A MECHANISTICALLY AND RISK BASED DESIGN METHOD FOR CONCRETE PAVEMENTS IN SOUTHERN AFRICA

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ABSTRACT

The Cement Industry identified the need to develop a design method that would be easy for practitioners to use. The method was to be mechanistically based in order to facilitate interaction with the mechanistic flexible pavement design methods currently in use and to promote the use of concrete to rehabilitate flexible pavements.

The paper describes the development of suitable models from finite element and multi-layer evaluations as well as the computer program that was subsequently compiled. The design procedure takes into account voids under the slab, load transfer characteristics through aggregate interlock and dowels, the influence of traffic mix, tyre pressures and speed of loading. Pavement characteristics change with time and the different parameters show statistical variation. All of this, together with actual field performance, was taken into account to generate the output which is expressed in terms of risk of failure. In order to achieve a practical design tool, the performance of different concrete pavement sections (roads, streets and hardstandings), some of which were accurately instrumented, were used to calibrate the method.

INTRODUCTION

The Cement Industry charged the Cement and Concrete Institute with promoting the use of concrete roads in South Africa with the aim of increasing the market share for concrete roads. To do this, concrete roads must be cost-effective (for equivalent performance and reliability) and environmentally acceptable. The existing design method of the Department of Transport, the M10 manual "Concrete Pavement Design and Construction"[(1)], essentially followed a "recipe-type" approach to design and used a series of nomograms. It did however contain some aspects of mechanistic design. The document was not intended to cover all concrete pavement options such as inlays, overlays and varying design periods. It became apparent from overseas research, performance of local pavements and some instrumented sections of a concrete inlay on the National Route 3, that current concrete design methods were inherently conservative and consequently resulted in expensive pavements.

A number of strategy sessions identified the need for a departure from existing practice. A new design method was needed that utilised a mechanistic approach and would result in more cost-effective pavements (for equivalent performance to asphalt pavements). This approach is fuelled by the fact that concrete pavements are increasingly utilised as overlays on old flexible pavements where characteristics are

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determined through linear elastic theory and software packages. An integration of flexible and rigid mechanistic design approaches is therefore becoming more and more important. The new method was, however, to be pragmatic and aimed at ordinary pavement design practitioners rather than researchers and academics.

A survey of the South African road network indicated that the great majority of structural failures of road pavements could be attributed to construction and materials problems. Structural failures were thus caused by deficiencies built into the pavement which were aggravated by traffic and environmental factors. It was also established that the traditional approach, using single values for input parameters, was not ideal as uncertainty in the input was not translated into uncertainty in the output and therefore in the inherent risk of the design.

The design package had therefore to incorporate variability of the different parameters. Its structure should also enable it to be used to assess the relative effects of poor construction, higher than planned for variation in properties and to develop a bonus/penalty scheme for contractual purposes.

MODELLING OF PERFORMANCE

Based on the requirement that the design procedure should be user friendly and that the software needed to run on relatively inexpensive and readily available hardware, the use of sophisticated methods in calculating pavement response was precluded. However it was recognised that, in order to develop suitable pavement response and performance models, the latest technological tools had to be employed. The decision was therefore made to develop a database using finite element techniques, multi-layer analysis software packages, instrumented pavement sections measuring dynamic effects and the actual performance of the concrete road network to develop performance equations.

Maximum tensile stress in a concrete slab that is placed on an elastic support can be calculated using several methods[2][3][4], the most familiar being Westergaard. The following relationship indicates the basic format of these theories:

$$\text{Stress} = f\left(C, \frac{P}{h_1^2}\sqrt[4]{\frac{D}{k}}\right) \quad (1)$$

where:

- Stress = maximum tensile stress close to a joint or crack in the pavement
- C = a coefficient that primarily depends on load/slab configuration and load transfer at a crack or joint
- D = slab stiffness
- k = slab support
- P = magnitude of load
- h = slab thickness.

Tensile stress at a joint or crack is calculated since structural failure affecting performance can usually be associated with it.

Coefficient *C*, the load transfer coefficient, depends on the extent of load transfer at a joint or crack through aggregate interlock or dowels (longitudinal reinforcement for continuously reinforced pavements).

The magnitude of slab loading *P* can be defined in terms of wheel loading with due consideration for the effect of dynamic loading and speed of loading.

Slab stiffness *D* is a function of slab thickness and concrete stiffness.

Slab support *K* is not only dependent on the stiffnesses and thicknesses of the supporting layers, but also on the uniformity of the support. Relative settlement of sublayers and/or erosion under traffic loading and the presence of water creating voids will have an influence on slab support.

The ratio of slab stress/ slab strength has always been used in calculating the number of load applications of magnitude *P* to failure:

$$\text{Expected life } N = a\left(\frac{\text{stress}}{\text{strength}}\right)^{b} \quad (2)$$

Equation 2 is discussed in more detail later on.

