototype

Prior to the development of the prototype it was necessary to decide whether to use either a system shell or a programming language. Whilst shells seem attractive as they provide complete application development environments which may contain one or more programming languages, an editor, debugging tools, software utilities and a library of functions, the alternative solution of a specific programming language was adopted. From a variety of such languages the POPLOG, (14) variant of Prolog (13, 15) was felt to provide the required flexibility from which a more closely tailored fit to the problem at hand could be obtained. However this resulted in considerably more design work to enable a suitable structure for the KBS to be achieved. The system was then developed under VAX/VMS on a VAX workstation.

The final architecture of the prototype conceived as shown in Fig 2 may be seen in Fig. 3. The important components are present, specifically:

1. Module A - The analytical program ROSTRA-1, written in FORTRAN.
2. Module K_1 The Knowledge Base, which in the prototype contains information linking pavement materials to their likely properties. This is written in POPLOG-Prolog. It should be noted that the prototype Module K_1 contains elements of the functions of Modules D_1 (FWD input field data), D_2 ("factorial" experiment analysis) and D_3 (results of previous analyses).
3. Module K_2 The Back Analysis programs written in POPLOG-Prolog.
4. The User Interface and control facilities which are programmed in the VAX/VMS DIGITAL Command Language (16).

5. Validation

Essentially the process was implemented and subsequently validated for the determination of appropriate values of Elastic Moduli and Poisson's ratio and not for remaining life or overlay thickness selection. For the validation three methods were used to determine the concerned material properties for the given deflections:

1. Manual - the back analysis program ROSTRA-1 is employed by the operator manually calling upon the data held in the Knowledge Base (K_1) to obtain a good fit of the data from the computer model and the observed field data.
2. Automated the system was run to obtain a good fit of the data for the computer model and the observed field data without access to that part of the knowledge base used to simulate the capacity of a KBS to learn (ie Module D_3).
3. Automated plus learning the system was run, as in 2, but with the ability to draw on previous experience.

The field data used in the validation was provided by the Transport Road Laboratory (TRL) and formed part of a wider study by the TRL of back analysis techniques (17). The deflections were measured by a Falling Weight Deflectometer on a series of motorway sites in 1990. The four sites provided examples of both cracked and uncracked surfacings together with up to four bituminous layers on top of a granular subbase and subgrade.

Deflections under a Falling Weight Deflectometer were made at offsets up to 2100mm for each of the sites. Thicknesses of the various layers were provided and the system was to determine the moduli of the constituent layers. The most complex pavement was that at Site A details of which are provided in Table 1. The measured deflections of the Falling Weight Deflectometer are given in Table 2. These deflections were "normalised" to those which would have been expected had the applied stress been 700 kPa and are also shown in Table 2.

For the purposes of validation the surfacing layers were combined, as were the road base layers, to give a four layer structure (ie bituminous surfacing, bituminous road base, granular subbase and subgrade). The deflections obtained using the three categories of operation noted above are given in Table 2. The moduli and Poisson's ratio values of the construction layers used to yield these deflections are presented in Table 3.

It is clear that the traditional mechanistic, or manual operation of the system, neither provided a good fit of the deflection bowls other than at the central point nor did it yield a likely result with respect to the modular ratio between the subbase and subgrade.

The system, used in its automated mode, draws on the knowledge base of the system and the answers by the operator to questions posed by the system. The consequent back analysis procedure and repetitive analysis were thereby assisted in its attempt to obtain a closer fit of the computer model to the field deflection bowl. Clearly (see Table 2) the fit is better than for the simple mechanistic application and the moduli appear to be more "reasonable" particularly with respect to the subbase subgrade modular ratio.

Finally the automated system was used as above but injecting the knowledge gained from previous analyses (ideally this would be done automatically, but in the prototype this was done by the developer). The deflection bowl fit is clearly superior to those from the previous operations with agreement to within 10% at offsets up to 900 mm and 30% up to 2100mm. Furthermore the values of Elastic Moduli would appear to accord to values that would be expected for such a pavement, particularly with respect to the cracked condition of the wearing course and the computed low modular ratio between subbase and subgrade.

6. Concluding Discussion

The system described is an initial prototype which contains a relatively simple knowledge base. However from its operation it is clear that it is:

1. vital to enhance the selection of the seed moduli by reference to earlier detailed analyses of a wide variety of pavements.
2. important to build in an extensive set of rules approximating to the knowledge of an expert, and indeed to allow the system to develop its own set of rules from experience.

