BLOCK PULL-OUT AND THE MODELLING OF INTERLOCKING CONCRETE BLOCK PAVEMENTS

F. ESER, Dip. Civ. Eng., Postgraduate Student, Department of Civil and Aeronautical Engineering, Royal Melbourne Institute of Technology

A.J. FRICK, B.E., M.Sc., Ph.D., Senior Lecturer, Department of Civil and Aeronautical Engineering, Royal Melbourne Institute of Technology

K.C. MAVIN, B.Sc., M.Eng.Sc., M.I.E.Aust, Senior Lecturer, Department of Civil and Aeronautical Engineering, Royal Melbourne Institute of Technology

ABSTRACT

A research program is described which tests the hypothesis that the surfacing of an interlocking concrete block pavement (ICBP) stiffens with time and trafficking. The force required to remove a single block from the pavement is used as a measure of the structural capacity of the block layer. 'Pull out' is employed both for in situ testing and laboratory simulation of the stiffening process. Data from these tests are being used to calibrate mathematical models in an attempt to provide a more complete understanding of the way in which ICBPs function under load.

INTRODUCTION

Interlocking concrete block pavements (ICBP) are used extensively in Australia for facilities ranging from car parks to container terminals. This type of pavement is particularly useful for low speed sites where aesthetics is important and for sites subjected to very heavy loading and/or rough treatment. In these two situations the ICBP compares favourably with asphalt and in situ concrete slabs. In fact, for container terminals, the concrete block is unchallenged since it provides a pavement which can withstand the sort of punishment which causes distress in all other types of pavement.

Despite the popularity of the ICBP in Australia, Europe, South Africa, Japan, New Zealand and more recently the U.S., there is a lack of reliable empirical data. The few data that are available from the monitoring of trafficked pavements indicate that the way in which an ICBP functions under load changes during its life. It is suggested that the layer of blocks stiffens with time and trafficking so that the pavement initially functions in a flexible mode and then later as a rigid slab.

If the block layer adds to the structural capacity of the pavement, then it can do so only by vertical interaction through the sand-filled joints and horizontal interlock due to the block shapes. A single block located within an ICBP is surrounded by a sand joint. The removal of this block from the pavement requires a force normal to the block surface. This force is a function of:

(a) the condition of the jointing sand, i.e. moisture content, foreign materials, density, etc.;
(b) joint width, height and length; and
(c) the lateral forces transferred from adjacent blocks.

If a gradual stiffening of the block layer occurs then the force required to remove a single block will increase.

TEST PROGRAM

Early work by Mavin (1980) included an assessment of the force required to remove a single block from a laboratory block pavement. During this work, the behaviour of the rest of the test pavement whilst the block was extracted was observed. Little data were recorded during these tests because block pull-out was a late addition to the research program which concentrated upon static loading of the pavement. Although limited conclusions resulted, observations did indicate that the pull-out force could be employed as a measure of the condition of the block layer.

As a result of these tests, a research program was commenced which had as its objectives the development of a suitable pull-out rig, and an examination of the relationships between pull-out force and various parameters relating to the condition of the pavement. Specifically the purpose of this research was to monitor the 'lock up' phenomenon which had been reported by Shackel (1980). Hence, the pull-out device was required for both laboratory and site work. The development and preliminary testing of the pull-out rig is described in Mavin (1984).

Pull-out tests have been carried out on a number of pavements in the field subjected to various levels of trafficking. Residential streets are being monitored during and following construction, including the period of greatest loading - the house construction phase (Schofield 1985). Other sites are at industrial locations, including a container handling depot and a quarry access road. The ICBP test pavement at the Australian Road Research Board (Sharp and Armstrong 1985) was also used for pull-out tests.

Testing in the laboratory has concentrated on establishing a link between the pull-out force and the laterally-applied load. Vertical deflections during pull-out have also been recorded. These tests have been carried out with different joint widths and different jointing sands. The procedure adopted for the tests was as follows.

(1) Place the blocks in a herringbone pattern on an uncompacted but levelled layer of bedding sand. (Spacers were used to ensure the joint widths were correct.)
(2) Spread jointing sand over the pavement surface.
(3) Vibrate each block with a poker vibrator for 5 seconds.
(4) Remove the spacers.
(5) Vibrate the target block for 8 seconds and remove the excess sand.
(6) Pre-load the pavement by applying lateral forces. Repeat this three times.
(7) Mount the pull-out rig over the target block and apply the lateral loads.
(8) Proceed with block pull-out.

The size of the pavement has enabled relaying to be achieved quickly so that an average total time of approximately 30 minutes per test is possible. In all laboratory work the target block is pre-drilled and this also helps to reduce delays to a minimum.

The testing procedure differs in the field because of the obvious constraints associated with a trafficked pavement. Pre-drilled blocks must be attached to the target blocks with an epoxy resin-based adhesive, since drilling of blocks in situ would influence pull-out. After a curing/setting period of approximately 10-15 minutes, the rig is placed in position and pull-out proceeds.

RESULTS

Data collected from laboratory tests have produced the following general conclusions:

(a) the importance of the jointing sand in the distribution of horizontal loads;
(b) variation in block pull-out force with changes in the grading of the jointing sand; and
(c) variation in block pull-out force with changes in the amount of vibration.