Based on the discussion above the modelling can be subdivided into:

- a load transfer component
- slab loading through moving traffic
- slab support including voids under the slab
- slab characteristics and stress calculations
- structural performance as a function of the stress/strength ratio.

Load Transfer at the Joint/Crack

Load transfer can be effected in two ways namely aggregate interlock and dowel action of longitudinal steel bars. In order to isolate the effect of load transfer at a joint/crack on slab stress from the influence of slab support as far as possible, the relative vertical movement at the joint/crack due to a load moving across the joint/crack is taken as indicative of joint/crack shear stiffness.

Based on work by Walraven[5] as well as a laboratory study of some typical South African concrete mixes using hard, crushed, granitic material[6], the following was found for aggregate interlock:

Relative vertical movement $\Delta y = f\left(\sqrt[4]{n}, \frac{1}{E_1}, \frac{\Delta x^{1,5}}{Agg}\right)$ (3)

where : Δx = crack width
Agg = nominal size of 20% biggest particles in the concrete mix
n = number of load applications
E_1 = stiffness of the concrete.

Applying the fundamental theory of dowel design[7] relative vertical movement at a joint/crack with steel bars through it can be written as a function:

$$\Delta y = f\left(P_d, \left(\frac{1}{E_1}\right)^{0,75}, \left(\frac{1}{dia}\right)^{1,75}, \sqrt[4]{\frac{1}{E_s}}, \sqrt[4]{n}\right) \quad (4)$$

where: P_d = load on a dowel
E_1 = stiffness of concrete
dia = diameter of steel bar (dowel)
E_s = stiffness of steel bar
Δx = crack/joint width
n = number of load applications.

In order to translate relative vertical movement at the joint/crack into a *C* value as depicted in equation (1) above, the following relationship is used:

$$C = f\left(\sqrt{\Delta y}\right) \quad (5)$$

where *C,* the load transfer coefficient, is of the order of 0,16 for interior loading and 0,55 for free edge loading of a slab (no load transfer to the next slab). These values of C were determined for typical South African roads with slab thickness ranging from 150 to 250 mm, concrete cube strengths of about 40 MPa after 28 days and fairly stiff subgrade support.

Loading of the Pavement

External loading of the pavement is primarily through moving truck traffic. In order to determine amongst other factors, the influence of speed on deflection of and stress in the slab, trial pavement sections were instrumented and tested under different speeds of a standard loaded dual-wheel single-back-axle truck. A typical plot of speed versus surface deflection for three different types of pavements is shown in figure 1 for illustrative purposes[8]. It is clear from deflection data that the undowelled jointed pavement is much more affected by speed if compared with dowel jointed and continuously reinforced concrete. Speed, however, has a smaller effect on stress in the slab. The simplified equation to depict speed in terms of horizontal tensile stress in the concrete is:

$$\text{Stress} = f\left(\frac{P}{v^{0,5(c-0,2)}}\right) \quad (6)$$

where = v speed of loading
= C load transfer coefficient.