The current system, whilst only a prototype, has demonstrated the ability of a KBS to perform both objective and reasonable analyses of the structural properties of flexible pavements. However it is felt that it is currently over-simplistic and that more extensive databases and self-learning modules are required. Furthermore it is felt that POPLOG-Prolog may not be the optimum language for the next variant of the system because of its inability to cater for all the specified functions of the overall system.

Acknowledgements

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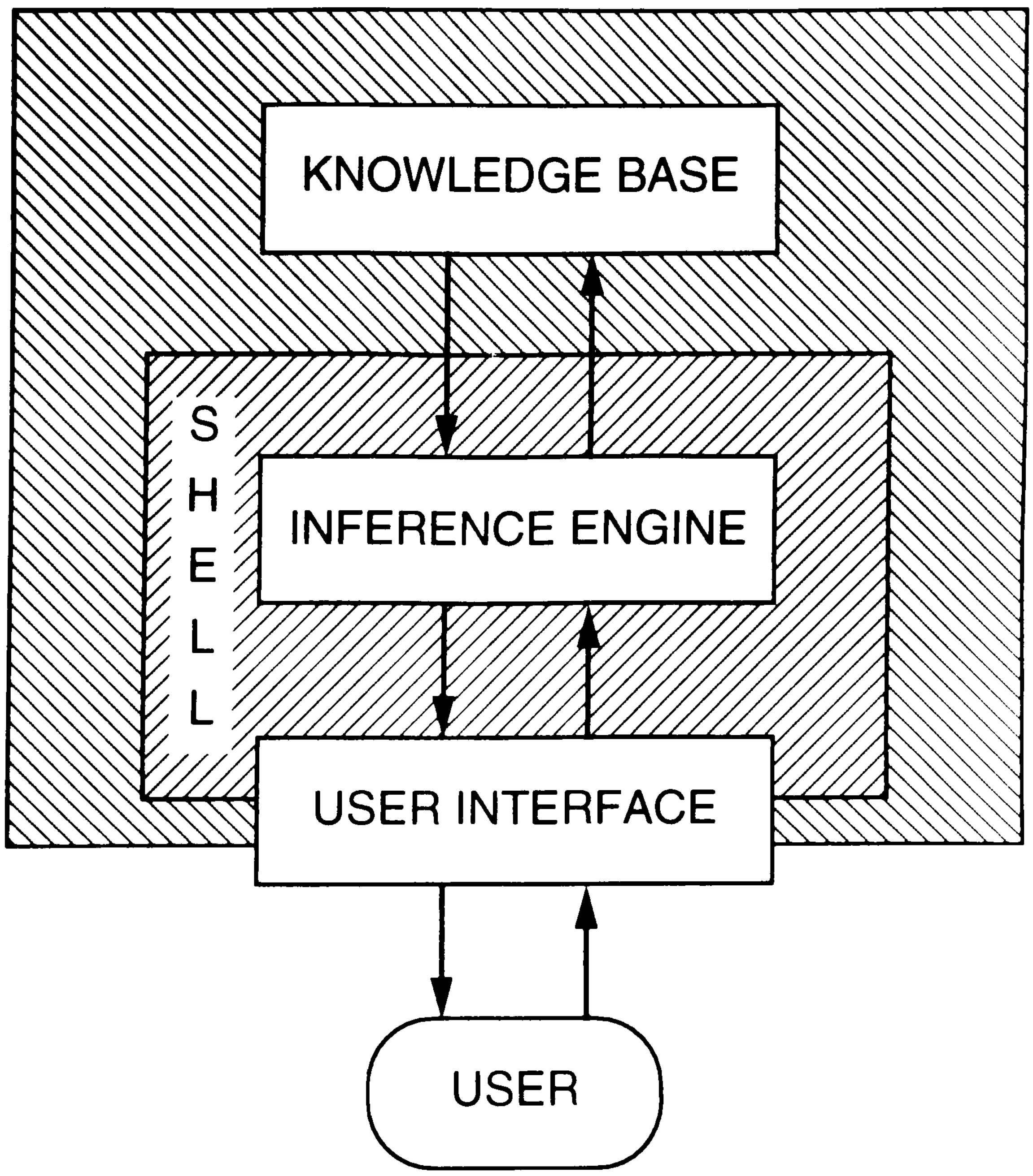

