A REVIEW OF RESEARCH INTO CONCRETE SEGMENTAL PAVERS IN AUSTRALIA

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ABSTRACT

This paper reviews the progress that has been made in Australia in research in the design and specification of trafficked interlocking concrete segmental pavements. The paper begins by summarising tests designed to explore the response of block pavements to traffic. These include accelerated trafficking tests, field trials of actual pavements and Falling Weight Deflectometer evaluations. Next, tests designed to delineate such intrinsic surface characteristics as skid resistance, noise generation and colour are reviewed. Finally, a brief overview of the evolution of design procedures for both roads and industrial hardstandings is presented.

INTRODUCTION

In the early 1970s the Australian concrete masonry industry was producing high quality wall masonry and was well equipped with a range of modern high volume production facilities. However, the industry faced the problem of having a significant excess of manufacturing capacity over demand and, accordingly, began to seek alternative products. Following visits to Europe and Mexico, C.F. Morrish, then Executive Officer of the Concrete Masonry Association of Australia (CMAA), advised the industry to consider the manufacture of concrete block paving. Shortly thereafter, Adelaide City Council began to evaluate trial areas of pavement to determine their suitability for use in the Rundle Street mall. A trail area of block paving was then constructed using paving units imported from Europe. The response to this new form of paving was sufficiently favourable to encourage full-scale production of block paving in Adelaide by early 1975. The introduction of block paving into Melbourne and then Sydney followed. By 1977, block paving was being manufactured in Perth and indeed could then be said to be available nation-wide.

At the time of its introduction into Australia there was little reliable technical literature on block paving available in English. The pioneering work of Balado (1965) in South America, Marais (1967) in South Africa, and the Heidemaatschappij (1967) in The Netherlands was unknown in Australia. Accordingly, many of the early design and construction recommendations for concrete block paving were based on heresay and precedent from Europe. Much of this was irrelevant to Australia and, indeed, often proved to be of dubious technical merit. However, from 1976 onwards a series of reports began to emerge from the work of the U.K. Cement and Concrete Association (e.g. Knapton 1976; Lilley and Knapton 1978). Unfortunately, this work was intended to be used in conjunction with Road Note 29 for pavement design in Britain (TRRL 1970). This severely diminished the usefulness of the British research to Australian engineers. For this reason, the CMAA asked the University of New South Wales in 1977 to undertake a series of accelerated trafficking trials of full-scale prototype block pavements with the objective of establishing a sound technology for the use of the new paving system in Australia. The results of this work were presented at an Australian Road Research Board (ARRB) Workshop on Interlocking Concrete Block pavements held in Melbourne in October 1978 and attended by a wide cross-section of engineers from around Australia (Sharp and Metcalf 1979). This proved to be the precursor of a similar symposium in Johannesburg in November 1979 and of international conferences on concrete block paving held in Newcastle, U.K. in 1980 (Jeffrey 1982) and Delft, Holland in 1984 (CBP 1984). Collectively, the Proceedings of these workshops and conferences represent a good overview of the emerging technology of concrete block paving.

The 1978 ARRB Workshop served as a valuable stimulus to block paving research in Australia. Since that time, studies have been undertaken not only within such tertiary institutions as the University of N.S.W. and the Royal Melbourne Institute of Technology (RMIT) but also by ARRB. At the same time, various block manufacturers have sponsored a wide range of field trials of interlocking pavements. This effort has been matched by the development and refinement of industry-based design procedures and materials and construction specifications. The purpose of this paper is to summarise and highlight the principal features of the Australian research effort up to 1986 and, where appropriate, to set the work in context with other research around the world. In this respect, the paper seeks to complement earlier studies viewed both from the research (Shackel 1980a; Sharp 1979; Sharp and Armstrong 1985) and industry (Morrish 1982 and 1984) standpoints.

The review is in two parts. It begins by summarising the wide variety of tests on concrete block paving conducted in Australia since 1976. The evolution of design procedures for both roads and industrial pavements is then described.

TESTS OF CONCRETE BLOCK PAVING

For convenience, the tests that have been conducted in Australia will be described under two headings:

(a) structural tests designed to delineate the factors controlling the in-service performance of block pavements carrying vehicular traffic; and

(b) material tests designed to explore the intrinsic properties of the block surface itself in terms of such factors as colour, skid resistance, noise generation, etc.

