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THE DEVELOPMENT AND APPLICATION OF MECHANISTIC DESIGN PROCEDURES FOR CONCRETE BLOCK PAVING

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ABSTRACT

This paper describes the evolution of a fully-automated computer based mechanistic design procedure for concrete block pavements. The method encompasses road, industrial and airport pavements. The benefits and limitations of the method are discussed and the importance of selecting appropriate input data is emphasised. The benefits of integrating cost analysis and the assembly of materials and construction specifications into the design process are also discussed and the implications of new paving techniques such as the use of permeable eco-paving are assessed.

1. INTRODUCTION

Design methods for concrete block paving (CBP) have been critically reviewed elsewhere [1,2,5,6]. In common with pavement design in general the design of CBP is increasingly orientated towards mechanistic design. In 1985 the author began the development of a mechanistic structural design procedure for CBP [3-6]. This program is known as LOCKPAVE and is now in use in many areas of the world including Australasia, North America, Scandinavia, Europe, Southern Africa and Asia. The program is capable of analysing roads, industrial hardstands, airport pavements and CBP overlays and can also assemble model materials and construction specifications. This paper describes the evolution of this program.

2. PRINCIPLES OF MECHANISTIC DESIGN

Mechanistic design applies routine analytical methodology to designing pavements based on computer analyses which are used to predict the long-term performance of the pavements from the stresses and strains that are caused by traffic. In this respect the mechanistic design of pavements is no different from most methods of structural design. Essentially, the designer calculates the stresses or, more commonly, the strains that will be caused by the design loads and uses these to predict the service life of the pavement. The service life depends on how long the pavement will take to develop unacceptable deformation or rutting under traffic and on how long it will take any bound pavement materials such as cement stabilised or asphaltic base or sub-base to fatigue and crack. Rutting can be related empirically to the magnitude of the vertical compressive strains induced by traffic at the top of the subgrade. Cracking can be related by fatigue test data measured in the laboratory to the horizontal tensile strains induced in the pavement by vehicle loads.

Essentially, mechanistic design involves the following steps:

1. A candidate pavement structure is chosen. This choice is normally based on experience but can be arbitrary. The candidate structure is represented as a series of layers placed over the natural soil or subgrade.
2. Material properties are assigned to the pavement layers and to the subgrade.
3. Each pavement course is assigned an initial thickness. In automated design these initial thicknesses usually correspond to the minimum thicknesses that are practical to install (e.g. it is normally not feasible to construct base or sub-base layers thinner than 100mm).
4. The vehicle wheel loads are characterised in terms of their magnitudes, locations, contact (tyre) pressures and the required service life is quantified in terms of the number of wheel load repetitions.
5. The stresses and/or strains induced in the pavement by the wheel loads are computed.
6. The computed stresses and strains are used to estimate the numbers of wheel load repetitions that will cause cracking in any bound pavement materials such as asphalt or cement-stabilised base. This provides one estimate of service life. A second, different estimate of service life is obtained by computing the numbers of load repetitions that will cause unacceptable rutting in the subgrade.
7. If the lesser of the two service lives computed in step 6 is smaller than that calculated in step 4 then it is necessary to increase the thicknesses of one or more pavement layers and repeat steps 3 to 6 until a satisfactory design is achieved.

Step 5 is almost impossible to implement without the use of specially written computer programs. For this reason and because it will be seen that the selection of pavement layer thickness is an iterative process (i.e. cycling steps 3 to 7) it is logical to automate the entire design process as a computer program.

3. ADVANTAGES OF AUTOMATED DESIGN

Automated design programs offer the following practical advantages:

a) The programs lead the user through a systematic design procedure. This ensures that all essential design requirements are met.

b) Computer-based methods can incorporate expert rules to aid the inexperienced designer in making correct decisions when selecting materials and other design inputs. The rules can also ensure that the designer's attention is drawn to the consequences of sub-optimal or incorrect decisions.

c) By providing fast solutions, computer-based methodology encourages a designer to refine progressively design assumptions and to compare a range of alternative designs.

d) The design programs can automatically assemble and print the specifications necessary to implement a particular pavement design.

e) As shown in Figure 1 below, the design process is modular and, therefore, is easy to update the design method as new knowledge or technology becomes available. In this respect LOCKPAVE has been progressively upgraded over the period that it has been available since 1985.