Fig. 1. Representation of a Knowledge Based System

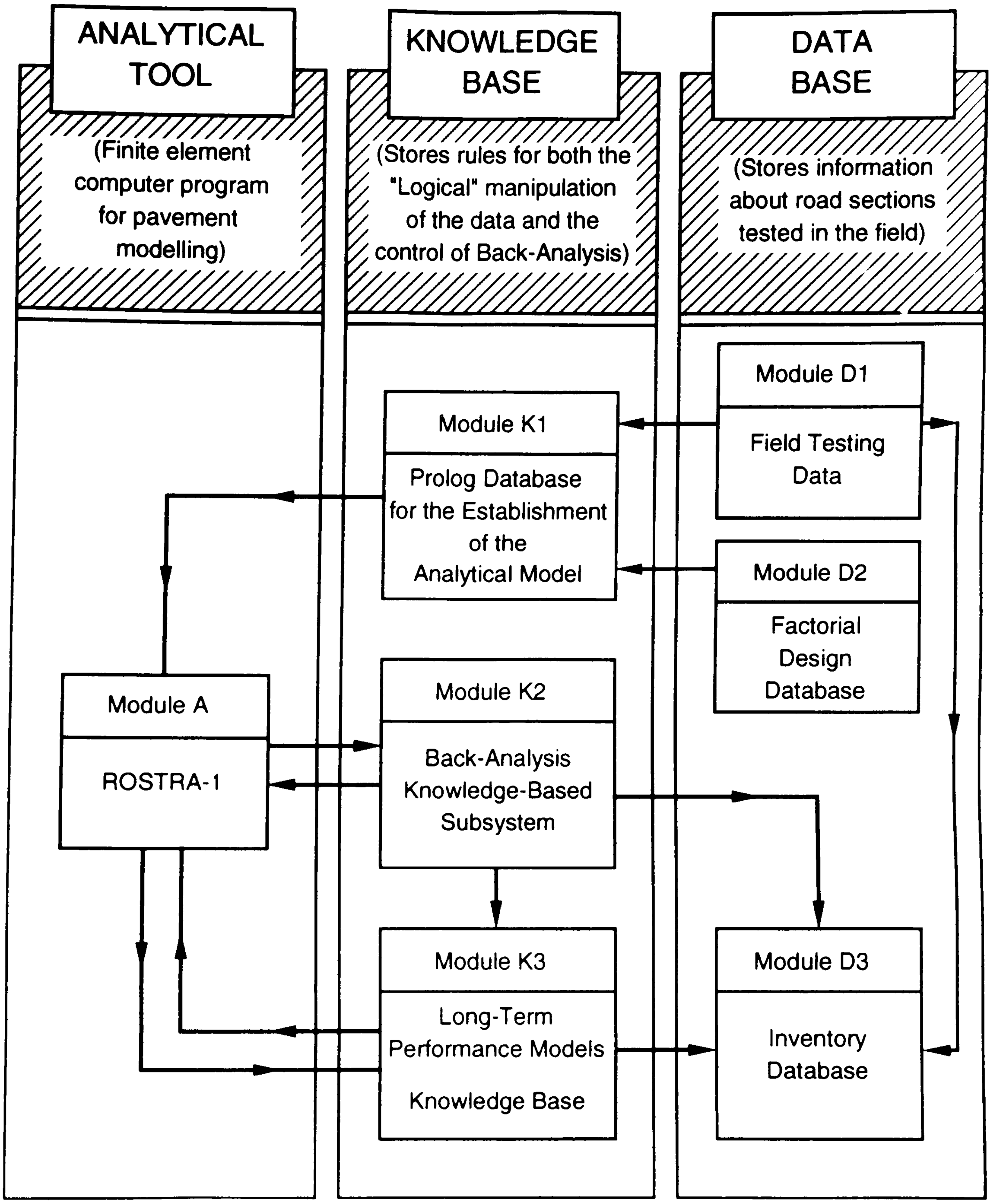

Fig. 2. An ideal structure for a pavement analysis K.B.S.