The influence of block shape has not yet been examined but this will be part of a future program, along with a study of different block materials/textures. The tests carried out so far have involved the pull-out of a single block while adjacent blocks remain undisturbed. It is proposed that future work will also investigate the situation where 'doming' occurs during pull-out in order to determine its influence on the pull-out force.

Typical results from work carried out to date are shown in Figs 1 and 2. The plot of pull-out force versus vertical deflection (Fig. 1) shows data collected for a 3 mm joint width. However, this pavement

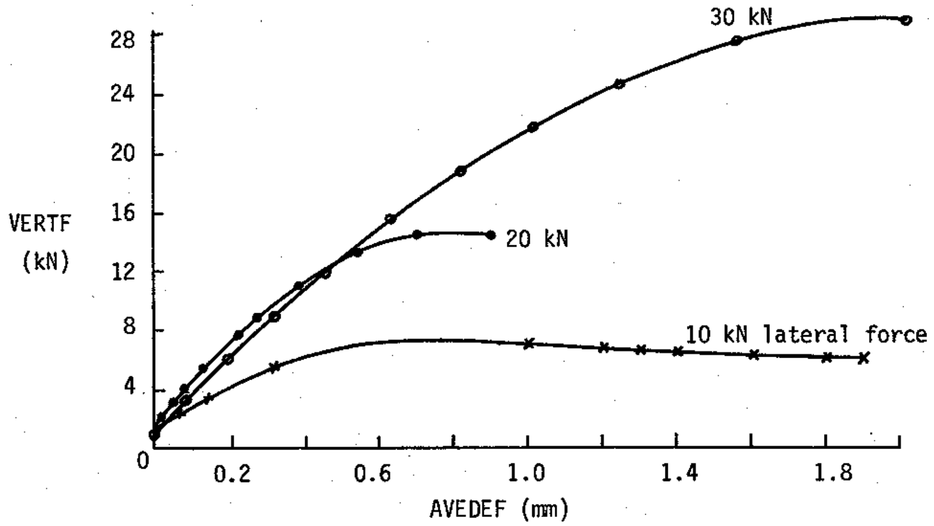

Fig. 1 - Laboratory pull-out testing showing the variation of force-displacement response with lateral force

contained jointing sand which did not lie within the CACA (1982) preferred grading envelope. The data provided in Fig. 2 were recorded from tests carried out using jointing sand which did conform with CACA requirements. This Figure also contains data from the test represented in Fig. 1.

In situ tests have generated data which can be compared with laboratory data as well as being used to assess the structural quality of the pavement. As already mentioned, a number of pavements are being studied. Data from two of these pavements are presented in Tables 1 and 2. A comparison of field data recorded at a number of Melbourne sites with that reported by Kellersmann, Bosch and Molenaar (1984) is provided in Fig. 3.

ICBP STIFFENING

Research at the National Institute for Transport and Road Research (Shackel 1980) showed that a trafficked ICBP develops 'lock up'.

> "In their early life block pavements stiffen progressively with the increase in the number of wheel passes. This indicates that there is an initial bedding-in period during which the blocks tend to develop interlock."

Further,

> "under trafficking block pavements tend to develop interlock. This is manifested as increases in the load-spreading ability of the blocks and reductions in the rate of accumulation of deformation."

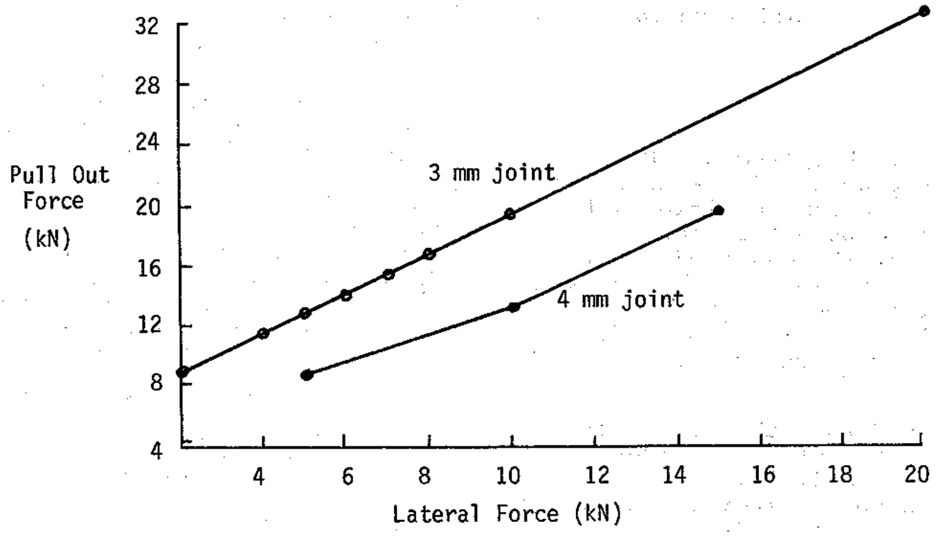

Fig. 2 - Laboratory pull-out testing showing the effect of varying the joint width

