THE DESIGN OF CONCRETE FLAG PAVEMENTS

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ABSTRACT

Recently in Australia concrete flags in pedestrian surfacing have been rediscovered by landscape architects and specifiers. In many pavement situations the flags need to be able to withstand commercial vehicle loads and to combine structural properties with superior aesthetics and durability.

This paper reviews world practice in the use of concrete flags under traffic. The development of an Australian industry code of best practice for the design and use of concrete flags is then detailed. Following a comprehensive review of design methods for concrete flag pavements, it was decided to develop a new design procedure which incorporates mechanistic analysis. The new design method is presented as a series of design nomographs. The paper also emphasises the need to integrate specification and detailing with structural design.

1. INTRODUCTION

Large format pavers (ie typically 300 mm x 300 mm and greater in plan) or "Flags" have long been accepted, worldwide, as one of the most attractive and durable methods of pavement surfacing. Concrete flags first came into common use about 110 years ago in the UK, when they started to replace traditional stone flags, used at that time for surfacing prestigious pedestrian areas in urban footways. They rapidly gained in popularity because they were cheaper in both cost and construction, the latter savings resulting mainly from the dimensional accuracy of the concrete flags. In many countries, especially in Europe, such surfaces are now commonplace. However, in countries such as Australia, the high costs of manufacturing flag pavers by traditional wet-cast methods meant that the usage of flags was limited. However, with the introduction, during the last decade, of modern versatile paver manufacturing plant, flags have become economically competitive with other forms of paving and have been rediscovered by landscape architects and specifiers.

Concrete flags began to be used in major projects around Australia during the mid 1990's. At that time, there was no industry or national code of practice for the specification, design and detailing of flag pavements. The need for structural design recommendations was soon demonstrated when problems were encountered where the pavements carried vehicular traffic and a number of the pavements failed in service. Often the problem was due to a failure to properly anticipate the volumes and type of traffic to be carried. It therefore became clear that design and construction recommendations for flags carrying traffic were required.

Worldwide, the most common definition of a small element paver is that it should have a surface area of 0.1 m^2 or less. However, this definition embraces the most popular size of flag (300 x 300mm) and needs to be revised because experience shows that the behaviour of flags under traffic is different and indeed generally inferior to that shown by most small element pavers. For this reason flag pavements should not be designed using the same norms as CBP nor can similar levels of performance in service be reasonably expected.

This paper describes the development of design and construction guidelines for flag pavements and comprised

1. A survey of the practice, specifications and design recommendations current in Europe.
2. A review of the literature relevant to flag paving.
3. The development of design curves for flag pavements.

This work is now summarised.

2. SURVEY OF FLAG TECHNOLOGY

Recognising that there was more extensive and varied experience in the use of flags in Europe than elsewhere, the authors visited various European paving associations and flag manufacturers during 1998 and 1999. Countries visited included Britain (flag production of 14 million m^2 p.a.), Belgium (3.6 million m^2 p.a.), Germany, Austria, Denmark and Sweden. Some of the more important findings of these visits are now summarised.

2.1 Flag Properties.

In some countries the strengths required in flags are independent of their dimensions. For example, the Belgian standard specifies tensile strengths of 5 MPa for individual units with a mean value of 6 MPa and a breaking load greater than 5kN whilst in Scandinavia strengths are typically specified to be around 6 MPa. By contrast, in Britain, a more rational approach is adopted. Here the strength required varies according to the flag dimensions. This recognises that the stresses generated by traffic depend on both the plan dimensions and flag thickness and that, consequentially, different strengths are required for different flag sizes to avoid cracking in service.

There was general agreement that the performance of flags under traffic is related to their size. In Belgium it was reported that flags 400 x 400mm or 500 x 500mm break under traffic and that, to ensure good service, a maximum size of 300 x 300 mm was recommended. Pavers 200 x 200mm or 220 x 220 mm were said to be widely used. In Britain, the maximum flag size for trafficked pavements has been specified to be 450 x 450mm.

