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COMPUTER BASED PROCEDURES FOR THE DESIGN AND SPECIFICATION OF CONCRETE BLOCK PAVEMENTS

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SUMMARY

Computer-based mechanistic procedures for the design of conventional pavements are well established in many parts of the world. This technology has been extended to concrete block pavements by the author and others. In this paper the nature of mechanistic design methodologies for both roads and industrial hardstands surfaced with concrete pavers is reviewed. The advantages and limitations of such methods are discussed and the importance of the input data for characterising the block surface and the applied loads is emphasised. The roles of environmental factors such as frost and drainage are described and the need for factors of safety is discussed. The need to support pavement designs by comprehensive materials and construction specifications is then stressed. Finally an assessment of mechanistic design is made by reference to a variety of block pavements already in service.

INTRODUCTION

Design methods for concrete block paving (CBP) have been critically reviewed elsewhere (1). These can be divided into four categories comprising design on the basis of experience (e.g. 2), empirical design (e.g. 3), modifications of existing design procedures for flexible pavements (e.g. 4) and computer-based mechanistic methods (e.g. 5-8). Of these, designs based on local knowledge or experiment are normally limited by the domain of the experience or tests from which they are derived. Historically, such methods have usually served as interim procedures in regions where block paving has been newly introduced (e.g. 9). An alternative approach has been the *ad hoc* modification of established design procedures for conventional flexible pavements. A recent example of this has been the adaptation to CBP of the AASHTO flexible pavement design procedure in the USA by NCMA (4). Such an approach has the advantage of using methodology familiar to many pavement engineers but, suffers the disadvantage that the modelling of block paving characteristics typically represents no more than the changing of a single design input rather than a modification of the entire design procedure to model the important and unique characteristics of CBP.

In contrast to the other procedures, mechanistic design applies routine analytical methodology to designing pavements. Here the procedure can attempt to model all of the important characteristics of a particular form of paving such as CBP. However, the methods are complex and normally entail computer-based analysis. Consequently, except in countries such as Australia where computer-based pavement design is now established as national policy, engineers have been slow to adopt mechanistic design for pavements. Despite this, mechanistic design offers a number of important advantages to both the experienced and tyro designer alike.

ADVANTAGES AND LIMITATIONS OF MECHANISTIC DESIGN

Mechanistic design is limited by the accuracy with which the design problem can be modelled. Typically a mechanistic design procedure for CBP is made up of a series of sub-models which characterise the loads, the subgrade, the pavers and the base and sub-base. These sub models are described in detail below. The advantage of a modular approach to design is that each sub-model can be modified to incorporate developments in paving engineering as they occur. In other words, mechanistic design procedures can be updated on a continuing basis to keep abreast of technical developments. This is important in such rapidly evolving areas of technology as CBP.

Mechanistic design computations are too complex to be done by hand and require the use of computers. This is sometimes perceived as a disadvantage but, in reality, conveys a number of important advantages. These can be summarised as follows.

a) Computer-based procedures speed up the rate which designs can be prepared. This enables the designer to study a much wider range of materials and pavement types in a given time than where hand calculations must be used. This makes it easier to select an optimal, cost-effective design from amongst the often large number of possible design alternatives.

b) The use of computer-based methods forces designers to be systematic. This ensures that all the relevant design factors are considered in the correct sequence during the design process.

c) Computer-based methods can easily incorporate expert rules to aid the inexperienced designer in making correct decisions when selecting materials and other design inputs.

DESIGN INPUTS

In this section of the paper the various inputs typical of a mechanistic design procedure are discussed using a design method evolved by the author since 1985 to illustrate the procedures.

Paver Model

One of the first decisions a designer must make is to choose the shape, thickness and laying pattern for the pavers. Each of these factors has been shown to influence the performance of block paving under traffic (1). Accordingly, it is desirable to guide the pavement designer in the choice of these input parameters by a set of expert rules. Rules which have already been incorporated into design procedures (e.g. 9) include statements such as:

1) 'Shaped pavers tend to perform better under traffic than rectangular pavers'.

2) 'For trafficked block pavements, herringbone patterns are preferable to stretcher bond'.

3) 'Pavers thinner than 80mm should not be used except for light traffic applications'.

These rules attempt to interpret and summarise the now substantial data on the performance of block paving under traffic (e.g. 1).