TABLE 1

PULL-OUT LOADS AT CONTAINER HANDLING DEPOT

Initial Pull-Out Load (kN)	Pull-Out Load - Replacement Block (kN)	Replacement as % of Initial Pull-Out	Time Between Initial & Replacement Pull-Out (weeks)
12.3	4.6	37	10
19.0	10.4	55	10
11.9	4.6	39	6
18.5	1.5*	8	6
6.6	0.4**	6	6
7.3	6.5+	89	6
7.8	2.7	35	6
10.0	4.6	46	6
3.8	2.3+	61	2
8.5**	3.8	45	2
5.0	2.3	46	2
12.3	4.6	37	2
7.8	10.0^	128	2

* little traffic ** failed area
^ badly deformed area ('wedging')
\+ initial pull-out reduced due to disturbance

TABLE 2

PULL-OUT FIELD DATA
Inner Surburban Residential Street

Location*	Pull-Out Force (kN)		Comments
	March 1986	May 1986	
1	5.4	4.8	lightly trafficked
	6.7	8.9	
2	21.7	21.0	heavier trafficking
	17.2	14.0	
3	-	12.9	lightly trafficked
		16.9	

* All located in near-side wheelpath.

Finally,

> "once a block pavement becomes fully interlocked it attains a stable equilibrium condition which is unaffected be either the amount of traffic or the magnitude of the wheel load (within the range 24 to 70 kN). The blocks then act as a structural layer rather than merely as a wearing course."

It is suggested that the load-carrying characteristics of an ICBP vary throughout its early life. If this is so, then it becomes important that the 'initial interlock', 'interlock' and 'full interlock' status be identified so that loading may progressively be increased.

The block pull-out test may be used to monitor the development of interlock since the pull-out force would increase. It could be expected that pull-out carried out at intervals during the early life of an ICBP would reduce and perhaps eliminate pavement failures since it would indicate whether or not the pavement was stiffening. As already indicated, in situ testing is under way which will monitor the changes which occur in residental street ICBPs in Melbourne.

ICBP MODELLING

Fig. 4 shows a two-dimensional representation of an ICBP. The ability to predict accurately the response to traffic under loading over

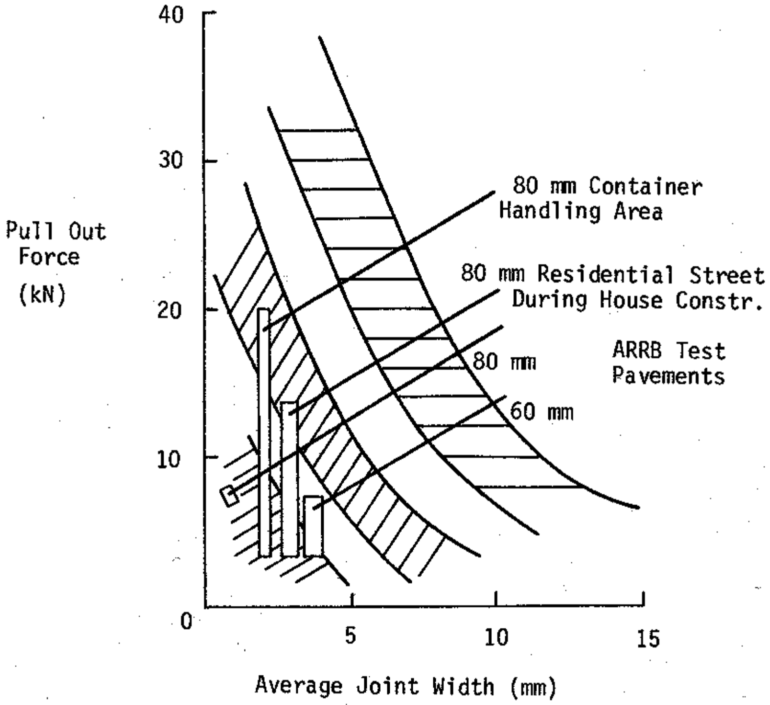

Fig. 3 - A comparison of Melbourne area field test results with published data

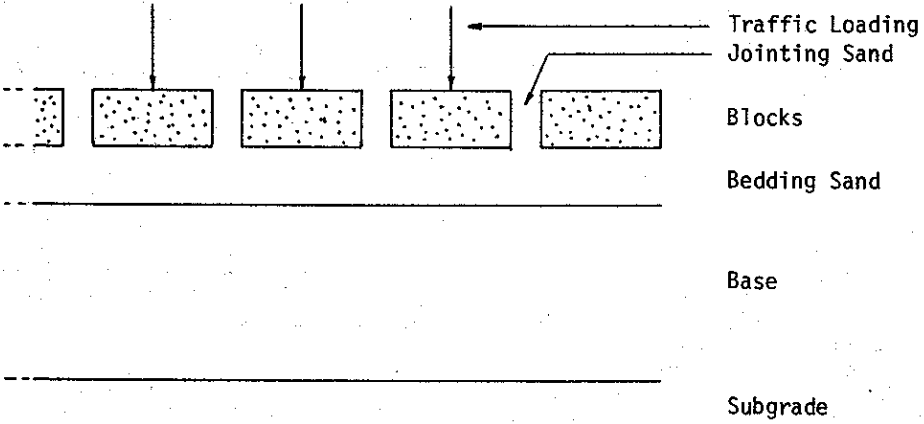

Fig. 4 - Two-dimensional representation of an interlocking concrete block pavement

the life of the pavement requires the development of a mathematical model of the pavement and the imposed loading. In modelling such a complex system, a compromise must be reached between mathematical tractibility and accuracy of response. In producing a model of a trafficked ICBP, four basic elements must be considered: the blocks; the joints; the bedding sand, base and subgrade; and the loading.