STRUCTURAL TESTS OF INTERLOCKING CONCRETE PAVING

Three forms of test have been used in Australia to evaluate the structural characterisitcs of block paving:

(a) accelerated trafficking tests of specially-constructed prototype pavements (Shackel 1979a and 1986; Sharp and Armstrong 1984 and 1985; Sharp, Armstrong and Morris 1982);

(b) field trials of actual pavements under normal traffic (Shackel 1980d and 1982a; Dossetor and Leedham 1976); and

(c) Falling Weight Deflectometer (FWD) tests of both prototype and in-service pavements.

Accelerated Trafficking Tests

Accelerated trafficking trials of block pavements in Australia have involved either the use of vehicle simulators (Shackel 1979a) or trafficking with fleets of specially-ballasted vehicles (Shackel 1982a and 1986a; Sharp and Armstrong 1984 and 1985; Sharp et al. 1982). The first work of this type was conducted using the full-scale road simulator of the University of N.S.W., commencing in October 1977 (Shackel 1979a). In these tests, full-scale prototype pavements were constructed using high quality crushed rock bases over a sandy-loam subgrade of CBR = 60 per cent. The following factors were studied:

(b) base thicknesses of 60, 100 and 160 mm;

(c) bedding sand thicknesses of 30 and 50 mm;

(d) three block shapes given as A, E and U in Fig. 1; and

(e) the pavements were subjected to simulated wheel loads of 24 and 36 kN.

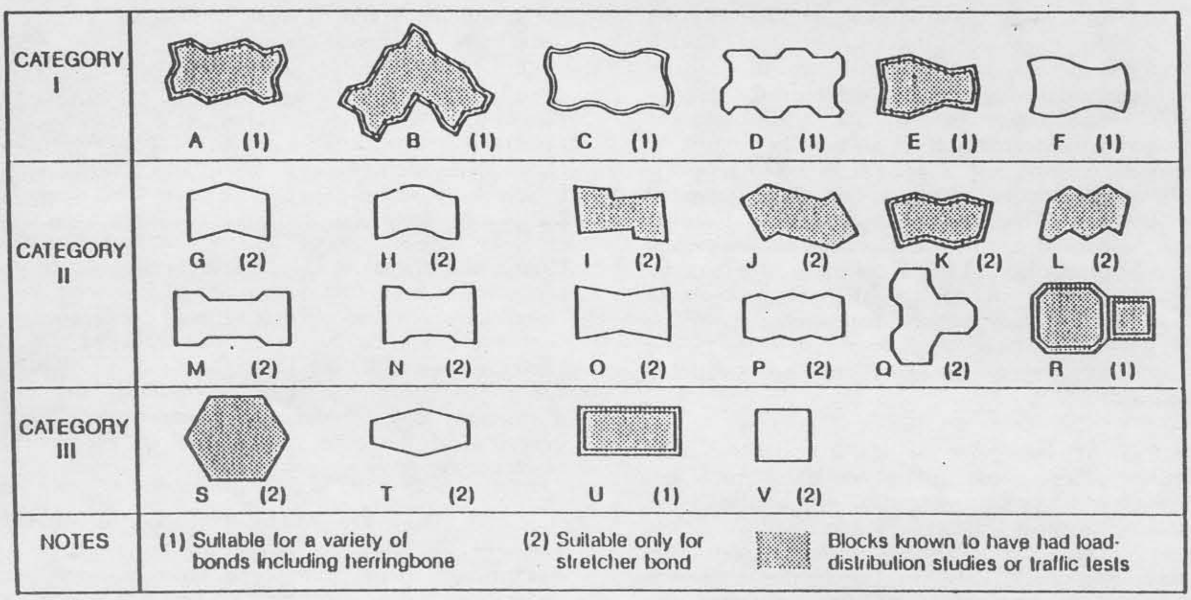

Fig. 1 - Common paving unit shapes and classifications

Typically the pavements were each subjected to at least 10,000 simulated wheel passes. Measurements were made of the vertical and horizontal surface deformations, the resilient vertical deflections and the stresses induced at various points within the pavement. The principal conclusions of the experiments were as follows.

(a) The block pavements progressively stiffened under traffic until a shakedown equilibrium condition (lock up) was attained.

(b) Increases in either the block or base thickness were beneficial to the performance under traffic. The effects of increases in the block thickness were more pronounced than the effects of similar increases in base thickness.