4. IMPLEMENTATION OF AUTOMATED MECHANISTIC DESIGN

Computer programs such as CIRCLY BISAR, ELSYM and CHEVRON have long been available for analyses of the distributions of stress, strain and deflection in layered elastic pavement systems. However, such programs execute only step 5 in the design process listed in Section X above. By contrast, LOCKPAVE is a fully automated program for the complete structural design of concrete block pavements.

The design process is illustrated schematically in Figure 1. It will be seen that stress/strain analyses form only a small part of the design process. Before the designer can use such analyses, a number of crucial decisions must be made. These include the choice of paver shape, thickness and laying pattern. In addition, the designer must nominate a trial cross-section for the pavement.

Once the outputs of the stress/strain analysis program are obtained the designer must decide whether to try another type of pavement structure. This decision is normally based on questions of economy. This requires cost analysis to be integral to the design process. Finally, once a satisfactory design has been achieved, the designer must draft materials and construction specifications.

It will be seen that the design process involves a number of decisions which each may affect the performance, economy or ease of constructing and maintaining the pavement. As shown in Figure 1, the design process is structured and systematic and the designer's task may be simplified either by automating or guiding decision making by the use of expert rules.

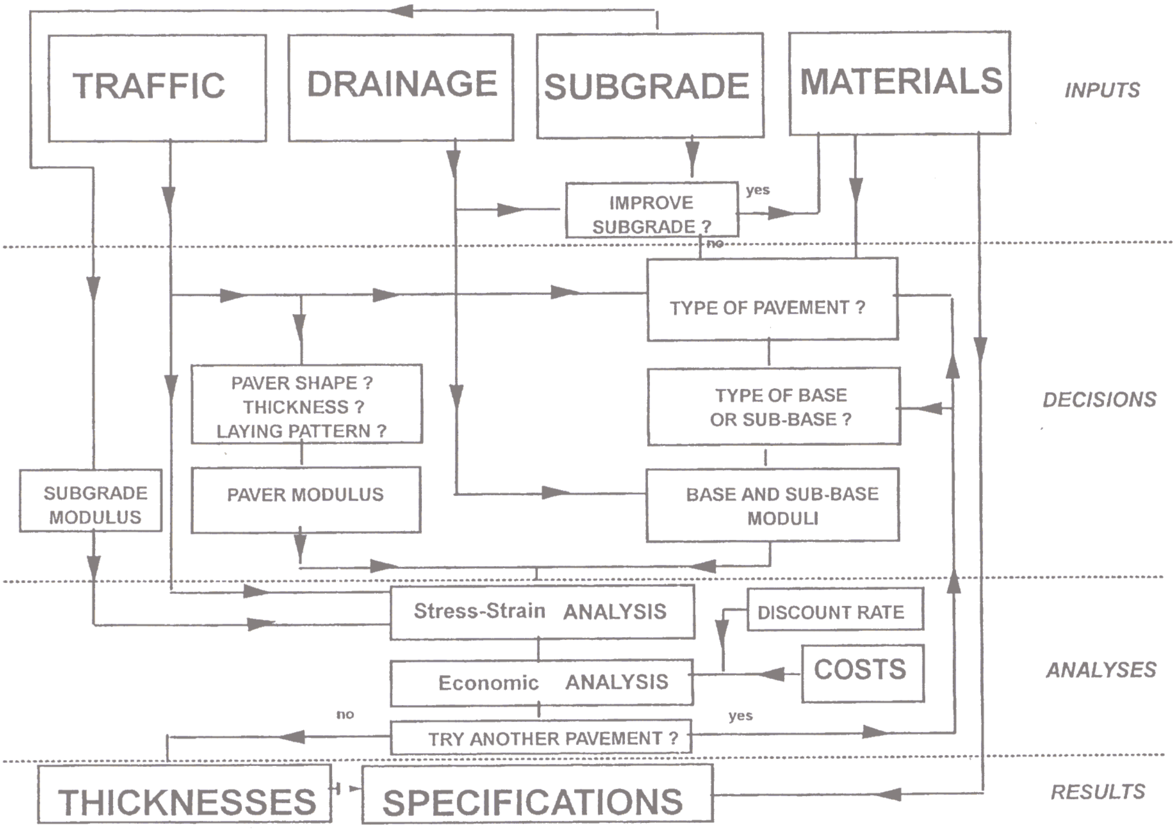

Figure 1. Schematic Overview of the Design Process for CBP

5. DESIGN INPUTS

As shown in Figure 1, the data required by the designer will typically include information on the subgrade characteristics, strength and drainage, the traffic loads and intensity and the availability of pavement materials. From these the designer must