BLOCKS

In the simplest case, the blocks may be modelled as rigid body elements (Houben et al. 1984), while a more sophisticated model may be developed using deformable rectangular plate elements (Nishizawa, Matsuno and Komura 1984). The latter model necessitates the determination of a large number of model parameters and, of course, leads to a mathematically more complicated analysis.

JOINTS

The authors mentioned above selected linear elastic elements to simulate the interaction between adjacent blocks via the jointing sand. Houben et al. (1984) and Molenaar, Moll and Houben (1984) considered only relative vertical displacements, while Nishizawa et al. (1984) also considered relative rotations between adjacent blocks.

BEDDING SAND, BASE AND SUBGRADE

A variety of elastic models is available, ranging from the simple Winkler foundation to finite element representations and multi-layered continuous models.

Nishizawa et al. (1984) made use of the Winkler foundation concept to model all three layers as a single element. It is noted that since the above models consist of elastic and/or rigid elements they will not directly predict the formation of permanent deformation (rutting). The elastic deformations may, however, be subsequently used, in conjunction with an empirical formula, to arrive at estimated rut depths (Houben et al. 1984; Molenaar et al. 1984). Houben et al. investigated two models. In the first, the bedding sand, base and subgrade were considered to be the lower layer of a two-layer continuous model in which the blocks were considered as the upper layer. In the second, the bedding sand was modelled by a Winkler foundation supported by a finite element representation of the base and subgrade layers, which were considered as a single equivalent layer.

LOADING

Whilst the traffic loading applied to a real pavement is a probabilistic phenomenon, it is widely accepted that the Equivalent Standard Axle concept may be usefully employed in considering general pavement response. For more detailed studies of pavement behaviour the use of a single wheel load may be more appropriate, and this may be modelled as an equivalent static load applied uniformly over some area or perhaps as a time-dependent point load applied to a single block.

ADOPTED ICBP MODEL

The selection of the model used in the present study is based on two criteria:

(a) it should be able to undergo instantaneous as well as permanent deformation; and

(b) it should be made up from discrete elements, thus permitting a relatively simple mathematical analysis.

In the adopted five-block model (Fig. 5), the blocks are assumed to be massless rigid elements which undergo only vertical displacement. The interaction between adjacent blocks is modelled by linear elastic elements. The bedding sand, base and subgrade are considered as a single equivalent layer which is modelled by a linear elastic element connected in series with parallel-connected linear elastic and frictional elements. The force-deformation response of the elements is shown in Fig. 6.

It is assumed that the parameters of all joint elements are identical (k_1), and that those of all supporting elements are also identical (k_2, k_3, F_0). It is noted that the disposition of sub-elements permits both instantaneous deformation as well as permanent deformation of the supporting layer.

In the present study, in order to maintain mathematical simplicity, the model is loaded by the application