(c) With increase in contact (tyre) pressure, block thickness was the principal determinant of performance.

(d) Blocks having dentented shapes such as A and E in Fig. 1 exhibited similar levels of performance which were measurably superior to that given by rectangular blocks of similar thickness.

(e) Block pavements could tolerate large resilient deflections of up to 2 mm without exhibiting distress.

(f) A reduction in the bedding sand thickness from 50 mm to 30 mm was beneficial to pavement performance.

Further trafficking tests were conducted to permit direct comparison of the performance of the blocks with the performance of asphaltic concrete (AC) and crushed rock (Shackel 1979b). This enabled materials equivalencies to be determined experimentally in terms of the degree of surface rutting or the magnitude of the stresses transmitted to the subgrade as follows:

(a) on the basis of rut depth:

10 mm of block thickness

≡ 29 mm of crushed rock
≡ 15 mm of AC

(b) on the basis of subgrade stress:

10 mm of block thickness

≡ 21 mm of crushed rock
≡ 14 mm of AC

As noted shortly, these equivalencies were to prove useful in the development of interim design methods for block paving.

The tests just described were soon supplemented and extended by a series of Heavy Vehicle Simulator (HVS) tests conducted in South Africa (Shackel 1980b and c, 1982b). These served to confirm the importance of block shape in influencing in-service performance (here the tests included shapes A, J, K, L and U in Fig. 1) and the need to control carefully the thickness of the bedding sand layer (Shackel 1980c and d). These tests further explored the effect of block and base thickness and the phenomenon of lock up, and also delineated the effects of the type of base on block pavement performance (Shackel 1980b and 1982b). Because the HVS tests were integrated with the earlier studies of the University of N.S.W., they were closely monitored by CMAA in Australia and many of the research findings were incorporated into CMAA documents for the design and construction of block pavements.

The alternative to the use of vehicle simulators to traffic test pavements is to used suitably-ballasted test vehicles. The first study of this type in Australia was initiated by the Australian Road Research Board (ARRB) in 1979, although construction of the pavements did not begin until late 1980. These trials differed significantly from the earlier University of N.S.W. experiments in that the pavements were constructed on a low-strength clay subgrade (CBR 5 per cent). Initially shapes A and B in Fig. 1 were studied and preliminary results confirmed the earlier studies that block shape influences performance and that block pavements can withstand large resilient deflections (Sharp et al. 1982). The ARRB pavements tested in the latter stages of the project were said to be designed in accordance with the then current CACA recommendations (Hodgkinson and Morrish 1982). However, several of the pavements performed poorly, exhibiting unacceptable levels of rutting deformation (Sharp and Armstrong 1984 and 1985). Although some controversy exists concerning the causes of the poor performance, the ARRB workers concluded that revision of the design guide at CBR values below about 4 per cent was desirable. Overall the ARRB research project was valuable in drawing attention to the need for adequate drainage, the need to use the laboratory soaked CBR value for design purposes, and the desirability of adopting adequate specifications for base and sub-base materials. Many of the recommendations eminating from this work, such as the suggestion that traffic be expressed in terms of the number of vehicles > 3 t gross, have now been incorporated into current Australian design procedures (as described in the author's companion paper to this Workshop - Shackel (1986c)).

Since 1982, the University of N.S.W, in collaboration with both Australian and overseas companies, has been actively engaged in conducting accelerated trafficking trials of segmental pavements at sites in Western Australia and N.S.W. In these trials, the pavements have been trafficked by fleets comprising not less than three fully-laden trucks, each towing a fully-laden trailer. To date more than 40 clay brick pavements and more than 30 concrete block pavements have been evaluated in this way. In the case of the concrete block pavements, the principal study has been conducted at Emu Plains to the west of Sydney and has involved an investigation of machine-layable Anchorlock pavers of the type illustrated as shape B in Fig. 1 (Shackel 1986a). The performance of these units has been compared with that of conventional Unipave blocks (shape A in Fig. 1). These tests have demonstrated that, provided care is taken in the choice of laying pattern, good levels of performance can be achieved under both truck and forklift axle loads. Here, the performance of shape B in Fig. 1 has generally been found to be superior to that exhibited by shape A. The experiment also included a direct comparison between the performance of unbound crushed rock and cement-stabilised basecourses laid in three thicknesses. In all cases the block pavements incorporating the stabilised bases exhibited less deformation and deflection under traffic than where unbound bases were used. This is consistent with the earlier findings already reported (Shackel 1980d, 1982a and b).