a) Choose an appropriate type of surface
b) Choose the appropriate type of pavement
c) Choose the base, sub-base and select-subgrade materials
d) Assign properties to the surface, base, sub-base and subgrade materials in the forms required by the stress/strain analysis.

Expert or experience - based rules can assist in each of these decisions by

i) Eliminating inappropriate choices or alternatives.
ii) Warning the designer of the consequences of particular decisions or combinations of decisions.
iii) Making the decision automatically where a particular choice becomes obvious by virtue of earlier decisions in the design process.

The inputs required for the design of CBP are now described in detail.

5.1 Paver Model

Tests conducted over the last twenty years have shown that the load distributing properties of pavers depend on the paver shape, thickness and laying pattern [1,2,10,11]. Many design methods for CBP ignore these factors and attempt to characterise all pavers as sharing a single universal set of design properties including some assumed value of the modulus. However, it is desirable to treat each type of paver on its own merits and to characterise it in terms of the actual stiffness that it is capable of developing in-service. Thus, one of the first decisions a designer must make is to choose the shape, thickness and laying pattern for the pavers to maximise the load spreading capabilities of the pavement. Each of these factors has been shown to influence the performance of block paving under traffic [1]. Accordingly, it is possible to guide the pavement designer in the choice of these input parameters by a set of expert rules which attempt to summarise data on the performance of CBP under traffic [e.g. 1].. Rules which have already been incorporated into the LOCKPAVE design program recognise that shaped pavers tend to perform better under traffic than rectangular pavers, that herringbone patterns are preferable to stretcher bond for trafficked pavements and that the thickness of the pavers and the choice of base and sub-base depend on the traffic and subgrade conditions[e.g. 1, 3-6]. It is important to note, however, that these rules are for guidance only and do not pre-empt decisions by the designer.

The modulus appropriate to the pavers can be obtained from Falling Weight Deflection (FWD) tests of block pavements currently in service or from structural tests of the pavers alone. Falling Weight Deflection studies have already been conducted in several countries including the Netherlands [7], Britain [8], Japan [9] and Australia [5]. These and other in-situ deflection tests of full-scale CBP share the common disadvantage that the data can only be used to calculate the moduli by making a series of assumptions about the pavement structure and materials. Some of these assumptions are incapable of verification. Consequently, there must always be some degree of uncertainty concerning the values of modulus derived from such procedures. For this reason, it is desirable to have a test procedure that permits the modulus to be measured directly without the need for unverifiable assumptions. Such a procedure has been developed for pavers by the author [13,14]. This test is less subject to interpretive errors than FWD tests but can only be performed on newly laid pavers. Consequently the stiffening of a paver surface that normally occurs under traffic cannot be simulated and, as a result, laboratory measurements may underestimate the in-service moduli of pavers.

Typical values of paver moduli are summarised in Table 1 for both FWD and laboratory measurements.

Table 1. Paver Moduli Measured by FWD and Laboratory Tests

Test Condition	Moduli (MPa)	Reference
FWD tests of trafficked rectangular pavers	500-700	7
FWD tests of trafficked pavers	720-9600	8
FWD tests of trafficked shaped pavers	75-19000	5
Laboratory tests of rectangular pavers	600-750	13
Laboratory tests of shaped pavers	400-6000	14
Laboratory tests of shaped eco-pavers	1000-4000	10

