ACCELERATED TRAFFICKING TESTS OF CONCRETE FLAG PAVING

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ABSTRACT

The use of flag paving under traffic poses particular difficulties to pavement engineers. Flag pavements bedded on sand are limited in the numbers of vehicles that they can carry and, hitherto, the use of mortared flags has often been associated with early failure under traffic. This paper looks at new ways of overcoming these shortcomings by the use of high technology mortars and adhesives to fix the flags on to a concrete base. These materials were evaluated by accelerated trafficking studies of four full-scale prototype flag pavements. These tests used the ARRB Accelerated Loading Facility (ALF).

In the tests, flags, 400 x 400 mm in thicknesses of 40 and 53 mm were fixed in both stack and stretcher bonds on a rigid concrete base. Two types of fixing were examined. These comprised mortar and adhesives. Tests panels were orientated both normal and at 45° to the direction of trafficking. Trafficking was conducted using a dual wheel driven in one direction over the pavements. Dual wheel loads from 40 kN to 80 kN were studied with up to 60,000 wheel passes per test panel. Overall, the tests showed that it is possible to achieve good levels of performance in flag pavements under traffic provided that care is taken to fix the flags securely to an adequate concrete slab base. The paper includes recommendations for design and construction.

INTRODUCTION

There have been many problems and failures in mortared flag pavements carrying traffic both in Australia and overseas (Shackel and Pearson, 2001). However, municipal authorities often wish to use flag paving because of its aesthetic qualities. Current design recommendations for such paving require the flags to be bedded on sand and impose strict limits on the amounts of traffic to be carried (Shackel and Pearson, 2000). There is, therefore, a need to explore alternative forms of flag paving construction that may permit higher traffic volumes to be safely carried. This paper presents an evaluation of a new proprietary system of bonded flag paving developed by Boral to meet this challenge. This system was evaluated by means of full-scale accelerated trafficking tests using the ARRB Transport Research Accelerated Loading Facility (ALF).

BACKGROUND TO THE PROJECT

In Australia, several major projects have used pavements with concrete flags mortared down on concrete slabs. Generally, these pavements have involved laying the pavers butt-jointed on traditional mortars such as 1:1:6 cement:lime:sand. In all cases the slabs supporting the pavers have been designed so that their thicknesses were adequate to carry the design traffic without requiring any structural contribution by the pavers or mortar. Despite this, many such pavements have failed under traffic including flag pavements in downtown Brisbane and Newcastle. Typically, failure has taken the form of cracking and spalling of the pavers often accompanied by pumping of broken down mortar from the cracks and joints. Occasionally pavers have become loose. Where this has occurred it has usually been because of the failure of the bond between the pavers and mortar or between the mortar and slab rather than failure within the mortar bed itself. The conclusions drawn from these failures were that the use of pavers laid butt-jointed on mortar was not suitable for normal down-town traffic and that this was not simply a question of the strength of the pavers since much stronger granite pavers have exhibited similar problems (Shackel and Pearson, 2001).

Following these failures and a detailed study of European practice current Australian Design recommendations for concrete flag pavements (Shackel and Pearson, 2000) specifically exclude the use of flags laid on mortar where traffic is to be carried. By implication, flags installed on adhesive are also excluded from use under traffic. However the new Boral proprietary system of flags laid on adhesive on concrete slabs was claimed to be capable of withstanding normal road traffic and, therefore, to provide a viable alternative to installing flags on a sand bedding.

PROJECT DESCRIPTION

The objective of the work described herein was to investigate the behaviour under traffic of flag pavers (Boral Stylestone) laid on both a proprietary adhesive (Boral Thin Bed Adhesive) and a mortar incorporating a mix improver (Boral Bond) over a rigid concrete base and to determine their performance under traffic chosen to reflect urban road traffic load distributions recommended by AUSTROADS for pavement thickness design (Austroads, 2001).

The test pavements were constructed at the ARRB Test Site at Dandenong, Victoria. The flags tested comprised Boral Stylestone large format pavers (flags) having nominal dimensions of 400 x 400 x 53mm and 400 x 400 x 40mm. Test data showed that these pavers typically achieved a full-unit Breaking Load of 9.1 kN and a flexural strength of 7.5 MPa.