In addition to evaluating the new Anchorlock machine-layable pavers, the University of N.S.W. truck trafficking trials have also embraced studies of the vertically-interlocking G-block paving system (Glickman 1984) and of grouted circular segmental paving developed in Zimbabwe. The results of these trials are yet to be published.

FIELD TRIALS OF BLOCK PAVING

The first field trial of concrete block paving was conducted in 1976 by the South Australia Institute of Technology (Dosseter and Leedham 1976). This comprised a short-term study of the performance of Unipave blocks laid in the entrance to the Monier Besser plant at Rosewater, Adelaide. Unfortunately, these trial areas deformed excessively under traffic because of improper construction and compaction and little useful data were obtained.

The second field study involved an investigation of a range of industrial block pavements in the port of Fremantle (Shackel 1982a). Here, a variety of pavements surfaced with 80 mm thick shape A blocks were installed using a range of base types and thicknesses. The pavements were trafficked using a forklift ballasted to apply an axle load of either 55 t or 90 t. Measurements were made of both rutting and resilient deflection under load. The principal finding of this test was that block pavements incorporating cement-stabilised basecourses performed better than where unbound bases were used. This was consistent with earlier studies of both road (Shackel 1982b) and industrial (Shackel 1980d) block pavements. The test was also valuable in demonstrating practically the ability of block pavements to accept very heavy axle loads. (In this respect the test is believed to be the most severe in terms of axle load yet carried out on concrete block pavements.)

In the case of road pavements, ARRB conducted comprehensive trials of a block pavement installed on a quarry access road in the Shire of Flinders, Victoria (Sharp et al. 1984). Testing commenced in July 1981. Measurements since that time have shown that good levels of performance have been achieved, with rut depths less than 3 mm accompanied by resilient deflections close to 0.7 mm (compared with approximately 0.45 mm for an asphalt control section) after about 150,000 ESAs had been applied over a two-year period. Increases in subgrade moisture content above that established at construction have apparently not affected performance. The trial has been valuable in demonstrating that excellent levels of performance can be achieved in block pavements carrying heavy truck traffic.

FALLING WEIGHT DEFLECTOMETER STUDIES

Comprehensive studies conducted in The Netherlands under the auspices of the Technical University, Delft (e.g. Fuchs, Houben and Molenaar 1983) have demonstrated that the Falling Weight Deflectometer (FWD) can yield valuable information on block pavements already in service. Following the introduction of the FWD into Australia in about 1983, the University of N.S.W., in conjunction with Monier Ltd, has obtained FWD measurements on more than 20 experimental pavements and on some 20 block pavements currently in service in South Australia. The analysis of the data gained in these studies is not yet complete but preliminary results indicate that, provided dentated blocks are used, the equivalent elastic modulus of the block course measured in situ can be expected to be within the range from 2000 to 6500 MPa depending on block shape and subsurface conditions. (This compares with an average value of 2860 MPa for rectangular blocks reported by Fuchs et al. (1983).)

TESTS OF CONCRETE BLOCK SURFACES

Tests designed to examine the characteristics of concrete block surfaces in Australia have included:

(a) investigations of skid resistance;

(b) studies of traffic noise generation;

(c) measurements of colour and luminance; and

(d) measurement of block strength and abrasion.

Measurements of strength and abrasion are discussed elsewhere at this Workshop (Rourke 1986) and this paper will therefore concentrate on the other three aspects.

SKID RESISTANCE

The first measurements of the skid resistance of Australian block pavements appear to be those supplied by Mavin (1982) at RMIT. These data showed that blocks tended to polish under plate vibration. For example, Mavin reported a drop in the average pendulum values from 81 for newly-delivered blocks to 74 after plate compaction. A similar decrease was subsequently reported by the author following tests in Western Australia (Shackel 1982a). The RMIT study also suggested, albiet inconclusively, that further losses in skid resistance might occur in service under traffic. The variations in skid resistance with time were examined further in a more comprehensive study conducted by ARRB (Sharp et al. 1984). This confirmed that concrete block surfaces may show an initial decline in skid resistance immediately after construction but indicated that, thereafter, the values tended to fluctuate seasonally. An interesting feature of the ARRB trials was that the concrete block paving tended to maintain skid resistance values that were consistently higher than those measured on adjacent control sections surfaced in asphaltic concrete.