From Table 1 it may be seen that the moduli of pavers vary depending on the test method, shape of paver etc. However, conservatively, values of modulus between about 2500 MPa for rectangular pavers and up to about 5000 MPa for shaped pavers can be recommended for design. Such a change in modulus has beneficial effects on the thickness of pavement needed especially when constructing CBP over low-strength subgrades. A designer should therefore chose a paver associated with a high modulus in preference to one exhibiting a low modulus. For example shaped pavers would be chosen in preference to rectangular pavers. Against this it might be argued that the benefits of using high modulus paver is typically to save just 10% to 15% of base thickness and that, consequently, the choice of paver is unimportant. This argument fails to recognise that some important aspects of performance are not considered in thickness design calculations. A prime example of this is the propensity of some pavers (e.g. rectangular) to creep horizontally under traffic. This is a function of neither the type nor thickness of base or sub-base and must be considered in design in some other way. It is in this area that the application of the expert rules mentioned above again play a crucial role in helping the designer to select the most appropriate paver shape and laying pattern

In mechanistic design, it is desirable to model the stiffening of the pavements that occurs in-service under traffic. This can be conservatively accomplished by assuming that the paver modulus immediately after construction will not exceed that of the basecourse. (In the case of unbound bases this gives moduli well below those measured in structural tests). It is then assumed that the pavers will gradually achieve their full stiffness during the passage of the first 10000 truck axle loads [6]. This increase can be automatically modeled in the design program.

5.2 Base, Sub-Base And Subgrade Characterisation

LOCKPAVE requires knowledge of the elastic properties of each pavement material determined from laboratory tests. The parameters required are the Young's modulus, E, and the Poisson's ratio, ν. Of these two parameters, E is the more important in controlling the material response. This modulus relates stress to strain and allows the strains and deflections resulting from the applied loads to be calculated. In practice, most pavement materials are not strictly linear and elastic and, for repeated cycles of loading and unloading, the materials will exhibit both non-recoverable or plastic deformations and recoverable or resilient deflections. For this reason it is customary to characterise the response of pavement materials carrying traffic in terms of the resilient modulus, M_r. This is defined as the ratio of the repeated stress to the recoverable strain and is closely analogous to the Young's modulus, E.

Over the last 20 years considerable effort has been directed towards obtaining M_r data for base and sub-base materials and, in most developed countries, there is substantial information on the likely range of moduli for different classes of material [e.g. 1]. The final choice of a design value will be governed by drainage considerations. Typical values have been given elsewhere [1].

The subgrade can best be characterised by repeated triaxial loading resilient modulus tests but it is also possible to work in terms of simpler, less fundamental soil properties such as the CBR provided correlations exist between such parameters and M_r [1,6,16]. In some practical design situations (eg. during feasibility studies) soil stiffness/strength data are not available. It then becomes necessary to infer a range of probable moduli based on soil classification data. Three classifications are in common use. These comprise the Unified Soil (ASTM) Classification, a general system, the AASHTO Classification and the Federal Aviation Administration Classification directed at road and airport pavement materials respectively. Relationships between classification and soil moduli have been given elsewhere [e.g. 16] enabling a designer to make an optimistic or pessimistic estimate of modulus depending on the site drainage.

5.3 Drainage Conditions

Changes in the moisture content or degree of saturation in unbound materials will be alter the stiffness and strength of all the subgrade and all unbound materials. It is, therefore, imperative that drainage be considered as an integral part of design. The simplest way to consider drainage during pavement design is to adjust the moduli of all unbound materials according to the drainage conditions. This is largely a matter of engineering experience and judgement. Based on a wide range of practical data, the factors given in Table 2 are suggested as suitable for general application to CBP. These are given as a function of the drainage conditions and time of saturation based on AASHTO nomenclature.

Table 2. Drainage Factors for Mechanistic Design

DRAINAGE CONDITIONS	Time pavement remains saturated			
	<1%	1% to 5%	>5% <25%	> 25%
Excellent – Drains in 12 hours or less (Pavement is usually dry.)	1.00	0.90	0.85	0.80
Good - Drains in 1 day	0.90	0.85	0.75	0.70
Fair - Drains in 1 week or less (Pavement is usually moist.)	0.85	0.75	0.70	0.60
Poor- Drains in 1 month	0.75	0.70	0.60	0.50
Very Poor - Will not readily drain (Pavement is often wet.)	0.70	0.65	0.50	0.40