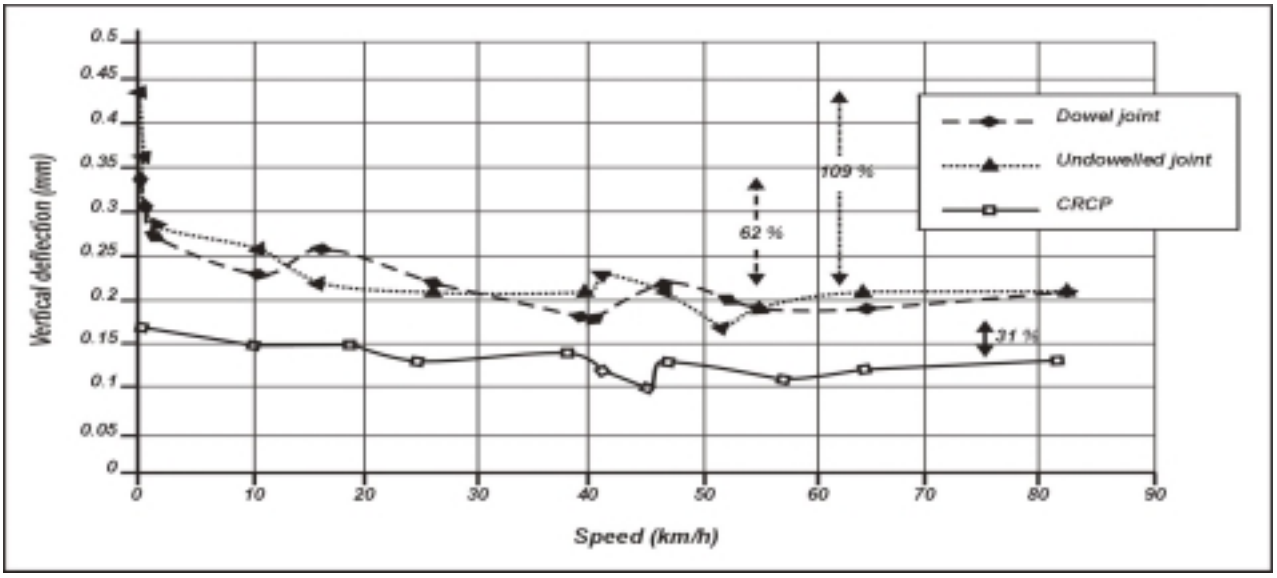

Figure 1 : Measured surface deflection vs speed

Slab Support

Slab support is provided through several layers of natural materials, some of which are modified or stabilised and the top layer, the subbase, consisting of asphaltic, cemented or high quality granular material. Since concrete overlays of flexible pavements are also becoming more popular, the use of multi-layer linear elastic software programs to calculate not only residual life of the old pavement, but also its stiffness as an input into the design of overlays, is essential.

Slab support can be simplified into a two-layer system, namely the subbase and an equivalent stiffness representing the contribution of lower layers. Using a multi-layer linear elastic program the equivalent stiffness of the layers below the subbase which render the same tensile stress in the slab, can be calculated.

Voids below the slab, as a result of erosion or pumping of the subbase, or settlement in the lower layers, can increase tensile stress within the slab by up to 40% if compared to uniform slab support conditions[9, 10]. Also the possibility of slab “lift off” as a result of temperature-induced curling can be regarded as a void and needs to be considered. However, using 4,5 m joint spacing, as is the case in southern Africa, this is not likely to be very common.

Slab Geometry and the Calculation of Stress

Recognising the need for simple equations, an attempt was made to utilise finite-element modelling together with actual measurement of strain on concrete roads under dynamic loading to develop models through regression techniques. A database was developed using a three-dimensional non-linear dynamic finite-element programme (STATAN), a three- dimensional linear elastic multi-layer programme (Elsym) and field measurements on pavements under traffic[8]. Eight variables were introduced to develop the basic equation: load transfer constant *C*, void length, concrete stiffness E_1, slab thickness *G*, subbase stiffness E_2, subbase thickness h_2, subgrade stiffness E_e and speed of loading. Submodels for load transfer through aggregate interlock and dowel action of steel bars, the effect of different loads and surface pressures and the combination of sublayers to form an equivalent subgrade stiffness E_e were developed separately using different databases.

The equation for maximum tensile stress at a joint/crack under dynamic truck loading finally arrived through regression analyses is:

$$\text{Stress} = \text{constant} \left[\frac{P\,(\text{Void}+1)^{0,80\,(C-0,1)}\, C^{0,4}\, E_1^{\,0,60}}{h_1^{\,a}\,(h_2 E_2)^{0,08}\,\left(3\sqrt{v+1}\right)^{0,5(c-0,2)}\, E_e^{\,0,27}} \right] \qquad (7)$$

where:
- void = length of void below slab
- C = load transfer constant derived from equations 3, 4 and 5
- $E_1\ h_1$ = slab stiffness and thickness
- $E_2\ h_2$ = subbase stiffness and thickness
- E_e = equivalent subgrade support stiffness
- v = speed of heavy vehicles
- a = $1,95/(h_2\ E_2)^{0,05}$
- constant = depends on wheel load and surface pressure.

The data on which the above equation is based was generated for 4,5 m joint spacing, a concrete shoulder 2,5 m wide, two travelling lanes each 3,7 m wide and the loading is by a 80kN single axle with double wheels.

Structural Performance

Many different performance curves or transfer functions are being used by designers to convert stress to expected number of load applications to failure. Figure 2 shows some typical data obtained from the literature. Both the RISC[11] and ARE[12] curves are based on AASHTO data, the first assuming a terminal serviceability index of 2,0 and the second (ARE) a terminal serviceability of 2,5. Both these curves are based on the format of equation 2 and thus the value of b for RISC is 4,29 and that of ARE 3,21. Darter[13] did laboratory beam fatigue tests to produce the curve in Figure 2 which is similar to the findings of other laboratory studies[14]. The performance curve used by

PCA[15] is also illustrated in this figure and is used, in similar format, for design procedures in Australia and Canada.