The flags were installed on a steel fibre reinforced concrete slab 4 m wide and 38 m long installed directly on the subgrade which was compacted using a plate compactor prior to placing the slab. The slab was laid without camber or crossfall. The nominal thickness of the slab was designed to be 220mm. This thickness was chosen to carry the full spectrum of loads planned to be applied during the test program. No allowances for any structural contribution by the pavers or the adhesive were made. This was because the tests were designed principally to investigate the performance of the pavers and adhesive rather than the structural design of the flag paving. For similar reasons, the slab was constructed using fibre reinforced concrete so that the possibility of wide shrinkage cracks developing in the slab was minimized. Such cracking was likely to have reflected through the pavers and, thereby, to have appeared as cracking in the pavers which would have recorded, falsely, to have been caused by traffic. The concrete had a 28-day nominal compressive strength of 25 MPa and was reinforced with 1.5 kg/m^3 of Dramix 80/60BN steel fibres, 60mm long and 0.75 mm in diameter. Eight cores taken from the slab gave compressive strengths between 28.0 and 33.5 MPa with a mean value of 31.1 MPa.

The layout of the test pavements is shown schematically in **Figure 1**. As shown in this figure, at the lead-in and the first 3 test panels (Panel A to C) the slab was specified to be 220mm thick whilst for the remaining panel and the lead-out the slab was to be 200 mm thick. This was to ensure that, when Panel D was laid using flags on 25mm of mortar, the finished surface was level with panels A, B, and C laid on 5 mm of adhesive. Under panels A, B, and C the finished surface of the slab was required not to deviate more than 5 mm from a 2 m straight edge placed in any direction. This slab was fitted with contraction joints sawn to a depth of 60 mm at nominal 3m centres. The sawn joints were 3 mm wide. Sawing was conducted as soon as the concrete had taken its initial set and could be sawn without fretting or tearing. This was to avoid uncontrolled shrinkage cracks developing during curing. Above the sawn joints the pavers were provided with 10mm wide expansion joints filled with Ableflex sealant.

Panels of flags each 6 m long and 4 m wide were laid on the panels labeled A to D in Figure 1. Each panel was subdivided into 2 portions each having pavers with a different finish. Panel D was laid in a bedding mix incorporating a proprietary additive known as “Boral Bond”. In panels A to C the pavers were installed on a proprietary adhesive known as “Boral Thin Bed Adhesive”. The thickness of adhesive was the minimum required to ensure good bonding and adhesion of the pavers and was nominally 5 mm. Three pull-out tests, using 50 x 50mm cross-sections, were conducted to measure the strength of the adhesive bond. The results are given in Tables 1 and 2. The tensile strength of the adhesive was found to be similar to that expected in conventional mortar. In the first test on Panel A it was observed that the tensile break was in the adhesive itself but in the second test the bond between the adhesive and paver failed whilst in the third test failure was 50% in the adhesive and 50% in the bond with the concrete slab. Lower bond tensile strengths were measured on Panel D laid on mortar than Panel A laid on adhesive.

Table 1. Pull-out Tests of Adhesive on Panel A

Sample No	Tensile Pullout Force kN	Tensile Strength MPa	Failure Mode(s)
1	1.12	0.47	In adhesive
2	0.69	0.28	In bond to paver
3	1.46	0.58	In adhesive & bond to slab
Mean Values	**1.17**	**0.47**	

Table 2. Summary of All Pullout Tests

Test Panel	Mean Tensile Strength MPa
A	0.47
D	0.36
D	0.28

The paving was installed with joints nominally 10mm wide. These joints were filled with an expanding grout (Boral Paver Grout) having a specified 7-day compressive strength of 38 MPa. In the case of flags laid in stretcher bond, the long unbroken joints ran across the direction of trafficking and cut pavers were placed only at the outer edges of the panels. Joints running in stack bond were placed so that one continuous joint ran along the centre line of the test panel. For stack bond orientated at 45° to traffic the diagonal axes of the flags ran along the direction of trafficking.