Skid resistance values similar to those obtained in Australia have been reported overseas (e.g. Lekso 1982; Miura et al. 1984). Most of these measurements have been confined to a period of just one or two years after construction. However, the author was able to evaluate a bus route in

Durban, South Africa, after 17 years of trafficking. Here, pendulum values having a mean of 61 and a standard deviation of 4.3 were obtained. Taken in conjunction with the other studies, this suggests that, subject to proper manufacturing controls, block paving can maintain good values of skid resistance throughout the life of the pavement.

NOISE GENERATION

Two studies of the noise generated by traffic running on block pavements have been made in Australia by the University of N.S.W. and by ARRB. So far only the ARRB measurements have been published (Samuels and Sharp 1984).

Noise measurements made by the author in Adelaide (1982), Sydney (1983) and Hobart (1984) showed that the effects of the size of the chamfers on the blocks influenced the noise both at the kerb and within a moving vehicle. Overall, the block pavements showed increased road noise with an increase in the size of the chamfers, yielding noise increases of up to 4.4 dB(A) when the chamfers were 10 mm x 10 mm. Generally, however, for chamfers not exceeding about 5 mm x 5 mm, the traffic noise measured at the kerb on a dry block pavement was little different to that generated on an asphalt surface. This conclusion was supported by the comprehensive ARRB study (Samuels and Sharp 1984).

Measurements made within a vehicle by the author and Samuels and Sharp (1984) have shown that, except in vehicles such as cars where the engine and transmission noise is low, no change in noise level was perceived for the vehicle running on either blocks or asphalt. In quiet vehicles, block pavements have been found to be associated with increases in the within-vehicle noise levels of between 2 and 4 dB(A) when compared to asphalt. Beneficial use of this effect has been made as a traffic control measure, especially in Adelaide.

In general, the Australian studies are consistent with overseas work (e.g. Miura et al. 1984) which indicates that block pavements generate no more traffic noise than asphalt surfaces when dry and tend to be quieter than wet.

COLOUR

Concrete block pavements are unique amongst pavement surfaces in respect of the ease with which colour may be controlled. This can have important implications concerning the visibility of the pavement surface by day and by night. The effects of a change in the colour of paving blocks can be conveniently characterised in terms of the luminance factor. This is defined as the ratio of the luminance of a material to that of a perfect diffusing reflector illuminated and viewed under the same conditions. In other words, the luminance factor can be regarded as a measure of the amount of light reflected by the material under study.

Measurements were made in 1982 at the University of N.S.W. of the luminance factors of concrete pavers manufactured by a single Sydney supplier. The blocks were studied using both CIE Illuminant C (a light source simulating average daylight) and CIE Illuminant A (a light source representing artificial incendescent lighting). For each sample measurements were made on three points, each roughly 20 mm in diameter, on the block surface. These observations are summarised in Table 1.

TABLE 1

LUMINANCE FACTORS FOR CONCRETE PAVING UNITS

Paving Unit Colour	Luminance Factor [P(0,45)]	
	Illum. A	Illum. C
charcoal grey	15	14
light grey	18	16
dark brown	18	16
light brown	29	27
light red	18	16
sandy yellow	29	27
natural	23	23
light brick	24	22

mean of 3 determinations

From Table 1 it may be seen that the luminance factor typically ranged between 0.14 and 0.27 for daylight and between 0.14 and 0.29 for artificial lighting. Irrespective of the block colours, these values are much higher than the luminance factors normally measured for asphaltic surfaces where values close to 0.07 are common.

Subsequently, the effect of the colour of paving units was studied in detail by Jenkins and Sharp (1985) at ARRB. These workers concluded that the response of a driver to two specific block colours (yellowish-brown and reddish-brown) depended on whether the surface was wet or dry.

Overall the University of N.S.W. and ARRB data showed that, in the dry state, good contrast can be observed by a driver between blocks of different colour and between blocks and asphalt. However, in wet conditions, the contrast is severely diminished. At this stage the surface finish and presence of joints in a block pavement are likely to provide the principal cues to the driver.

Both studies appear to be breaking new ground in block paving evaluation. In this respect, only one other scientific study (in Europe) appears to have been made of the visual characteristics of block paving (Burghout 1984).