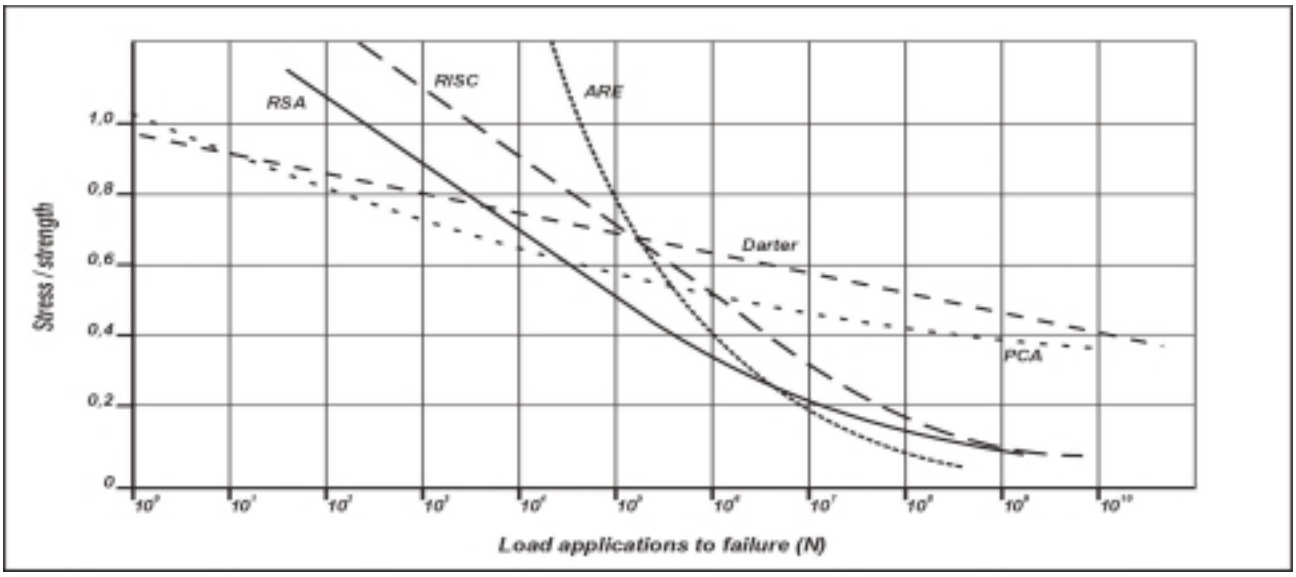

Figure 2 : Performance curves used by various designers.

Using equation 2 as a basis for the performance curve, as was done by Majidzadeh[11] and Treybig[12], the constant *a* leads to the situation that at high stress ratio e.g. 1,0, the number of load applications to failure is between 2 300 and 230 000. To overcome this problem, *a* can be defined as a function of the category of road in terms of the number of vehicles for which the pavement is designed. The curve depicted as *RSA* in Figure 2 is being used in the model until such time that present research suggests an improvement. The value of *b* for this curve in equation 2 is 4,2.

Deflection at a Joint

Using the same database that was developed for generating the equation for stress and supplementing with calculated field-measured information, the relationship for maximum deflection at a joint is:

$$\text{Deflection} = \text{constant}\left(\frac{C^{0,4}\,(\text{void}+1)^{0,2}}{h_1\,E_1^{\,0,25}\,(h_2\,E_2)^{0,1}\,E_e^{\,0,4}\,(v+1)^{0,02/C}}\right) \quad (8)$$

where the constant depends on surface loading i.e. vehicle traffic or by falling weight deflectometer.

DESIGN EVALUATION BASED ON THE VIEW OF CONSEQUENCES

Background

An effective but simple approach was adopted to evaluate the quality of design and thus facilitate competent decision-making. The approach is based on the evaluation of consequences. The consequences of a certain pavement design are expressed in terms of three output variables, namely risk of premature pavement failure, excessive deflection, and – in case of continuously reinforced concrete – excessive crack spacing.

Conceptually, pavement failure occurs when demand exceeds supply. In practice this happens when the number of load applications *n* a pavement is supposed to carry over the design period exceeds the number of load application *N* the pavement can carry at an acceptable level of structural and/or functional integrity. The ratio *n / N* is called cumulative damage *CD*. By definition *CD = n / N*. The risk *R* of premature pavement failure is defined as the probability of *n* being greater than *N*. In other words, *R* is the probability (*P*) of cumulative damage *CD* being greater than unity:

$$R = P\{CD > 1\}$$

One should mention that the complement of risk, i.e. *1 – R*, is called *reliability*.

Input

The proposed design method requires five input constants, namely the Damage factor *b*, Damage constant *a* (as in equation 2), Ratio $k1 = E_c.f$, Ratio *k2 = ITS / f* (where f is the flexural strength and ITS the indirect tensile strength), and Steel diameter *dia*. Apart from these, the method relies on nineteen input variables, such as aggregate size, crack width, slab thickness and others. Due to uncertainty, the designer may find it difficult to determine appropriate values for these variables. Many designers realise the uncertainty about correct input and, consequently, try to avoid the use of single point-estimates. Instead, they prefer indicating a range of reasonable practical values. Triangular probability distribution was used to express the stochastic nature of input variables. A triangular distribution is defined by three parameters, namely a minimum practical value, the best estimate, and a maximum practical value (see Figure 3). The triangular distribution has been chosen in preference to the Normal, Lognormal, Gumbel or Weibull types of probability distribution, because the determination of its parameters appeals to intuition, and is conducive to a direct application of the designer's experience.