Once the paver has been selected it must be characterised in terms of parameters compatible with the analysis procedure. For classical elastic layer analyses it is necessary to assign a stiffness or modulus to the paver course. This can be done by idealising the actual paver surface in terms of an equivalent homogeneous elastic layer of the same thickness. The modulus appropriate to this layer can be selected from typical data obtained from Falling Weight Deflection (FWD) tests of block pavements currently in service. Such FWD studies have already been conducted in several countries including the Netherlands (10), Britain (11), Japan (12) and Australia (8). Typical moduli have been summarised elsewhere (6,8).

Trafficking tests have established that block pavements tend to stiffen under traffic because of the progressive rotation and wedging of the pavers. Eventually, an equilibrium or lock-up condition may be attained. This condition typically occurs during the first 10000 axle load repetitions. FWD studies have mostly been conducted on block pavements which have already carried substantial traffic. Consequently, moduli from FWD tests represent maximum values rather than those ruling during the early life of the pavement. Thus, in mechanistic design, it is desirable to model the stiffening of the pavements following construction. This can be conservatively accomplished by assuming that the paver modulus immediately after construction will not exceed that of the basecourse and that, thereafter, the pavers will gradually achieve their full stiffness during the passage of the first 10000 truck axle loads (13). This is represented schematically in Figure 1.

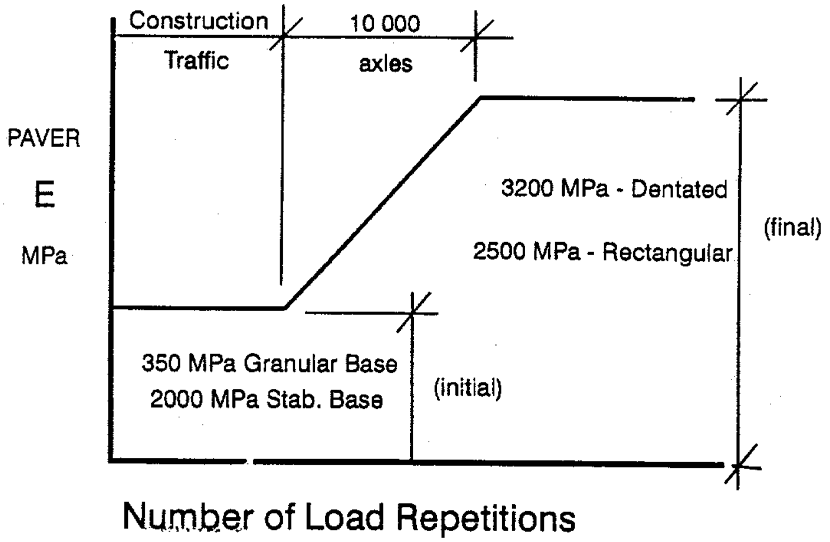

Figure 1. Development of Paver Modulus with Traffic

Subgrade, Base and Sub-base Characterisation

The subgrade needs to be characterised in terms of a modulus, E, and Poisson's Ratio, v. These are best measured directly by repeated triaxial loading (resilient modulus) tests. However, such testing is not yet routine and, in most cases, the modulus will need to inferred from simpler, less fundamental measures of soil properties such as the CBR using empirical relationships such as

$$E = 10 \text{ CBR} \tag{1}$$

or alternatively

$$E = 17.6 \text{ CBR}^{0.64} \tag{2}$$

where E is in MPa. In some cases not even CBR data are available. It then becomes necessary to infer a range of probable moduli based on soil classification data. Two classifications are in common use. These comprise 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.

For base and sub-base there is substantial information on the likely range of moduli for different classes of material (e.g. 1). Again the choice of a design value will be governed by drainage considerations. Alternatively, for major projects, the data can be obtained directly by laboratory tests of the materials.

Drainage Conditions

The drainage conditions at the pavement site will influence the properties of subgrade and of unbound base or sub-base materials (crushed rocks and gravels). Generally, the effects of an increase in saturation in unbound materials will be to reduce the stiffness and strength. Thus 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 1 are suggested as suitable for general application to CBP.

TABLE 1. DRAINAGE FACTORS

Drainage Condition	Reduction in Modulus (Factor of Safety)
EXCELLENT - Drains very quickly, dry, saturation is most unlikely	0% (FOS = 1)
AVERAGE - Drains slowly, moist, occasional saturation is likely	25% (FOS = 0.75)
POOR - Little or no drainage, wet, regular saturation is likely	50% (FOS = 0.5)

Frost Action

In regions prone to frost it is necessary to assess the CBP sub-structure in terms of the depth of frost penetration and the frost susceptibility of the base, sub-base and subgrade materials. The latter may be assessed using criteria based on the proportion of soil finer than 0.02mm and the plasticity index (13). A reduced strength (and stiffness) may then need to be assigned to the subgrade. 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.