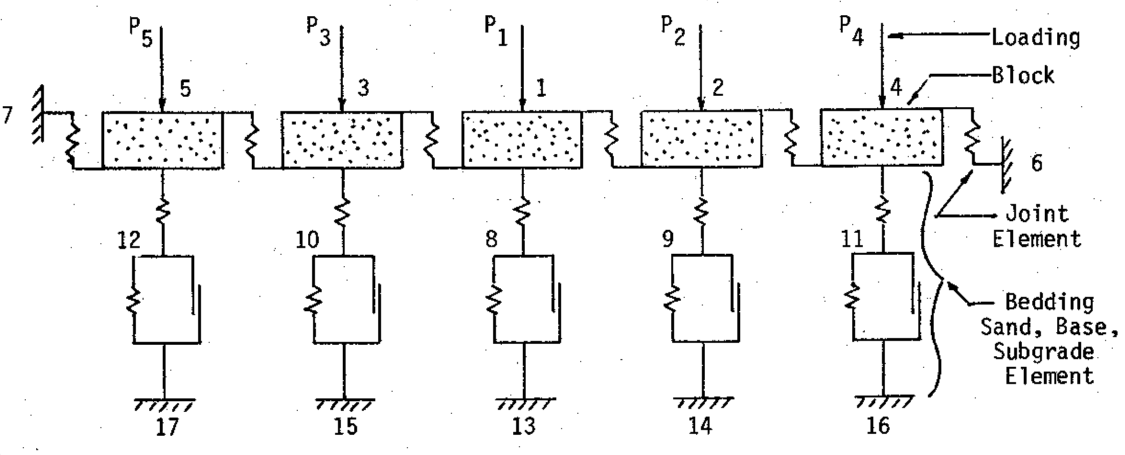

Fig. 5 - Adopted model of an interlocking concrete block pavement

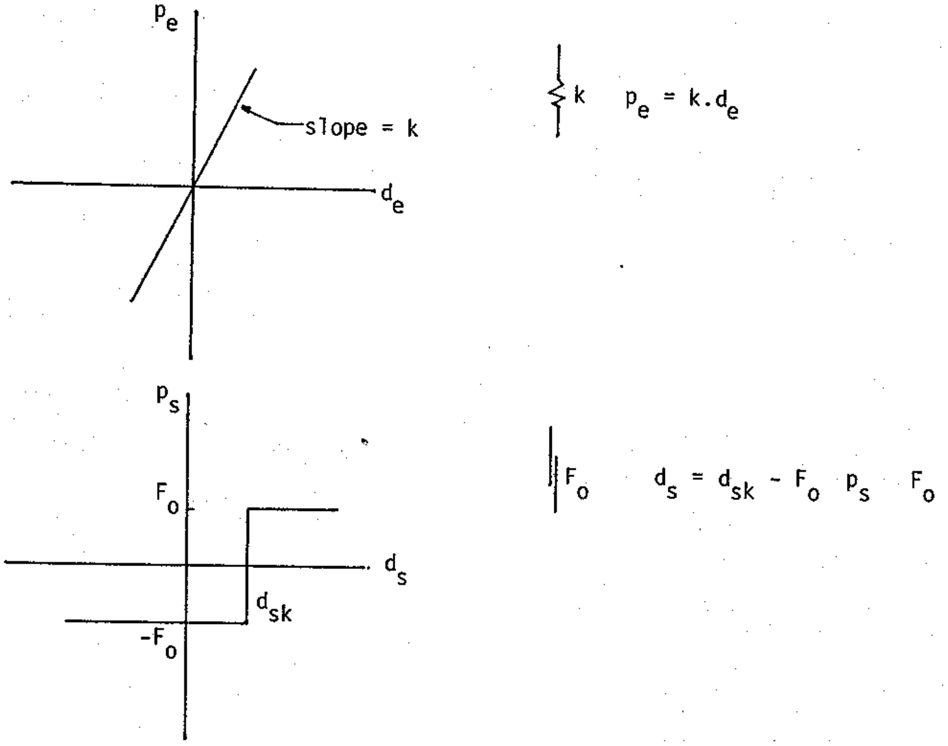

Fig. 6 - Force-displacement response of elements used in the adopted model

of a series of half-sine pulses (Fig. 7) to the central block only. It is noted, however, that a transversely-moving wheel load may also be readily simulated.

A more convenient arrangement of the model is shown in Fig. 8, in which the blocks are represented by nodes 1-5, a typical joint element by 1,2 and a typical supporting element by 1, 8, 13. It is apparent that the model may be readily extended to include any number of blocks, but it is also noted that an extension will only be necessary if the reaction forces at nodes 6 and 7 are unacceptably large proportions of the applied load P_1.

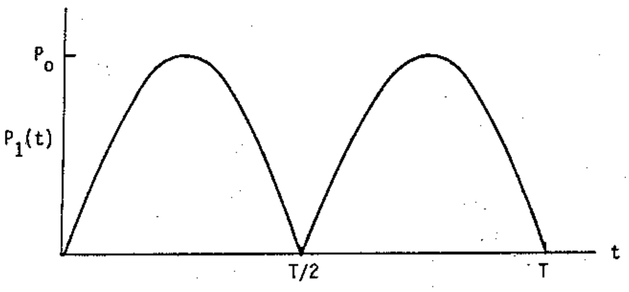

Fig. 7 - Cycles of load applied to the central block of the ICBP model

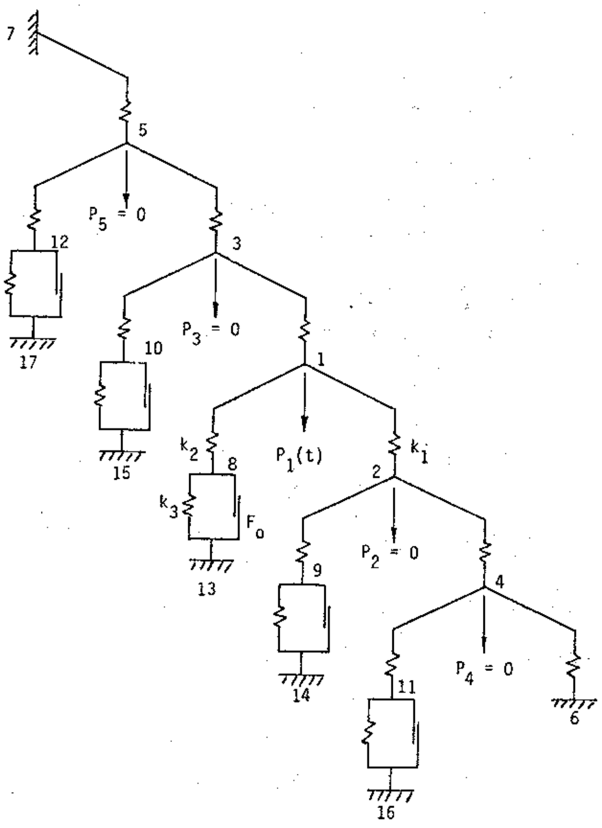

Fig. 8 - Schematic representation of the adopted model: blocks are represented by the nodes 1 ... 5

MODEL ANALYSIS

The force-displacement-time response of the model is most concisely developed using matrix algebra. Irrespective of which, if any, of the frictional elements are slipping, the model response may be written in the form:

$$\{P\} = [K]\{D\} + [B_1]\{p_{fk}\} + [B_2]\{p_{fu}\}$$

where:

$\{P\}$ = vector of nodal forces including the applied block loading;

$\{D\}$ = vector of nodal displacements including the block displacements;

$\{p_{fk}\}$ = vector of (known) forces on frictional elements which are actively slipping;

$\{p_{fu}\}$ = vector of (unknown) forces on frictional elements known not to be slipping;

$[K]$ = stiffness matrix associated with the elastic elements; and

$[B_1]$ = an appropriate sub-matrix of the model equilibrium matrix.