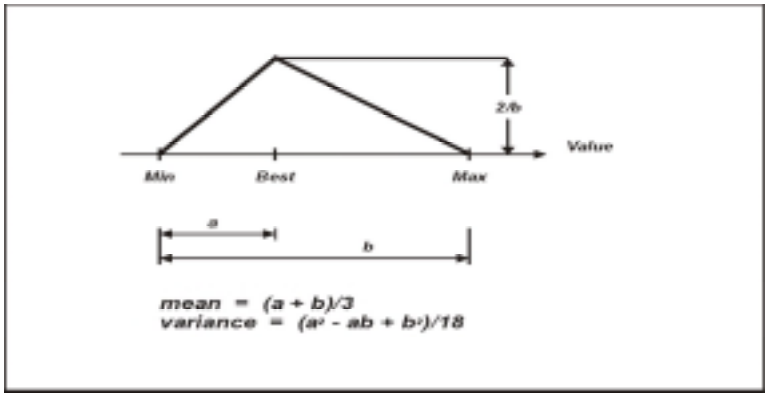

Figure 3 : Triangular distribution of input variables.

Of the nineteen input variables eighteen have triangular distributions, whereas one – the dynamic axle load – follows an empirical distribution. A practical example of such empirical distribution of axle loads, which was obtained from weigh-in-motion measurements, is shown in Figure 6.

Output

Because of the complexity of calculations, a Monte Carlo simulation technique was used to translate the uncertainty about the input into the uncertainty about the output. The magnitude of this uncertainty was established in terms of the probability distributions of the output variables, namely the cumulative damage *CD*, pavement deflection *y*, and crack spacing *x*. The risk of premature failure *R* is then represented by the area of the *CD* distribution that lies right of the line for *CD = 1*, outside the graph, see Figure 7.

The simplified flowchart on which the Monte Carlo simulation was based is shown in Figure 4.

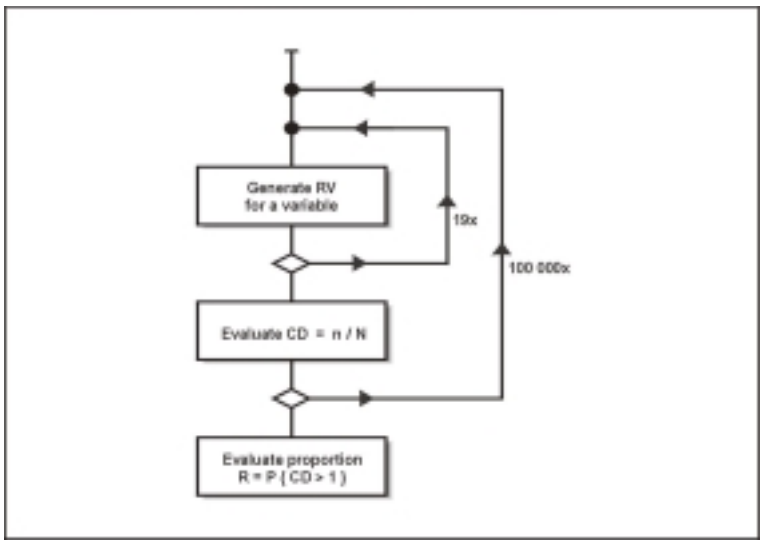

Figure 4 : Simplified simulation flowchart.

Computer Simulation Program

A computer program was developed to perform the above simulation. The program is called cncRisk and runs on a PC under the Windows operating system. The user interface is divided into five panels, namely Main control, Statistics, Advanced input, Operating instructions and Manual highlights. A panel can be selected by clicking its tab.

Main control panel

Figure 5 shows the Main control panel of the program, together with default values of the input variables and constants. The values of main output variables – risk, deflection and crack spacing – are also shown on this panel. In addition, three dials are displayed. During a simulation run, the needles indicate the current level of cumulative damage, deflection and crack spacing, respectively, to continuously inform the user.