PAVEMENT DESIGN

An early major obstacle to the successful adoption of block paving in Australia was the lack of a proven, soundly-based design procedure. Accordingly, much of the research effort in Australia since the introduction of block paving has been concerned with evolving and evaluating design methods for both roads and industrial hardstandings surfaced in concrete blocks. This has been reviewed elsewhere (Sharp and Armstrong 1985; Shackel 1980e).

ROAD PAVEMENTS

The first Australian design method for concrete block pavements was published in an interim form by Cruickshank (1976). Like most methods than available in Europe, this represented an ad hoc procedure which, in view of the lack of knowledge of the response of segmental paving to traffic, not surprisingly failed to recognise the unique engineering features of this type of pavement. In 1978, following the accelerated trafficking tests at the University of N.S.W., this interim procedure was replaced by a hierarchy of empirically-based methods (Shackel 1979b and 1982c; Hodgkinson and Morrish 1982).

The justification for an empirical approach lay in the fact that block pavements can be manufactured and laid to much more consistent tolerances than most other types of flexible pavement material. Thus the properties of a mat of paving blocks are less likely to vary from one job to another (assuming that the laying techniques are maintained constant) than, say, a bituminous concrete surfacing. Accordingly, it was argued that, provided the properties of the mat could be characterised in one set of circumstances such as an accelerated trafficking test, then a mat of similar blocks laid in the same manner elsewhere would have similar properties. Adopting this philosophy, a design procedure was evolved by first using trafficking tests to characterise the traffic-associated deformations of block paving systems and secondly by using simple mechanistic procedures to extend that data to cover a wider range of subgrade conditions than could be studied in the characterisation tests. Details of the methodology have been given elsewhere (Shackel 1979b and 1982c). This procedure was put into a practical form by Hodgkinson and Morrish and issued as an interim procedure in 1978. Tests conducted in 1979 and 1980 in South Africa (Shackel 1982b) tended to support the earlier Australian tests and the CMAA design procedure was issued in a final form with only minor amendments in 1982.

The empirically-based design procedure was shown to be conservative when compared to earlier methods (Shackel 1982c). Nevertheless, two criticisms could be directed at the procedure. Firstly, the design philosophy assumed a priori that the quality of materials and standards of construction achieved in practice would, at least, equal those attained during the accelerated trafficking tests used to derive the design methodology. However, experience showed this was not always the case in Australia. Secondly, the method had only been experimentally verified down to CBR values of 15 per cent or more (Shackel 1982b). Despite these limitations, the design method was widely used both in Australia and overseas with more than 10,000 copies being distributed world-wide. Nevertheless, when, as already noted, poor results were obtained in the ARRB trials of block pavements (Sharp and Armstrong 1985) said to be designed in accordance with the guide, a major reappraisal of the design procedures was undertaken by CMAA and CACA. This led to the emergence of a computer-based mechanistic design methodology.

The emergence of a mechanistic methodology for roads was chosen, so far as practical, to conform with the guidelines then being laid down (e.g. Potter and Donald 1984) for the revision to the NAASRA Interim Guide to Pavement Thickness Design (NAASRA 1979). The method has far greater flexibility in the choice of pavement materials than the earlier empirical procedure. In particular, it facilitates the use of stabilised base and sub-base layers which, as already noted, have been demonstrated to offer a number of performance advantages in block pavements. Details of the method have been given elsewhere (Shackel 1984, 1985 and 1986b), including a companion paper to this Workshop (Shackel 1986c).

INDUSTRIAL PAVEMENTS

As well as evolving methods for road pavements, it was also necessary to develop methods for the design of heavy duty industrial hardstands. The first published design procedures in Australia (Shackel 1982d) were based on ad hoc modifications of conventional flexible pavement design methodologies using the materials equivalencies measured in the University of N.S.W. tests (Shackel 1979b). This approach soon yielded to more comprehensive mechanistic procedures (Shackel 1984, 1985 and 1986b). These have been widely used both in Australia and in many overseas projects for the design of industrial pavements. Again details are given elsewhere in this Workshop (Shackel 1986c).

CONCLUDING COMMENTS

As shown in this paper, Australia has been a pioneer in research into the practical application of concrete block paving. In this respect, Australian research has embraced virtually all aspects of block paving performance as well as the design of block pavements for both road and industrial applications. Few other countries can claim to have mounted so comprehensive or extensive a research effort. Yet, significantly, this has been accomplished with little or no governmental assistance. Although some projects at the University of N.S.W. have been funded from overseas, most research has been funded in Australia, either through CMAA or the Cement and Concrete Association of Australia (CACA) or directly through their member companies. At a time when Australian industry is being criticised for a lack of investment in research and development, this is a notable exception and deserves recognition. Indeed, without this support, little of the work reviewed in this paper could have been carried out.