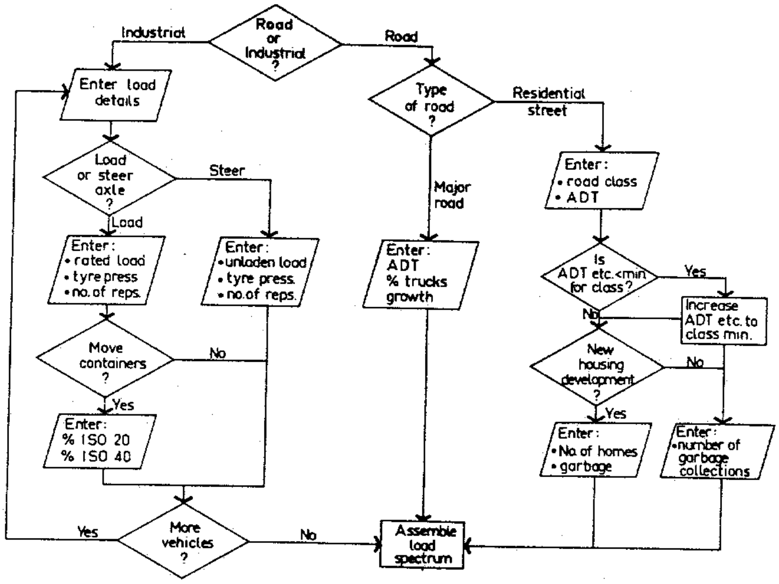

Figure 2. Loading Sub-models for Roads and Hardstands

Loading

The elements of the loading sub-model are shown in Figure 2. A major benefit of mechanistic design is that the loads can be represented as a spectrum of all the axle loads and their respective repetitions. This is in contrast to most other CBP design procedures which use either just the maximum axle loads applied to the pavement or concepts of equivalent axle or vehicle loads (1). Such concepts have, however, been shown to be inconsistent with the results of trafficking tests of block pavements (e.g. 14). Moreover, the use of load equivalencies has been demonstrated to give CBP designs which are sometimes less conservative than those associated with axle load spectra (8).

The axle load spectra appropriate to roads and industrial pavement have been described elsewhere (1). For roads, the spectrum can often be derived from loadometer studies, whilst, for industrial pavements the spectrum is obtained from the predicted mix of vehicles that will use the facility.

As shown in Figure 2, for industrial vehicles, distinctions must be made between the loading and steering axles of vehicles such as forklifts and 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).

For roads, as shown in Figure 2, it is necessary to distinguish between residential streets and more heavily trafficked pavements. For new residential streets the pavement will often be constructed prior to the houses being built (so as to assure all-weather access to the building sites). This means that the heaviest traffic that will ever be carried by the street will be the construction vehicles bringing in building materials. Based on published data it is possible to calculate the average numbers of truck movements per building site and, therefore, for the street as a whole. Conservatively, it is convenient to assume that, as shown in Figure 1, all of the construction traffic will be applied before the pavers have developed their full stiffness or interlock.

Once residential CBP streets are in service the heaviest vehicle routinely to use the pavement will be garbage trucks. These are often overloaded. For this reason, it is important to consider these loads at the design stage. These can be incorporated into a mechanistic design procedure using data from axle load surveys.

For roads and industrial pavements designers often wish to impose factors of safety on the loads to guard against the effects of overloading and in recognition of the fact that the relationships between the strains computed in the pavement analyses and the predicted rutting or cracking behaviour of the pavement are subject to significant variability. The choice of load safety factors is largely subjective although good precedents exist in the case of industrial pavements (15). Suggested load factors are given in Table 2. For industrial hardstands the cumulative effects of braking, acceleration etc. can be obtained by multiplying the individual factors of safety together.