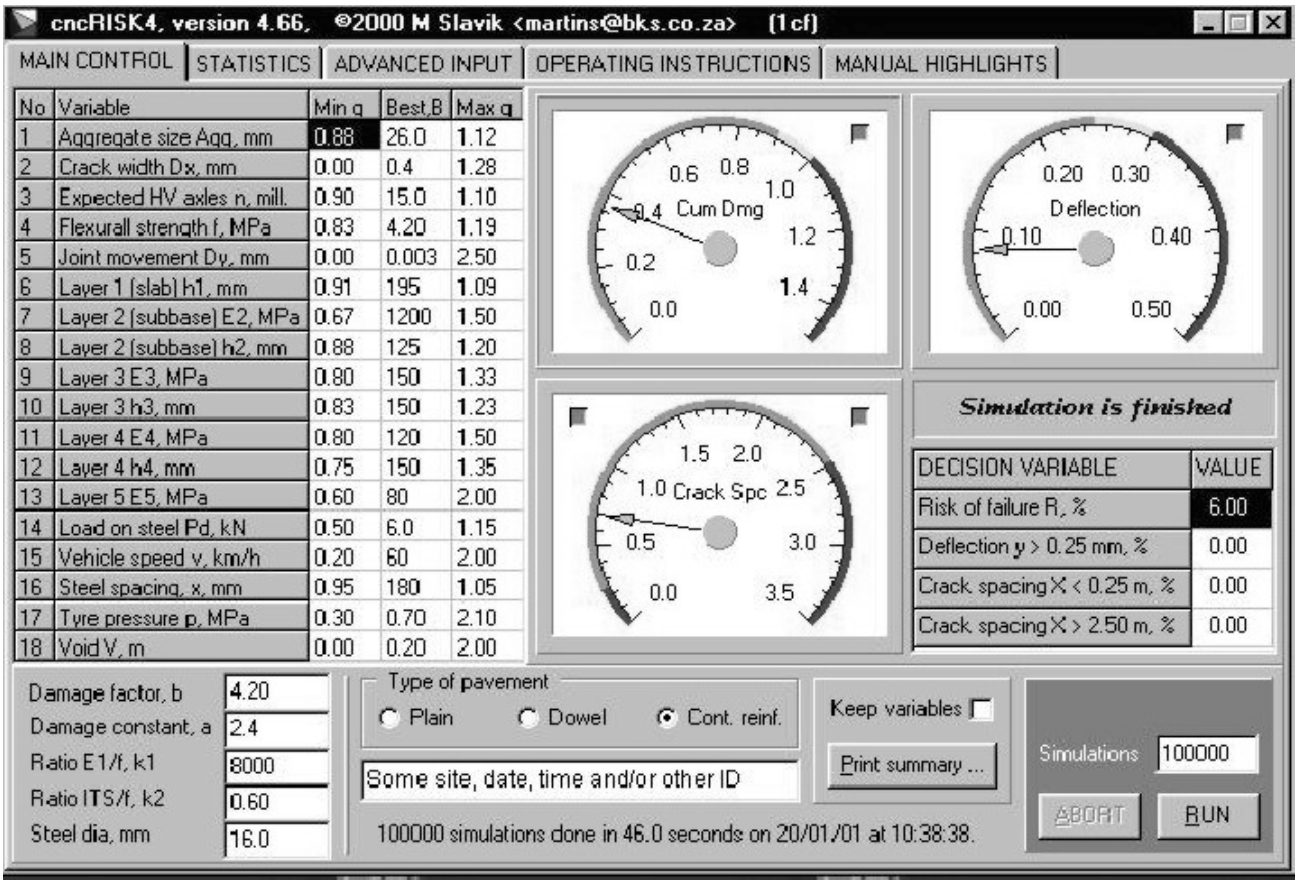

Figure 5 : Example of the Main control panel.

The minimum and maximum practical values of the input variables are entered as factors *q*, by which the best value is multiplied to obtain the respective extreme. Three main types of concrete pavement – plain, dowelled and continuously reinforced – are selectable by means of 'radio' buttons. The number of simulations can be selected from 1 000 to 10 000 000. Although a small number of simulations will be done very quickly, it may produce jagged output distribution curves and give dissimilar output figures for repeated simulation runs. In contrast to the above, a large number of simulations (say, over 100 000) will take more time to complete, but will yield relatively smooth probability distribution curves, and ensure good repeatability of output results.

Advanced input panel

The panel called Advanced input, which is shown in Figure 6, gives the user an opportunity to enter the distribution of dynamic axle loads that are applicable in his or her case. A typical distribution can be selected from a provided list. Alternatively, entering frequencies can create an individual distribution. In any case, a frequency plot is shown in a graph to guide the user. Also, the presence of a shoulder is selectable on this panel.