Once the designer specifies the drainage conditions, LOCKPAVE automatically modifies the moduli of all unbound base and sub-base materials by these factors . However, the program also allows the designer to change the factors as required. From Table 2 it should be noted that the full modulus of a material is assumed to be achieved only for excellent drainage conditions. This is a more conservative approach that that adopted in many other pavement design procedures [e.g. 17]

A recent development in CBP has been the introduction of permeable eco-paving [10]. This type of pavement facilitates drainage of water through the pavement and uses the pavement for water retention. This complicates pavement design. Although tests have shown that the moduli of permeable eco-pavers are little different from those of conventional pavers [10] repeated loading triaxial tests conducted by the author indicate that the resilient moduli of saturated unbound base and sub-base materials are typically only 50% or less of the moduli that these materials can develop when normally compacted at or below Optimum Moisture Content. For this reason it is prudent to specify drainage factors of 0.5 or less (vide Table 2) when designing eco-pavements. Alternatively, the use of permeable cement-bound drainage layers should be specified. In either case, is desirable to complement the structural design of the pavement by a hydraulic analysis to ensure that the eco-paving can accommodate the water flows required.

5.4 Frost Action

In frost regions the depth of frost penetration and the frost susceptibility of the base, sub-base and subgrade materials should be considered. The subgrade may be assessed using criteria based on the proportion of soil finer than 0.02mm and the plasticity index [9]. A reduced subgrade strength (and stiffness) can then be assigned. The depth of frost action should also be calculated. Within this depth, only non-frost-susceptible materials should used. This depth, the potential for frost heave and the potential loss in pavement serviceability due to frost can be calculated from the Freezing Index, the depth of the water-table and the drainage conditions. Such data therefore form essential inputs to the mechanistic design of CBP in cold regions. LOCKPAVE adopts the well-known US Army Corps of Engineers method to solve these problems [11]

5.5 Design Loading

The design loading carried by CBP can be represented in terms of two inputs. These comprise the spectrum of load magnitudes and the repetitions of each load in the spectrum. Each of these inputs is now considered in more detail.

5.5.1 Load Spectra

The axle load spectra appropriate to roads and industrial pavement have been described elsewhere [1,4,5]. For roads, the spectrum is obtained from loadometer or weigh-in-motion studies, whilst, for industrial and airport pavements the spectrum is obtained from the predicted mix of vehicles that will use the facility. For industrial vehicles or aircraft distinctions must be made between laden and unladen vehicle movements. In addition, for vehicles moving containers, the variation in container weights typical of different sizes of container (20 and 40ft) must also be considered [1,4]. The use of axle load spectra requires numerous calculations but this is easily accomplished using computer-based methods such as

LOCKPAVE. The importance of such an approach is that it gives CBP designs which are more conservative (i.e. thicker) than those associated with axle load equivalencies [4-6].

For industrial pavements, designers often wish to impose factors of safety on the loads to guard against the effects of overloading. The choice of load safety factors is largely subjective. LOCKPAVE uses the load safety factors suggested by the British Ports Authority [15]. These allow the cumulative effects of braking, turning, acceleration etc. to be modeled.

5.5.2 Load Repetitions

Engineers assume the design repetitions simply to be the product of the number of vehicle movements and the number of axles.. However this is not always correct for vehicles with multiple axles. As shown in Figure 2 for tandem axles, the effects of load overlap as the loads are distributed deeper in the pavement. At the surface (A), each axle generates a separate load pulse but with increase in depth (B) the pulses merge to form a large pulse, S_a, followed by a smaller pulse, S_b. Deeper in the pavement (C) the overlap of load distribution gives rise to just a single pulse of load, S_c. In other words, the number of design repetitions varies with depth. This is of particular importance when dealing with multi-axle industrial vehicles or aircraft but can often be ignored for road vehicles. The LOCKPAVE program automatically considers this effect and avoids the repetitive and tedious calculations that would otherwise be needed. To achieve this also requires that the program calculate the location of the maximum strains i.e. whether beneath one of the wheels, between the wheels or between the axles. Again, this would be difficult and time consuming to achieve without the use of a computer program but is essential if the loading conditions are to be correctly modeled.