TABLE 2 LOAD SAFETY FACTORS

Application	Factor of Safety		
a) Roads			
Residential (ADT<800)	1.0		
Collector (ADT<5000)	1.1		
Arterial (ADT<12000)	1.2		
b) Industrial	Braking	Accelerating	Cornering
Straddle Carrier	1.5	1.1	1.6
Forklift Cranes	1.3	1.1	1.4
Side Lift trucks	1.2	1.1	1.3
On-road trucks	1.1	1.1	1.1
Tractors/trailers	1.1	1.1	1.3

PAVEMENT ANALYSIS

The central element in a mechanistic design procedure is the analysis module. Most analyses of concrete block pavements have been based on classical elastic layer theory although limited use has also been made of finite element analyses. Typically, of an elastic mechanistic design the pavement is modelled as a series of horizontal layers overlying a semi-infinite subgrade. The objective of the analysis is to calculate the critical strains generated in this structure by the prescribed system of loads. These strains comprise the maximum tensile strains in all bound layers and the vertical compressive strain in the subgrade. These strains can give rise respectively to cracking and rutting in the pavement under traffic. The objective of mechanistic design is to choose systematically some combination of layer thickness and layer properties that will ensure that the critical strains will not be of sufficient magnitude to lead to unacceptable levels of cracking and/or rutting within the design life of the pavement.

The computational techniques of layered elastic analyses are well known and their application to block paving has been described in detail elsewhere (6,7,8). An implementation made by the author is shown schematically in Figure 3. Essentially this comprises an interactive procedure in which first the base and then the sub-base is designed by progressively varying the layer thicknesses until the rutting and cracking criteria are satisfied. Details of the criteria and the computation methods have been given elsewhere (1,6).

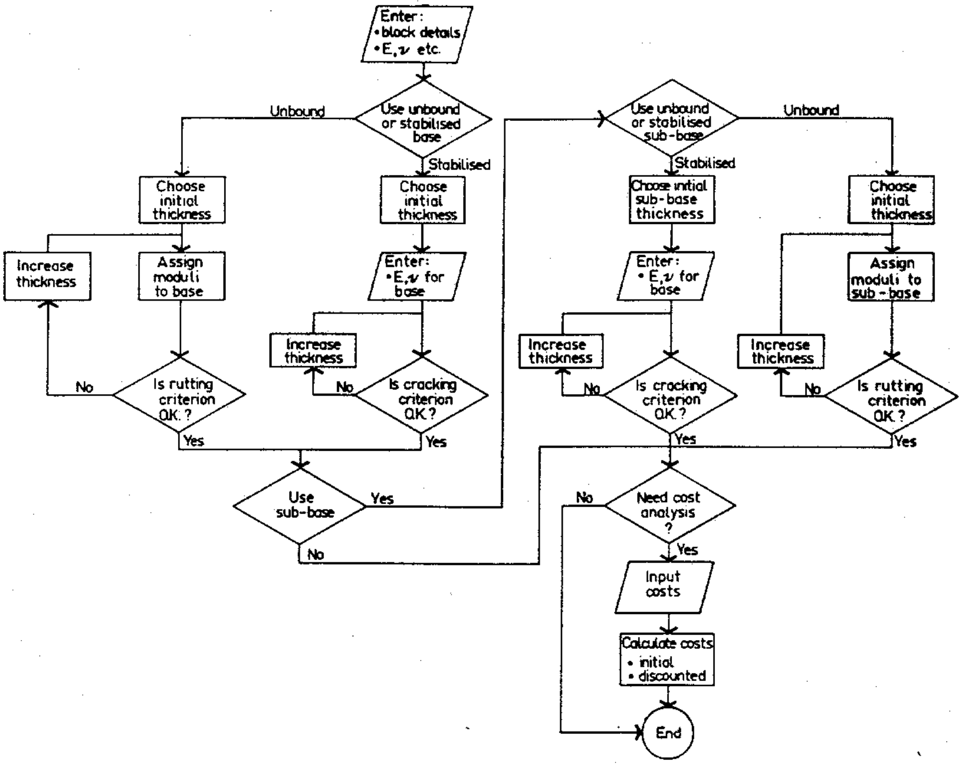

Figure 3. Analysis Module for the Design of CBP

Figure 3 shows that the final stage of analysis involves pavement costs expressed as initial (construction) costs or as total costs discounted over time. This is done so that all the feasible alternative designs can be rationally assessed against one another. Up to 12 combinations of base and sub-base (or stabilised subgrade acting as sub-base) can be considered. These are shown in Table 3.