REFERENCES

BALABO, G. (1965). Pavimento con bloques articulados de homigon. Proc. 5th Argentinian Road Cong., Argentina.

BURGHOUT, F. (1984). Light reflection by concrete blocks. Proc. 2nd Int. Conf. Conc. Block Pavements, Delft, Vol. II.

CBP (1984). Proceedings of the Second International Conference on Concrete Block Paving, Delft. (CBP: The Hague.)

CRUICKSHANK, J.W. (1976). Interim guide to the design and construction of interlocking sett pavements. Cement Conc. Assoc. Aust. Tech. Note, TN32, October.

DOSSETOR, J.E. and LEEDHAM, A.G. (1976). Concrete block pavements. Dept. Civ. Eng., S.A. Inst. Technol. CT Seminar, III.

FUCHS, G.H.A.M., HOUBEN, L.J.M. and MOLENAAR, A.A.A. (1983). Evaluatie von vestaande betonstraatsteen verhardingen tekst. Tech. Univ. Delft, Rep. 7-83-200-5, April.

GLICKMAN, M. (1984). The G-block system of vertically interlocking paving. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 345-48.

HODGKINSON, J.R. and MORRISH, C.F. (1982). Design of interlocking concrete pavements for road traffic. Cement Conc. Assoc. Aust. Tech. Note, TN40, March.

JEFFREY, H. (Ed.) (1982). Concrete block paving - Proceedings of the First International Conference. (DAP: Sussex.)

JENKINS, S.E. and SHARP, K.G. (1985). Some laboratory tests to investigate the colour difference between concrete paving blocks and asphaltic concrete. Aust. Rd Res. 15(3), pp. 187-89.

KNAPTON, J. (1976). The design of concrete block roads. Cement Conc. Assoc. Tech. Rep. 42.515.

KONINKLIJKE NEDERLANSCHE HEIDEMAATSCHAPPIJ (1967). Onderzoek ten behoeve van de veshardings-constructies op de container terminal van de N.V. Prinses Margriethaven te Rotterdam. KNH Rep. 0111-0272/33, Arnhem.

LEKSO, S. (1982). The use of concrete block pavement for highway. Proc. 1st Int. Conf. Conc. Block Paving, Newcastle Upon Tyne, 1980.

LILLEY, A.A. and KNAPTON, J. (1978). Concrete block paving for roads. Cement Conc. Assoc. Pub. 46.021.

MARAIS, L.R. (1967). Investigation into the load bearing capacity of SF concrete roadstones. Portland Cement Inst., Johannesburg.

MAVIN, K.C. (1982). Interlocking block paving in Australian residential streets. Proc. 1st Int. Conf. Conc. Block Paving, Newcastle Upon Tyne, 1980.

MORRISH, C.F. (1982). Interlocking concrete paving - the state-of-the-art in Australia. Proc. 1st Int. Conf. Conc. Block Paving, Newcastle Upon Tyne, 1980.

---------- (1984). Recent developments in trafficked interlocking concrete pavements in Australia. Proc. 2nd. Int. Conf. Conc. Block Paving, Delft, pp. 191-96.

MUIRA, Y., YOSHIDA, K., KOMURA, M. and SAEKI, Y. (1984). On the servicability of concrete block pavements used on streets and bus bays. Proc. 2nd. Int. Conf. Conc. Block Paving, Delft, pp. 212-15.

NATIONAL ASSOCIATION OF AUSTRALIAN STATE ROAD AUTHORITIES (1979). Interim guide to pavement thickness design. (NAASRA: Sydney.)

POTTER, D.W. and DONALD, G.S. (1984). Revision of NAASRA Interim Guide to Pavement Thickness Design. Presented at 12th ARRB Conf., Hobart. Also, Aust. Rd Res. 15(2), pp. 106-08, 1985.

ROURKE, J.T. (1986). Factors which were considered and a summary of research which was undertaken in the preparation of 'MA20 - 1986 Specification for Concrete Segmental Paving Units' by the Concrete Masonry Association of Australia. Proc. Int. Workshop on Interlocking Concrtete Pavements, Melbourne, September.