Following suitable partitioning, matrix inversion and multipication, the block displacements, support forces, frictional element slip deformations and forces may be determined in terms of the applied load P_1.

While the computations are in progress, the forces on the frictional elements must be closely monitored since the initiation or cessation of slip requires a re-partitioning of the matrices and hence a change in the computational details. For time periods between slip initiations and/or cessations, the force-displacement response of the model is linear so that attention need only be paid to the end-points of such time periods.

SELECTION OF NUMERICAL PARAMETER VALUES

Values must be assigned to the model parameters k_1, k_2, k_3, F_0 as well as to the load parameters P_0 and T. While in the present study rounded values have been selected, they have been based on the following criteria.

k_1 selected on the basis of block pull-out tests (see, for example, Fig. 1).
k_1 = 10 kN/mm selected.

k_2, k_3 selected to produce a maximum block displacement of less than 5 mm.
k_2 = 25; k_3 = 50 kN/mm selected.

F_0 a series of values was selected so that the model response could be fully investigated.
F_0 = 50, 30, 20, 5, 2, 1, 0 kN selected.

P_0 in view of the 'standard axle' loading concept:
P_0 = 80 kN selected.

T as a result of considering a vehicle travelling at 60 km/h over a block of length 180 mm:
T/2 = 0.01 seconds selected.

It is anticipated that as more experimental data become available, the model and loading parameters will be able to be selected on a more sophisticated basis. For example, time/traffic-dependent deflection bowl information could be usefully employed.

MODEL RESPONSE TO LOADING

The response of the model is highly dependent upon the choice of Fo, the magnitude of the force at which the frictional elements slip. For F_0 = 0 kN and for $F_0 > 50$ kN (approx.) the model behaves elastically but with differing stiffness (Fig. 9). The straight line response is retraced during the second (and subsequent) loading cycles. The deflection profiles at the peak load (P_1 = 80 kN) are also shown in Fig. 9.

The responses for F_0 = 10, 20 and 30 kN are shown in Figs 10, 11 and 12. For the case of F_0 = 10 kN: following an initial elastic response, slip occurs in frictional element 8, 13 and is followed by simultaneous (because of symmetry) slip in frictional elements 9, 14 and 10, 15. Slip in all three elements ceases when P_1 reaches its peak value of 80 kN and begins to decrease. The model recovers elastically until frictional element 8, 13 slips in tension. This slip continues until the end of the first load cycle, at which time the residual 'permanent' deflection profile is adopted. During the second loading cycle, initial elastic response is followed by slip in frictional element 8, 13 which continues until the peak load is reached. At P_1 = 80 kN, frictional elements 9, 14 and 10, 15 are about to slip again but are prevented from doing so by the decreasing applied load. Thereafter (and for subsequent load cycles) the established response curve is followed.

The model responses for F_0 = 20 kN and 30 kN differ only in the number of frictional elements which slip.

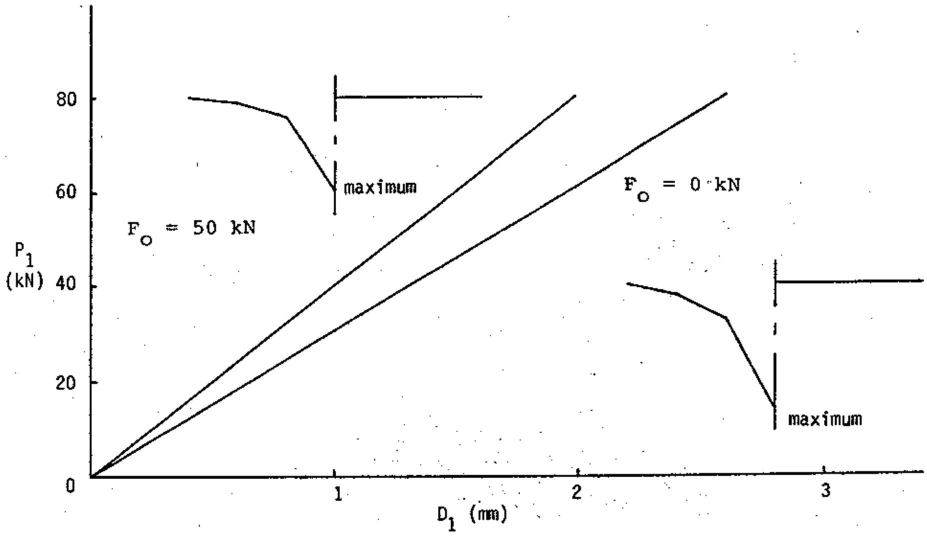

Fig. 9 - Two possible elastic responses of the virgin model: the deflection profile at maximum loading is shown in each case