TABLE 3 PAVEMENT TYPES

LAYER TYPE	ALTERNATIVE											
	1	2	3	4	5	6	7	8	9	10	11	12
Block Sand	*	*	*	*	*	*	*	*	*	*	*	*
Crushed Rock Base	*	*	*	*								
Stabilized Base					*	*	*	*				
Asphalt Base									*	*	*	*
Gravel Sub-base		*				*				*		
Stabilized Sub-base			*				*				*	
Stabilized Subgrade				*				*				*

SPECIFICATIONS

Once a particular design alternative has been chosen one further task remains for the pavement designer. This is prepare the specifications. For unfamiliar technology such as CBP this can be a problem for the inexperienced designer who must specify the correct materials for base and sub-base, the appropriate ranges of strength for stabilised materials and the corresponding compaction levels, tolerances and construction techniques. These specifications depend on the choices made by the designer in the various input sub-models described above. It is possible to flag all these decisions as part of the design program. At the same time it is possible to draw up a series of individual specifications in the form of ASCII files for each of the base, sub-base and stabilised subgrade materials given in Table 3. These files may then be automatically called according to the flags set to reflect the design choices to assemble a full set of specifications that will ensure that the design assumptions will not be violated during construction. For the methodology described above a program has been developed which will automatically generate both the materials and construction specifications for any of the pavement alternatives given in Table 3. Thus the production of CBP specifications has been integrated with the thickness design.

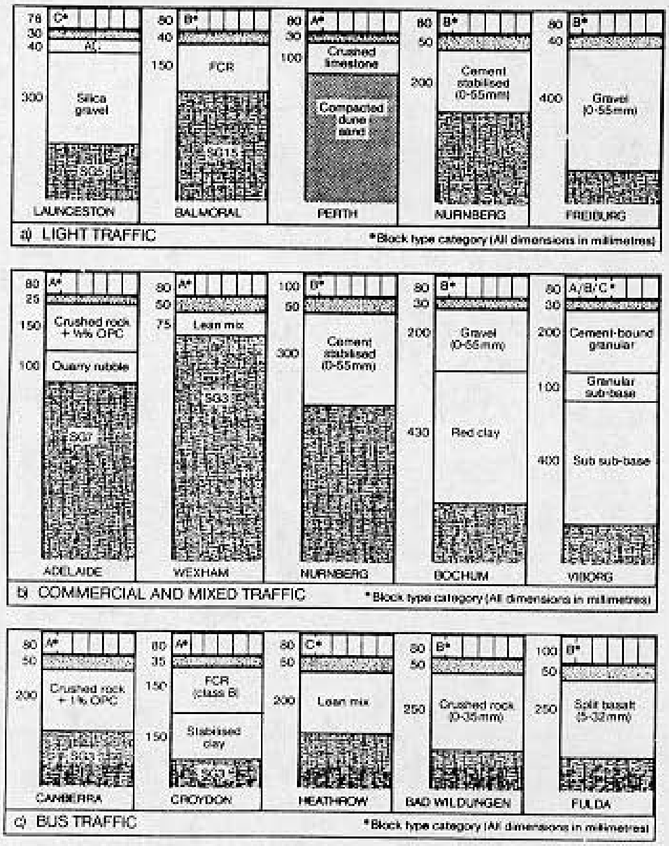

Figure 4. Typical CBP Cross-sections for Roads

UTILITY OF THE MECHANISTIC DESIGN

It has been noted elsewhere that there is little agreement between the various design procedures published for CBP(1). For the mechanistic procedure described above the thickness can vary widely depending on the factors of safety chosen to model the drainage and/or load conditions. Consequently, the design thicknesses may on occasion be either greater or less than those associated with other procedures. For road pavements the thicknesses given by the mechanistic procedure are similar (albert marginally greater) to those given by an earlier empirical design method (3). However, to assess the procedure overall it is convenient to compare the thicknesses required by the mechanistic methodology with the thicknesses of existing block pavements designed by other methods.

Figure 4 and 5 show a range of road and industrial CBP cross-sections drawn from around the world. A few of these have been designed using the procedure outlined here; for others no reliable background data exist or unusual materials have been used. Ignoring such cases, it is possible to draw up a limited comparison of back calculated thicknesses compared to the as-constructed thicknesses. Here, the load and drainage factors of safety have been set to unity. The results are shown in Figure 6. From this figure it may be seen that, the mechanistic procedure tends on average to require slightly greater thicknesses than those actually constructed. This tends to suggest that the method is conservative.