Panels A, B and C were installed prior to Panel D and the thickness of Boral Bedding Mix used in Panel D was adjusted to ensure that the finished levels of all panels were the same. Flags were not laid over the contraction joints and were left clear to give a joint width of 10 mm in the flag surfacing.

ACCELERATED TRAFFICKING TESTS

Trafficking began with the ALF test load set to a 40 kN dual wheel with tyres inflated to 0.7 MPa i.e. simulating one end of the maximum legal axle load for on-road vehicles. AUSTROADS weigh-in-motion axle load data show that, in normal traffic, many vehicles are overloaded with dual wheel (half axle) loads ranging up to 80 kN i.e. twice the legal limit. For this reason, during the tests of Panels C and D, the load on the ALF half axle was progressively increased to 50 and 60 kN. The numbers of repetitions applied at each of the load levels was chosen to simulate the distribution of axle loads recommended by AUSTROADS for urban pavement design (Austroads, 2001). This assumes 3.6% of axle loads will be at 100 kN and 0.92 % of axle loads will reach 120 kN, corresponding to ALF half axle loads of 50 kN and 60 kN respectively. After the pavers had successfully withstood this traffic without damage it was decided to increase the ALF half axle load to 80 kN corresponding to a full axle load of 160 kN even though few axle loads reach this level in practice. Thus, in these tests, the observed patterns of actual road traffic were closely simulated including the anticipated numbers of vehicle overloads that occur in practice and this was then followed by severe overloading under the 80 kN half axle, This meant that, overall, the tests simulated a much greater degree of truck overloading than occurs on actual roads

The pavements were unidirectionally trafficked in the direction shown in Figure 1. The ALF trafficked two adjacent panels consecutively. It should be noted that the ALF wheel was driven not towed. It therefore applied traction forces to the pavement surface thereby simulating the drive axles of trucks. For most of the trafficking of the tests panels there was no lateral distribution of wheel load i.e. the ALF half axle trafficked always along the same wheel path. This concentration of wheel load ensured that the flags in the wheel path received the maximum intensity of traffic repetitions. This meant that the numbers of repetitions applied in the ALF tests effectively correspond to up to about 1.5 times more traffic in an actual road. Before deciding to concentrate the wheel passes, part of the trafficking of Panels A and B was conducted with transverse load distribution to examine whether varying the lateral position of the test wheels across the pavement might loosen or damage the pavers. There was, however, no evidence of this and lateral load distribution was therefore discontinued.

Trafficking began with Panels A and B with the ALF test load set to a 40 kN dual wheel. The trafficking history is summarized in Table 3 below.

Table 3. Axle Loads and Repetitions.

Test Panels	ALF Half Axle Load (kN)	Number of Axle Load Repetitions
A and B	40	75000
C and D	40	38000
	50	1500
	60	2350
	80	10550

The traffic applied to test panels A and B was typical of malls designed to CMAA minimum requirements of 20 commercial vehicles per day and a 10 year design life (Shackel and Pearson, 2000). This amount of traffic would also cover 20 year design traffic for all categories of street up to Collector Roads as set out in Table 13.7.3 of the AUSTROADS publication "Design of New Pavements for Light Traffic" published in 1998 (ARRB TR and Austroads, 1998). In the case of test Panels C and D the actual cumulative number of ALF load repetitions was smaller than for Panels A and B but 38% of all the repetitions were overloads.

Falling Weight Deflectometer Tests

Falling Weight Deflectometer (FWD) tests of the pavements were made prior to ALF trafficking. These results indicated mean deflections of 0.133 mm, 0.123 mm, 0.132 mm and 0.131 mm for Sections A, B, C and D respectively at 700 kPa. It is worth noting that such values of deflection are typical of heavy duty flexible asphalt pavements. This shows that the test pavements were not constructed to be exceptionally rigid and that significant pavement deflections would have occurred, particularly under the higher ALF loads. In this respect, pumping was observed at one contraction joint after rain under the 80 kN half axle ALF load. This pumping was also an indicator of pavement deflection. Overall, therefore, it can be argued that the support provided to the pavers by the slab, whilst adequate for the traffic carried, was not unrealistically high or unrepresentative of real pavements.