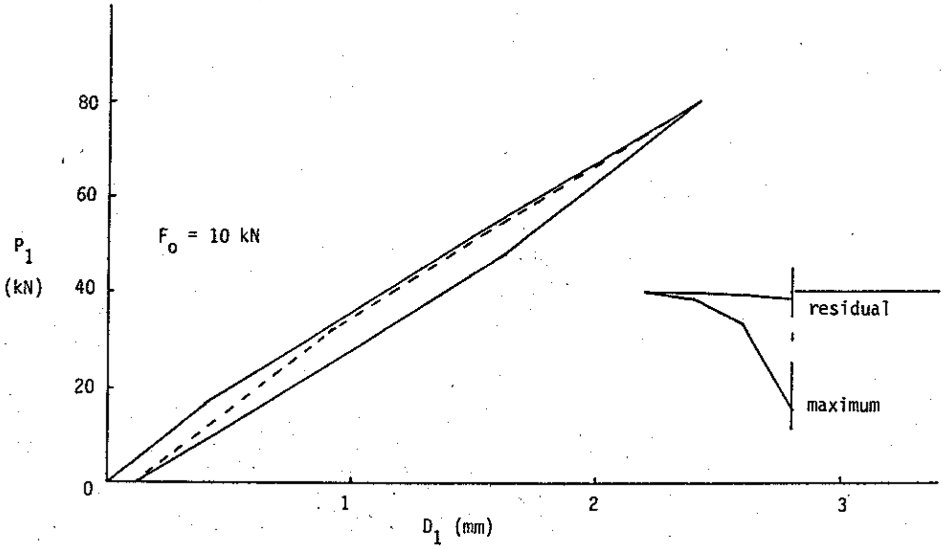

Fig. 10 - Model response for F_o = 10 kN showing maximum and permanent surface profiles

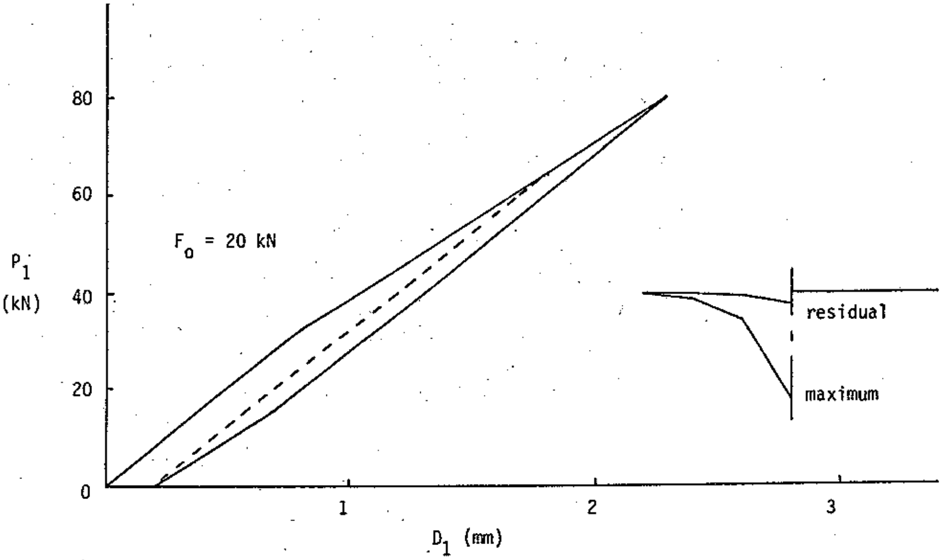

Fig. 11 - Model response for F_o = 20 kN showing maximum and permanent surface profiles

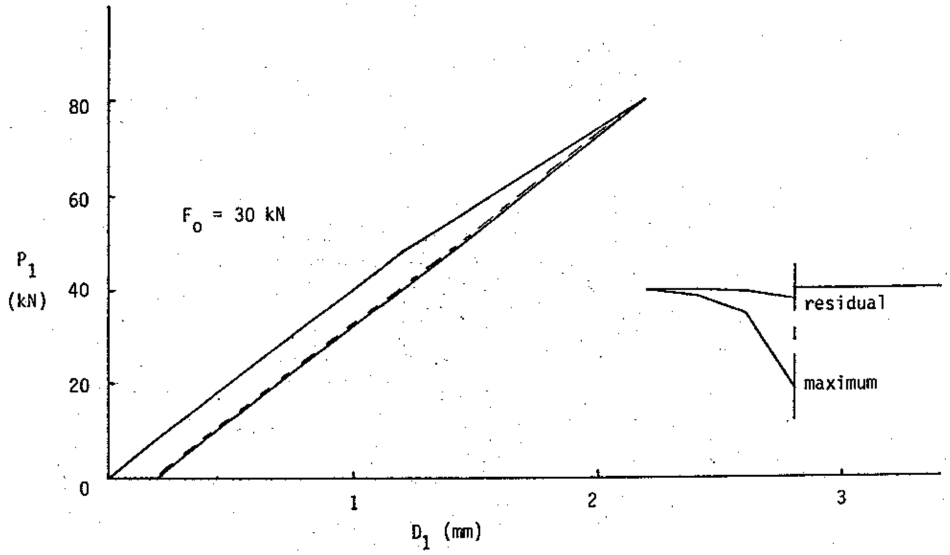

Fig. 12 - Model response for F_o = 30 kN showing maximum and permanent surface profiles