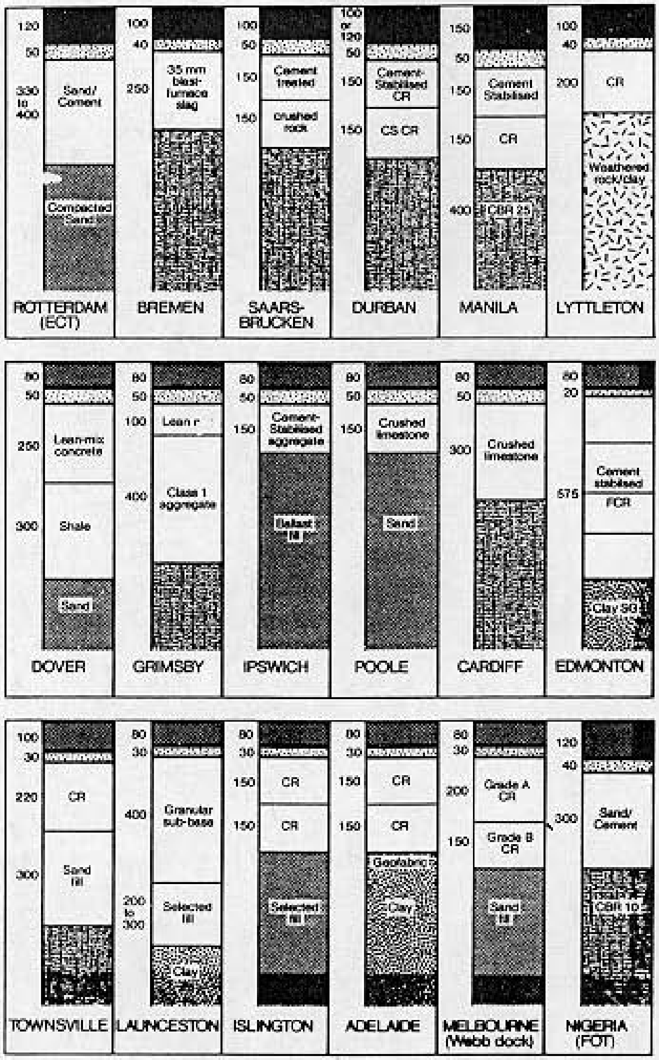

Figure 5. Typical Industrial CBP Cross-sections

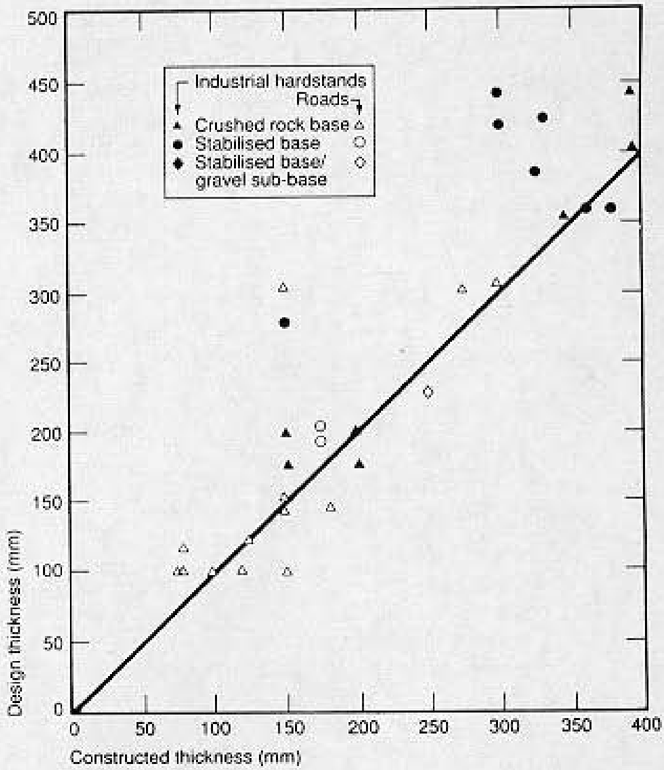

Figure 6. Comparison of the Output of the Mechanistic Procedure with As-constructed Thicknesses

CONCLUDING COMMENTS

This paper has canvassed the advantages and features of mechanistic design by reference to a particular procedure developed over many years by the author and now in wide use. The method enables designers to model drainage and loading conditions in less simplistic ways than has, hitherto, been the norm. It has also proved feasible to incorporate cost analysis and the drafting of materials and construction specifications as integral parts of the design process. At its present state of development the design procedure appears adequately conservative for most common paving applications. This is not intended to imply, however, that the method is not capable of improvement. Indeed, in this respect mechanistic design is an inherently flexible methodology which is easily modified or updated as needed to reflect advances in CBP technology.

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