Pavement Performance Under Traffic

It had been anticipated that under traffic some distress might be caused to the pavers such as cracking or chipping. However, there was no damage caused to any or the pavers even at the highest axle load. Nevertheless, in places, there was some hairline cracking along the interface between the pavers and the grout filling the joints. However, the grout itself remained intact and there appeared to be no adverse consequences of this cracking.

There was no difference in performance between the different laying patterns or the different paver finishes. Nor was there any effect of paver thickness or bedding material. Within the limits of the tests all the pavements performed well. The sole difference, as noted below, was that pavers installed over mortar exhibited some evidence of incomplete bonding even before the commencement of trafficking.

The only observation of significance during trafficking was that a small number of pavers became "drummy" i.e. sounded hollow when tapped with a metal hammer. The drummy pavers were located both inside and outside the ALF wheel path and were unaffected by transverse distribution of the ALF wheels. Seven pavers were affected in this way in Panels A and B. In panel D seven pavers were reported to be drummy prior to the commencement of trafficking and one additional paver became drummy under traffic. The assessment of drumming was subjective but in all panels the degree of drumming was judged to have increased progressively under traffic. These results suggest that not all pavers were fully bonded during construction where mortar bedding was used and that some loss of bond may have occurred under traffic irrespective of the bedding type. For these reasons it would be inappropriate to assume that the pavers acted monolithically with the supporting slab. However, it is also important to note that none of the drummy pavers cracked under traffic.

DISCUSSION

In the tests reported here the flag pavers exhibited much better levels of performance than would have been predicted from previous experience of trafficked flag paving whether in Australia or Europe (Shackel and Pearson, 2001). The pavers were thinner relative to their plan dimensions than is currently considered necessary according to best practice recommendations in either Australia or Europe (e.g. 2). It is therefore appropriate to identify those factors by which the test pavements differed from current world norms. These can be listed as follows:

1. The pavers were fixed in place using proprietary adhesives or improved mortars having properties unlike those hitherto recommended for routine paving use either in Australia or overseas.
2. In contrast to most previous Australian practice, the paving complied with European recommendations that mortared pavements not be butt-jointed but rather incorporate grouted joints. These joints were filled with a proprietary jointing compound. Whilst some evidence of separation between the jointing compound and the pavers was observed there was no obvious damage to the joint material under traffic.
3. The pavers exhibited flexural strengths around 7.5 MPa that were significantly higher than those hitherto routinely manufactured by many Australian paver producers.
4. The pavements were fitted with expansion joints at spacings which were typically only about half those normally required. In this respect, it should be noted that the tests were conducted in the autumn and winter months and there was little exposure of the paving to thermal shock which, as noted below, can lead to delamination between the pavers and the mortar or base.
5. The pavements were kept free of traffic for a period of roughly 3 months before being opened to traffic. This would have been expected to produce a more complete development of strength and bond in the bedding than may routinely occur in mortared flag paving. However, removal and replacements of flags using Boral Rapid Set Adhesive showed that it was possible to traffic the pavements without incident after as little as 2 days curing.