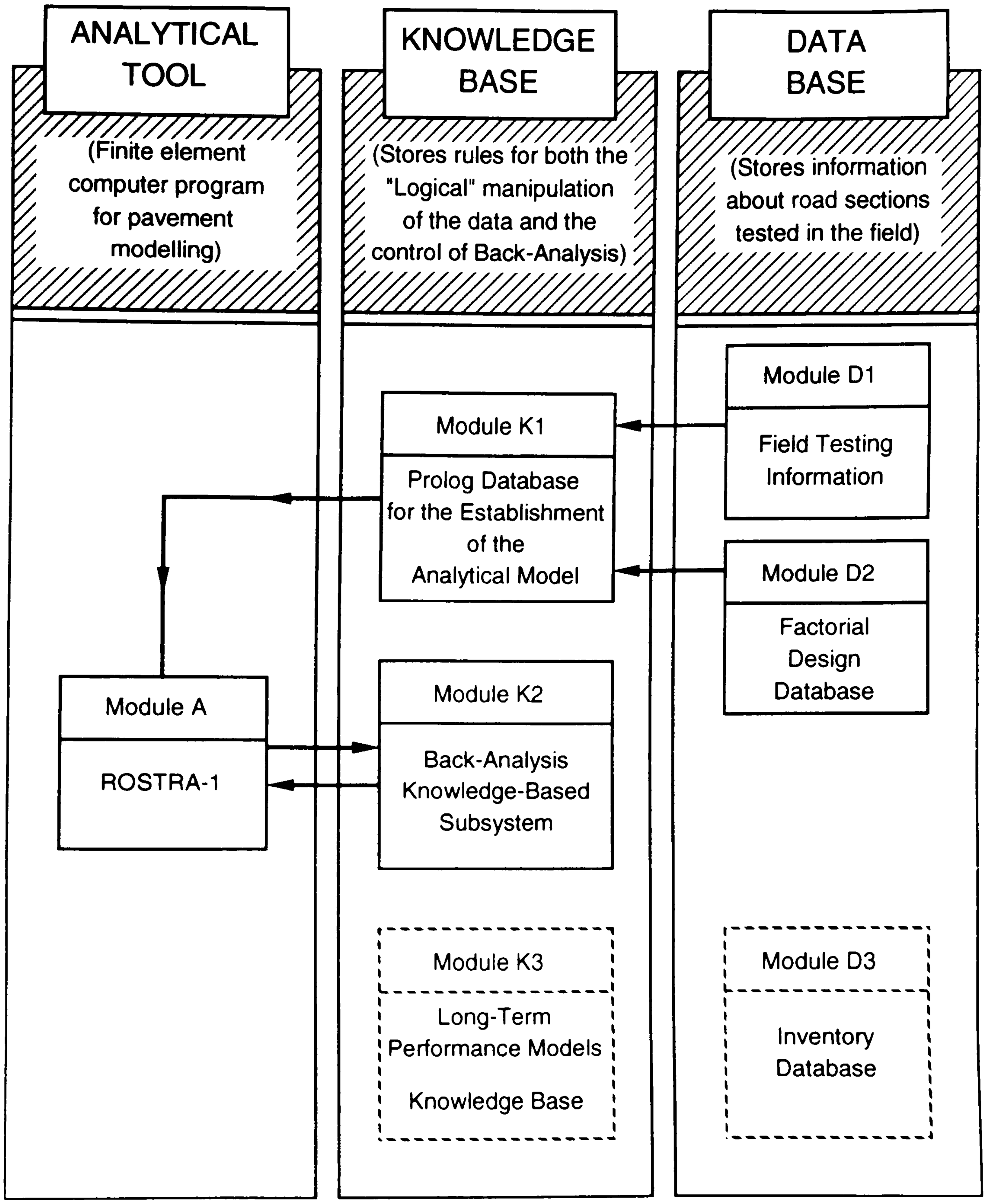

Fig. 3. The Structure of the working prototype K.B.S.

Table 1: Construction and Condition Information - Site A

Surface Condition	Thickness of bituminous material (mm)				
Cracked	Wearing course	Base course	Road base 1	Road base 2	Total
	38	69	115	100	322
Nominal granular subbase thickness is 330 mm.					

Table 2 - Measured and Computed Deflections for Site A

Offsets (mm)	0	300	600	900	1200	1500	2100
Measured deflections (microns)	254	194	147	109	88	65	36
Normalised deflections (microns)	241	184	139	103	83	62	36
Manual operation (microns)	242	116	71	45	26	13	0
Automated (microns)	265	201	148	99	58	26	3
Automated plus learning (microns)	245	172	128	92	64	42	25

Table 3 - Computed Moduli (MPa) and Poisson's ratio for Site A

Layer / Methods	Surfacing	Roadbase	Subbase	Subgrade
Manual Operation	1500	1000	500	150
Automated	2845	3844	126	50
Automated plus learning	2200	3000	200	120
Poisson's ratio	0.35	0.35	0.3	0.4

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