A preliminary investigation of the effect of trafficking a recently-layed pavement may be undertaken. If an untrafficked model with F_0 = 10 kN is subjected to a load cycle, then its response is represented by the solid line in Fig. 10. It is assumed that, as a consequence of the first load cycle, F_0 has been increased to 20 kN. The second load cycle follows and it is assumed that, at the end of the cycle, F_0 has been increased to 30 kN. The computations indicate that the subsequent response is entirely elastic and will remain elastic provided the magnitude of the peak load does not increase. This response is shown in Fig. 13.

This approach may be extended by incrementing not only F_0 but also the stiffnesses of the supporting elastic elements between loading cycles.

CONCLUSIONS

There is some evidence to suggest that the layer of blocks in an ICBP stiffens as trafficking progresses (e.g. Shackel 1980; Houden et al. 1984). Why and when it occurs are questions yet to be satisfactority resolved. It is suggested that any stiffening of the block layer may be conveniently monitored by measuring the force required to remove a single block from the pavement. A program has been described which will assess the performance of trafficked ICBPs at a number of sites in Melbourne. This program will generate block pull-out

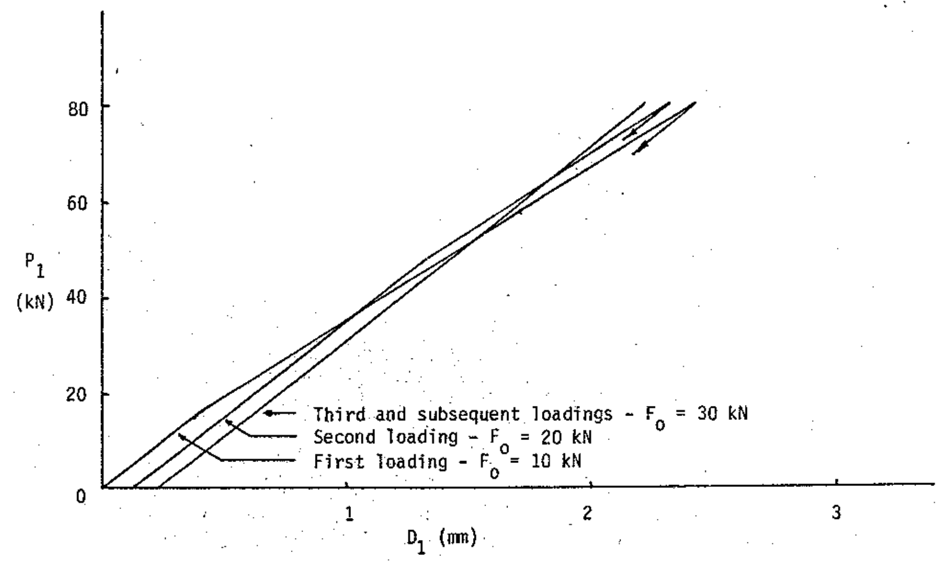

Fig. 13 - Model response showing the effect of increasing F_o for successive loading cycles

data which will supplement laboratory test data. In conjunction with this work, a mathematical model has been developed which allows the simulation of elastic and permanent deflections. The response of the model to simple loading has been demonstrated and it is anticipated that the use of field and laboratory data will lead to the further development of the model, which will in turn lead to an increase in the understanding of ICBP behaviour.

Much progress has been made recently with design aids and construction techniques for ICBPs. This progress has resulted in an increasing popularity for this type of pavement in many countries, including Australia. However, the ICBP will only become truly competitive with alternative pavements if the lock-up phenomenon is explained to the satisfaction of pavement designers. The research described in this paper is an attempt to provide this explanation.

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Fatih Eser is a M.E. candidate in the Department of Civil and Aeronautical Engineering at the Royal Melbourne Institute of Technology. He received a Diploma of Civil Engineering from the Istanbul Government Academy of Engineering and Architecture and obtained several years design office and site experience in the Republic of Turkey before coming to Australia to continue his studies.

Anthony Frick is Senior Lecturer in Civil Engineering at the Royal Melbourne Institute of Technology. He received a B.E. from the University of Adelaide and subsequently obtained his M.Sc. and Ph.D. from Brown University, Rhode Island, U.S.A. After spending four years as Assistant Professor, Engineering Science, at the University of Western Ontario, he joined RMIT where, in recent years, he has been investigating the modelling of interlocking concrete block pavements.

Ken Mavin is Senior Lecturer in the Department of Civil and Aeronautical Engineering and Assistant Director of the Industrial Technology Centre at the Royal Melbourne Institute of Technology. He worked for local authorities in the U.K. and the former Commonwealth Department of Works in Darwin before joining RMIT. His research interests are in the area of road pavements, particularly materials, although he has worked recently on a variety of projects outside this area. For example, he is a member of a Standards Association of Australia Committee examining synthetic sporting surfaces.