IMPLICATIONS OF THE TESTS

The test pavements were designed primarily to evaluate the pavers and the bedding layers rather than the complete pavement structures. Accordingly the concrete slab base upon which the pavers were installed was, in itself, adequate to carry the full range of traffic loads and repetitions applied during the tests whilst still permitting significant deflections under traffic. Accordingly, the tests did not provide any direct measure of the structural effectiveness of the pavers but served rather to demonstrate the excellent in-service performance of the pavers combined with proprietary Boral bedding materials. For this reason, in deriving design principles for this new type of bonded paving it would be unwise to assign any structural value to the pavers or bedding on the basis of the data presented herein. Rather, it would be better to design pavements using the new surfacings on the basis that the underlying concrete slab will have adequate capacity to carry the predicted traffic by itself. In particular it would be imprudent to assume that the paving behaves monolithically – an assumption made erroneously by designers of some previous unsuccessful applications of mortared flag paving in Australia. In this respect, as noted above, drumming of several of the pavers was observed and that this increased slightly under traffic. Studies in the USA (Grimm, 1994) suggest that delamination between pavers and mortar bedding is inevitable over time because of dimensional changes caused by moisture and temperature variations. In other words, attempts to make the pavers, bedding and concrete base serve as a monolithic form of construction are unlikely to succeed in the long term. Based on these North American studies, even in well constructed pavements with mortared slab surfaces, a minimum failure rate of about 2% of the surface area is to be expected under pedestrian traffic alone (Grimm, 1994).

Based on the foregoing, the design of bonded paving using the system described here should consider the following principles:

1. The concrete base should be designed to take the full range of expected traffic loads and repetitions without assuming any structural contribution from the pavers, adhesive or bedding mix.
2. The pavers should be specified to achieve characteristic Breaking Loads and flexural strengths at least equal to those exhibited by the test pavers.
3. No attempt should be made to extrapolate the test results to pavers of greater plan dimensions or other thicknesses than those evaluated in the tests reported here.
4. The results should not be extrapolated to higher numbers of axle load repetitions than those actually applied during the ALF tests .i.e. the results of the tests should not be extrapolated beyond the domain of the experiments described here.
5. The results should not be extended to pavers, adhesives, paver grouts and or bedding mix improvers other than those products actually tested.
6. The quality of workmanship and materials should match those achieved in the construction of the test pavements

SUMMARY AND CONCLUSIONS

The Boral Stylestone bonded paving system achieved very much better levels of performance that would have been predicted on the basis of earlier experience of mortared pavers whether in Australia or overseas. Under traffic that first closely modeled actual road traffic including normal overloads and subsequently under traffic which applied severe overloading beyond that encountered in real traffic, no damage to the pavers was observed.

The levels of traffic applied in the trials modeled those expected in malls (Shackel and Pearson, 2000) and Minor and Local Access streets (ARRB TR and Austroads, 1998) and suggest that the new system can be successfully used in such trafficked applications. The system may, therefore, provide a viable alternative to the use of flags laid on sand bedding for pavements carrying traffic.

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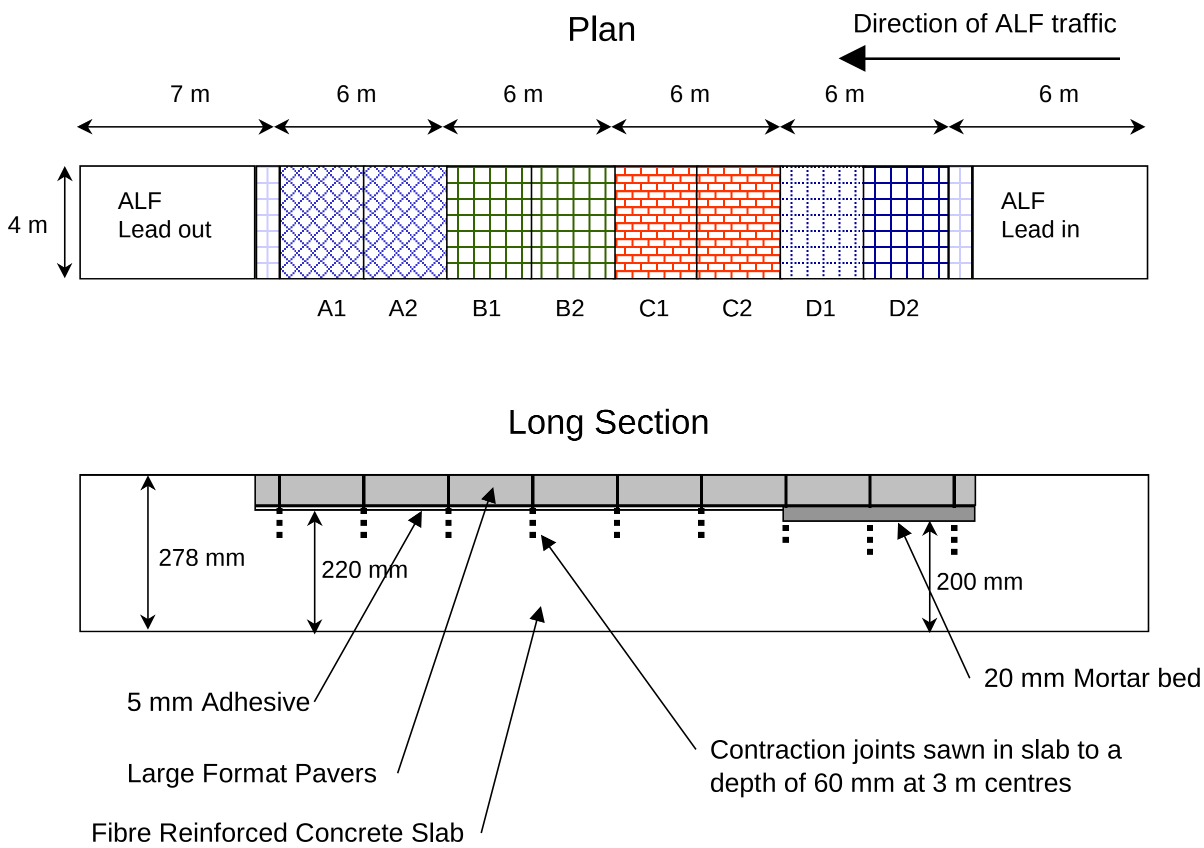
BIOGRAPHIES