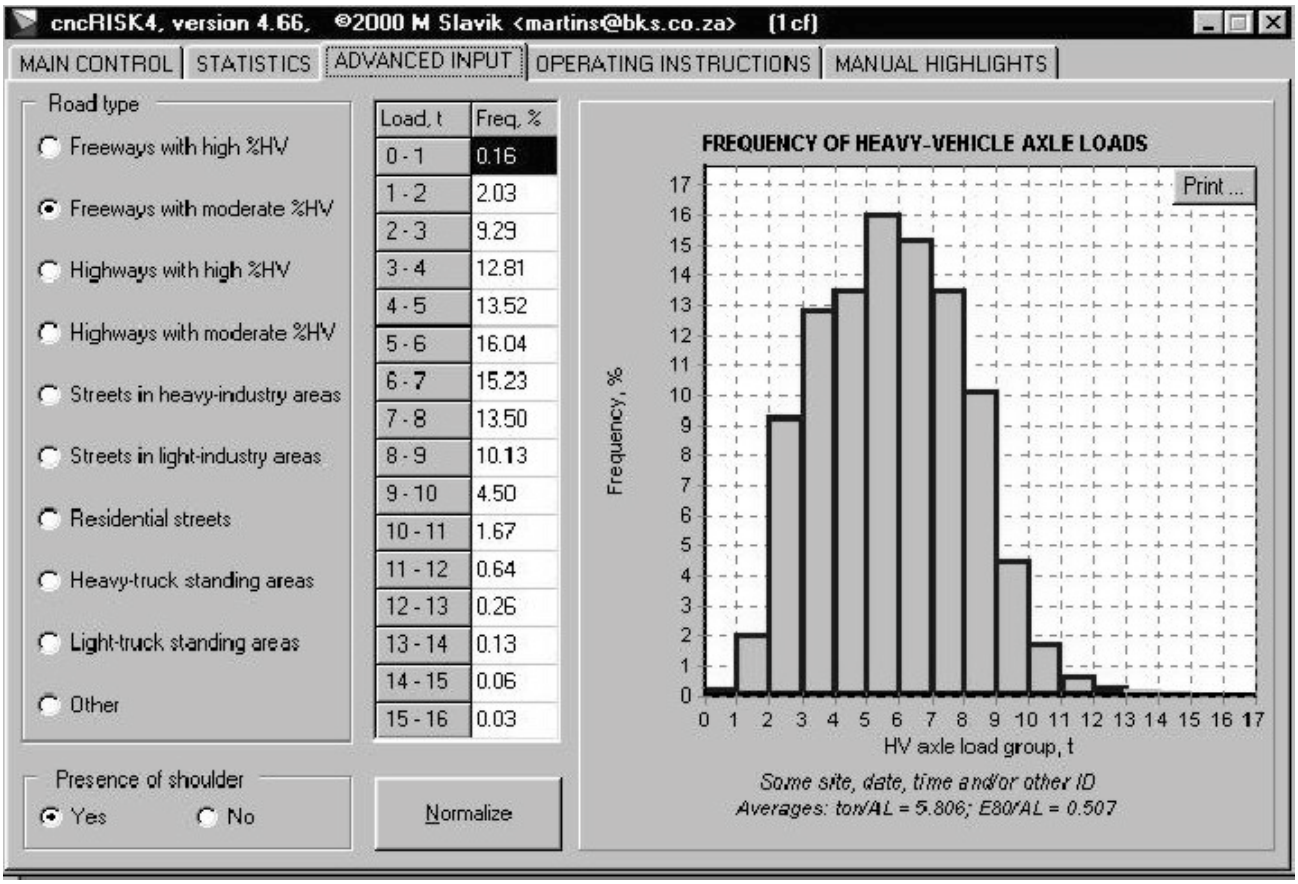

Figure 6 : Example of the Advanced input panel.

Statistics panel

The probability distributions of the output variables, together with other figures of interest, are shown on the panel called Statistics – see an example in Figure 7. As mentioned earlier, the quality of design is reflected by the three main output variables, namely cumulative damage, deflection, and crack spacing in case of continuously reinforced concrete. To facilitate evaluation and competent decision making, certain standards were laid down to guide the designer. As a rule of thumb, the risk *R* should not exceed 5% in case of national and strategic roads, 7% in case of provincial and less important roads, and 10% in case of low-standard roads. Similarly, the probability of deflection at a joint or crack exceeding 0,25 mm should also comply with the above standards. These percentages can also be applied to the probability of excessive crack spacing, which should never be less than 0,25 m and never more than 2,50 m.