SAMUELS, S.E. and SHARP, K.G. (1984). The noise produced by a concrete block pavement. Australian Road Research Board. Internal Report, AIR 258-6. Also Proc. Aust. Acoustical 1985 Conf., Leura Gardens, November 1985, pp. 124-29.

SHACKEL, B. (1979a). An experimental investigation of the response of interlocking block pavements to simulated traffic loading. In K.G. Sharp and J.B. Metcalf, 'Workshop on Interlocking Concrete Block Pavements. Proceedings.' Australian Road Research Board. Research Report, ARR No. 90, pp. 11-44.

---------- (1979b). The design of interlocking concrete block pavements. In K.G. Sharp and J.B. Metcalf, 'Workshop on Interlocking Concrete Block Pavements. Proceedings.' Australian Road Research Board. Research Report, ARR No. 90, pp. 53-70.

---------- (1980a). A review of the technology for interlocking concrete paving blocks for roads and industrial pavements. Nat. Inst. Transp. Road Res. Tech. Rep. RP8.

---------- (1980b). A study of the behaviour of block paving under traffic using a Heavy Vehicle Simulator. Proc. 10th ARRB Conf. 10(2), pp. 19-30.

---------- (1980c). An experimental investigations of the roles of the bedding and jointing sands in the performance of interlocking concrete block pavements. Conc./Beton 19.

---------- (1980d). Loading and accelerated trafficking tests on three prototype heavy-duty industrial block pavements. Nat. Inst. Transp. Road Res. Tech. Rep. 12.

---------- (1980e). Progress in the evaluation and design of interlocking concrete block pavements. Paper presented to Biennial Conf. CMAA, Brisbane, March.

---------- (1982a). Loading and accelerated trafficking evaluations of heavy duty interlocking concrete block pavements in Fremantle. Proc. 11th ARRB Conf. 11(2), pp. 101-11.

---------- (1982b). An experimental investigation of factors influencing the design of interlocking concrete block pavements for roads. Proc. 11th ARRB Conf. 11(2), pp. 6-15.

---------- (1982c). The design of interlocking concrete block pavements for road traffic. Proc. 1st Int. Conf. Conc. Block Paving, Newcastle Upon Tyne, 1980.

---------- (1982d). The systematic design and construction of heavy duty industrial interlocking concrete block pavements. Proc. Biennial Conf. CMAA, Perth.

---------- (1984). The analysis and design of concrete block paving subject to road traffic and heavy industrial loading. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 139-46.

---------- (1985). Evaluation, design and application of concrete block pavements. Proc. 3rd Int. Conf. Conc. Pave. Design and Rehabilitation, Purdue Univ.

---------- (1986a). Accelerated trafficking trials of machine-layable concrete block paving. Aust. Rd Res. (in press).

---------- (1986b). The design and application of concrete segmental paving in transportation. ACI, Vancouver.

---------- (1986c). Computer-aided and analysis of concrete segmental pavements. Proc. Int. Workshop on Interlocking Concrete Pavements, Melbourne, September.

SHARP, K.G. (1979). Interlocking concrete block pavements: preliminary state-of-the-art review. In K.G. Sharp and J.B. Metcalf, 'Workshop on Interlocking Concrete Block Pavements. Proceedings.' Australian Road Research Board. Research Report, ARR No. 90, pp. 3-10.

---------- and ARMSTRONG, P.J. (1984). The performance of concrete block pavements constructed on low CBR subgrades. Proc. 12th ARRB Conf. 12(3), pp. 121-36.

---------- (1985). Interlocking concrete block pavements. Australian Road Research Board. Special Report, SR No. 31.

---------- and MORRIS, P.O. (1982). The performance of two interlocking concrete block pavements. Proc. 11th ARRB Conf. 11(2), pp. 152-65.

SHARP, K.G. and METCALF, J.B. (Eds) (1979). Workshop on Interlocking Concrete Block Pavements. Proceedings. Australian Road Research Board. Research Report, ARR No. 90.

SHARP, K.G., ARMSTRONG, P.J., GOSCHNICK, S.B. and BUFFINGTON, S. (1984). The performance of a heavily-trafficked concrete block pavement at the Shire of Flinders. Aust. Rd Res. 14(3), pp. 149-52.

TRANSPORT AND ROAD RESEARCH LABORATORY (1970). A guide to the structural design of pavements for new roads. Road Note 29.

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