Brian Shackel graduated in Civil Engineering from the University of Sheffield, Britain, in 1962 and immediately thereafter joined the Department of Main Roads, New South Wales. In 1964 he was appointed Shire Engineer to Central Darling Shire, NSW. He left municipal engineering in 1966 to accept a Teaching Fellowship at the University of New South Wales, and subsequently joined that university taking the degrees of M.Eng.Sc. and Ph.D. He has published more than one hundred research papers dealing with geomechanics and pavement engineering and has been invited to lecture on pavement design and construction in 23 countries worldwide. In addition, he has been retained as a consultant for a variety of road, airport and industrial pavement projects around the world. Professor Shackel's book "The Design and Construction of Interlocking Concrete Block Pavements" was published by Elsevier Science Publishers, London and New York, in 1990 and, has subsequently been republished in Japanese, German and Hungarian editions.

Richard Yeo

After graduating from Monash University in 1988, Richard Yeo joined consultants Maunsell Pty Ltd as a civil engineer. In 1990 Richard joined the Australian Road Research Board undertaking research in the areas of construction quality, pavement performance, accelerated pavement testing and overlay design. From 1995, Richard was seconded to the Victorian State road authority VicRoads as Development Engineer, Pavement Technology and was subsequently was appointed to this position by VicRoads in 1998. In this role Richard lead research projects in the areas of pavement surface characteristics, recycled materials, unbound materials and concrete roads as part of VicRoads, corporate R&D program. In 1999 Richard was appointed Co-ordinator Research and Development with VicRoads Corporate Planning Department. Richard was awarded his Master of Engineering degree by RMIT University in 2000. His thesis topic was "Construction Quality and Performance Tradeoffs for Local Roads". Richard Yeo rejoined ARRB Transport Research in 2001 as a Senior Engineer to lead a variety of projects in the Research and Information Group.



Panel	Large format paver construction details
A1, A2	53 mm thick pavers laid on 5 mm adhesive in stack bond at 45 degrees to direction of traffic
B1, B2	53 mm thick pavers laid in stack bond on 5 mm adhesive
C1, C2	53 mm thick pavers laid in stretcher bond on 5 mm adhesive
D1	53 mm thick pavers laid on 5 mm adhesive on a 20 mm mortar bedding mix in stack bond
D2	40 mm thick pavers laid on 5 mm adhesive on a 33 mm mortar bedding mix in stack bond

Figure 1. Layout of the Test Pavements