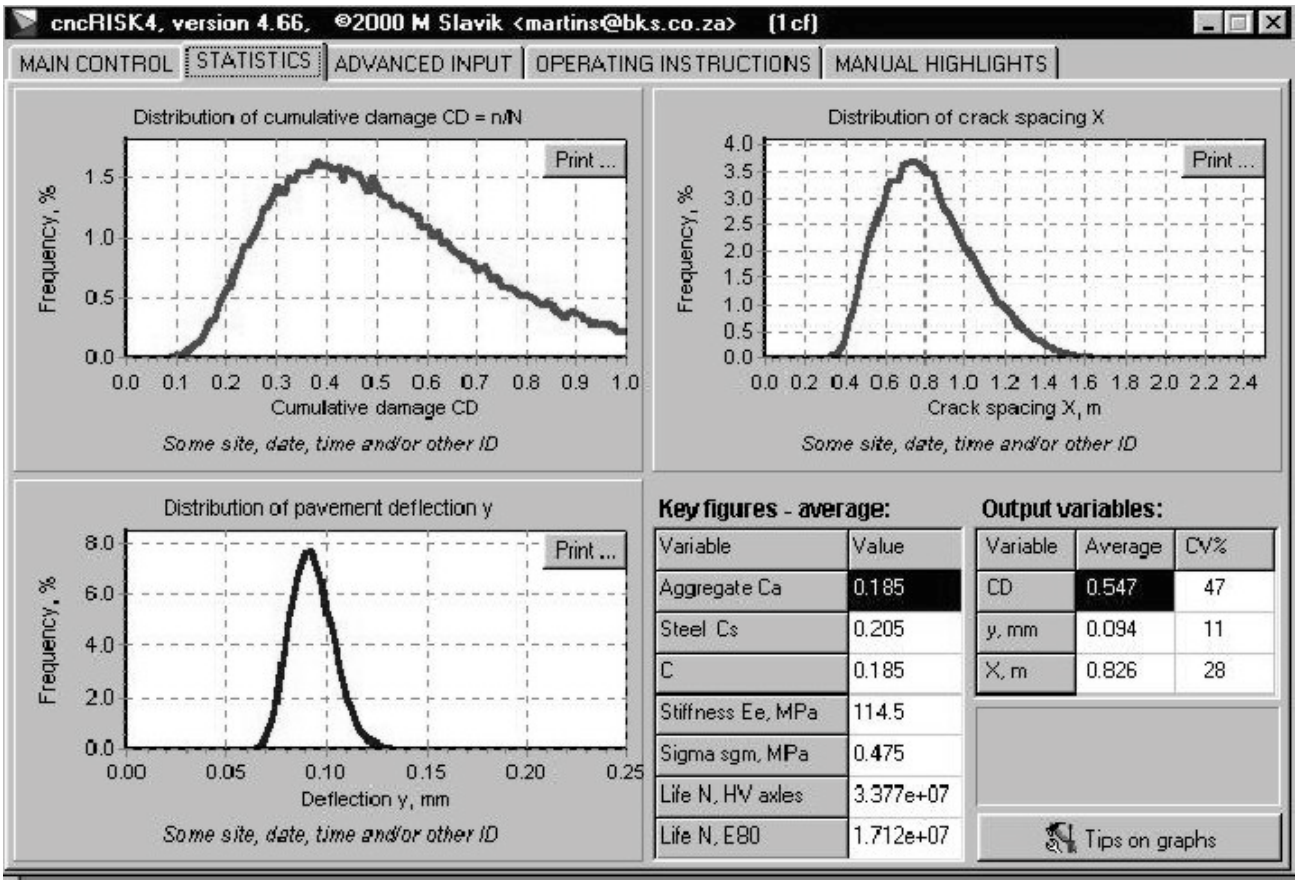

Figure 7 : Example of the Statistics panel

One should consider the relation between the above figures and the uncertainty about the input. A conservative uninformed, or unsure designer would specify the respective triangular distributions with low minimum, and high maximum, practical values. This will result in "fat" distributions of the output variables, with probabilities exceeding the recommended figures. To bring the figures down to the standard, a stronger – and more expensive – design will have to be employed. The extra cost of such a design can then be viewed as a cost of imperfect knowledge of the input.

General

The program is written in the C++ language and operates quickly. Typically, on Pentium 400 MHz machines, performing 100 000 simulations takes less than 20 seconds. Because of this, the program is particularly suitable for "what-if" and sensitivity analyses, and for the trial-and-error fine-tuning of final design. Currently, work is under way to restructure both the input and the output modules of the program. In the future the output will include life-cycle costing, which will allow the decision to be based on monetary values, rather than on interim quantities, such as the risk of failure.

Research is also presently under way to further develop both the load transfer functions (dowel and aggregate). This will increase the accuracy of the stress equation.

However, the refinement of the performance curve is of the greatest importance and, in order to increase confidence in the prediction of performance, the program has been released for use by a selected group of practitioners. Feedback from them on the performance of pavement structures together with further research using the Heavy Vehicle Simulator (HVS) will be implemented within the next 12 months.

CONCLUSION

A mechanistically based design method for concrete pavements has been developed in South Africa, to facilitate interaction with the mechanistic flexible pavement design methods currently in use, and to promote the use of concrete to rehabilitate flexible pavements.

Suitable models have been developed from finite element and multi-layer evaluations and a user-friendly computer program has been compiled. The design procedure takes into account a large number of input variables, the fact that pavement characteristics change with time, and that the different parameters show statistical variation. All of the above, together with actual field performance, was taken into account in generating an output which is expressed in terms of risk of failure. The design method has been calibrated against actual performance on various sections and pavement types, such as roads, streets and hardstandings.

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