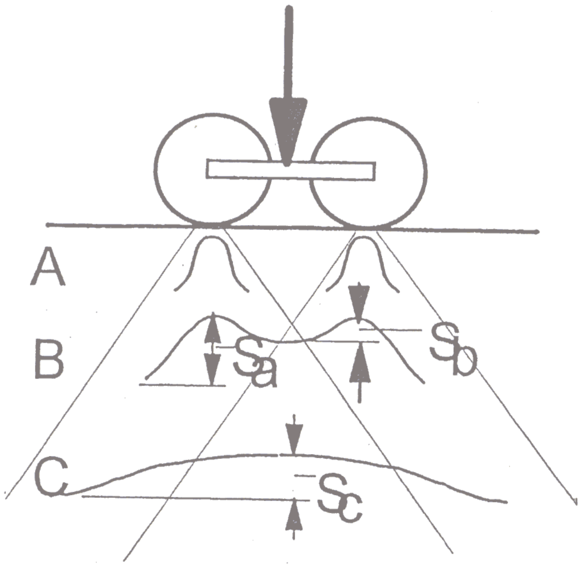

Figure 2. Effects of Depth on Repetitions Received by Pavement

6. PAVEMENT DESIGN

The various inputs described above are processed by the stress/strain analysis module shown in Figure 1. This calculates the critical strains generated in the pavement by the design loads. As noted above, these strains comprise the maximum tensile strains in all bound layers and the vertical compressive strain in the subgrade. These give rise respectively to cracking and rutting in the pavement under traffic. The LOCKPAVE program progressively varies the layer thicknesses until the rutting and cracking criteria are satisfied. Details of the criteria and the computation methods have been given elsewhere [1, 3-6].

The outputs from the stress/strain analysis need processing to determine the economy of the pavement in terms of the initial (construction) costs and/or the discounted (eg Present Worth) costs. Provided unit costs and, in the case of discounted costs, an appropriate discount rate are entered as part of the design data, the costs for each alternative pavement structure can be readily considered. These costs then provide a basis for comparing alternative designs. In this respect, LOCKPAVE enables up to 12 combinations of base and sub-base (or stabilised subgrade acting as sub-base) to be considered and includes a user-defined database of costs.

7. SPECIFICATIONS

Specifications provide the crucial link between thickness design, materials characteristics and construction. Thus, once a particular design alternative has been chosen one further task remains for the pavement designer. This is to prepare the specifications. Decisions concerning the type of pavement materials must already have been made at the thickness selection stage of the design process and, accordingly, the incorporation of appropriate materials in the specifications can be handled automatically by the design program. Similar comments apply to the specification of the appropriate lift thicknesses, compaction standards and construction tolerances. Thus the designer need only decide on the paver characteristics and the type and amount of binder in any bound (stabilised) layers. These decisions must be taken earlier in the design process so that suitable material properties can be entered in the stress/strain analyses. All other decisions concerning the drafting of the specifications can be handled automatically in accordance with local engineering practice without needing intervention from the designer. Thus the production of CBP specifications that will ensure that the design assumptions will not be violated during construction can be integrated with the thickness design.

8. CONCLUSIONS

The LOCKPAVE methodology described above is now in widespread use by engineers around the world. Many major projects have been designed using the procedure.. It has also been used to prepare and verify design charts and nomographs [16]. By automating and largely hiding the minutiae of calculations, the engineer is free to give more thought to critical inputs such as the selection of paver type and laying pattern and to the choice of base and sub-base materials. In this respect the program can assist the inexperienced designer working with unfamiliar technology such as CBP by using expert rules to guide the selection process. Because of the speed of the design process, the engineer is encouraged to examine a range of alternative solutions. If construction and maintenance costs and the discount rate are input as design data, selection amongst design alternatives can then be made on the basis of present or whole-of-life cost. For this reason, cost analysis has been made an integral part of the design process. In this way computer-based methods have a greater potential to yield optimal cost-effective designs than manual procedures. Implementation of the project is also simplified by making it possible to automatically assemble model specifications. In other words thickness design and specification writing can be integrated in the one process. However, despite these many benefits, it is important to recognise that automated programs such as LOCKPAVE are merely tools and are not substitutes for engineering skill and judgement.

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