Opinions concerning the required thickness of flags vary widely. In Belgium and Scandinavia, the flag thickness for trafficked pavements is generally required to be 80mm. In Britain the minimum flag thickness depend on the plan dimensions but is required to be within the range from 60mm to 70mm for trafficked pavements. In many places, including Britain and Belgium, there were widely expressed opinions that a minimum flag thickness of 100mm might be warranted under bus or heavy truck traffic. In Germany and Austria much greater thicknesses, up to about 180mm, are routinely specified. Such flags are too heavy to

be installed by hand and require specialised laying equipment. Since this equipment is not available in Australia, it was decided to restrict the flags to be covered by the Australia design guide to those capable of hand laying. This implied a maximum flag size of 450 x 450 x 70mm.

2.2 Construction Practice

There was wide agreement that flags laid on mortar beds are only suitable for pedestrian applications with the added proviso that the joint widths should be at least 8mm (Belgium) or 5 to 10mm (Britain). For trafficked pavements most authorities preferred flags laid with narrow joints on sand. Here much closer grading tolerances are specified than those typical for small element pavers with strict limits imposed on the fines. In Belgium the maximum amount passing 75 μm is specified to be less than 5 to 6% whilst in Britain the limit is set at 3% with some authorities recommending just 1.5%. This is to minimise sand migration should the flags rock under traffic.

2.3 Research

Except in Holland and Britain little research has been undertaken into the in-service performance of flags. Tests of flags were conducted by the Delft Technical University in the 1980s [1,2]. These pavements were laid on sand bases and showed that such pavements are not suitable for traffic. In Britain, tests have been conducted by the Transport Research Laboratory , TRL, [3]. These tests complement theoretical studies at the University of Newcastle-upon-Tyne by Bull [4].

2.4 Design Guides

In Europe most design recommendations for flags are *ad-hoc* and largely unproven modifications of small element pavement design procedures. Britain provides an exception to this practice. Here two conflicting design guides have been published. First, the Precast Concrete Paving and Kerb Association (PCPKA) published design guides in 1989 and 1991 based on Bull's theoretical analyses [5,6]. Some authoritative commentators, such as Allan Lilley, have said that these design procedures are conservative. Later, TRL produced a design guide for footpaths subject to occasional truck over-runs [7]. This appears to be more soundly based than the PCPKA procedure and claims to have been verified by trafficking tests [3]. In the authors' view, whilst both of these guides have technical merits, their lack of consistency makes them unsuitable for adoption elsewhere. For this reason, the authors have developed a new design procedure which incorporates some of the technical features of both British methods. This has also been made consistent with established, well-proven, mechanistic design methodology for segmental pavements.

3. SCOPE AND PRINCIPLES OF THE DESIGN PROCEDURE

3.1 Traffic

A flow chart for the new design procedure is given in Figure 1. From this figure it may be seen that the principal factor determining the design choices is the presence or absence of vehicles, the type of vehicles and the traffic volumes over the design life of the pavement. In this respect experience, worldwide, has shown that flags are not suitable for pavements

carrying high traffic volumes. The most common applications of flags are malls, precincts and vehicle crossings. Such pavements can be classified as being subject only to pedestrian traffic, to a combination of pedestrians and light vehicles or to a combination of pedestrians, light vehicles and commercial vehicles. Light vehicles when fully loaded are assumed to have a gross weight less than 3 tonnes. This category includes cars, utilities, delivery vans and some light 2-axle trucks. Commercial vehicles (cv's) are defined as vehicles having a gross weight of 3 tonnes or more and which comply with legislation for the axle loads, tyre pressures and dimensions of normal on-road vehicles. This vehicle category principally comprises 2 and 3 axle trucks. Trucks having 5 axles or more are assumed not to total more than 5% of the commercial vehicles. Where data on the gross weights of the vehicles to be carried on the pavement are not available then all vehicles fitted with dual tyres and all trucks are classed as commercial vehicles.

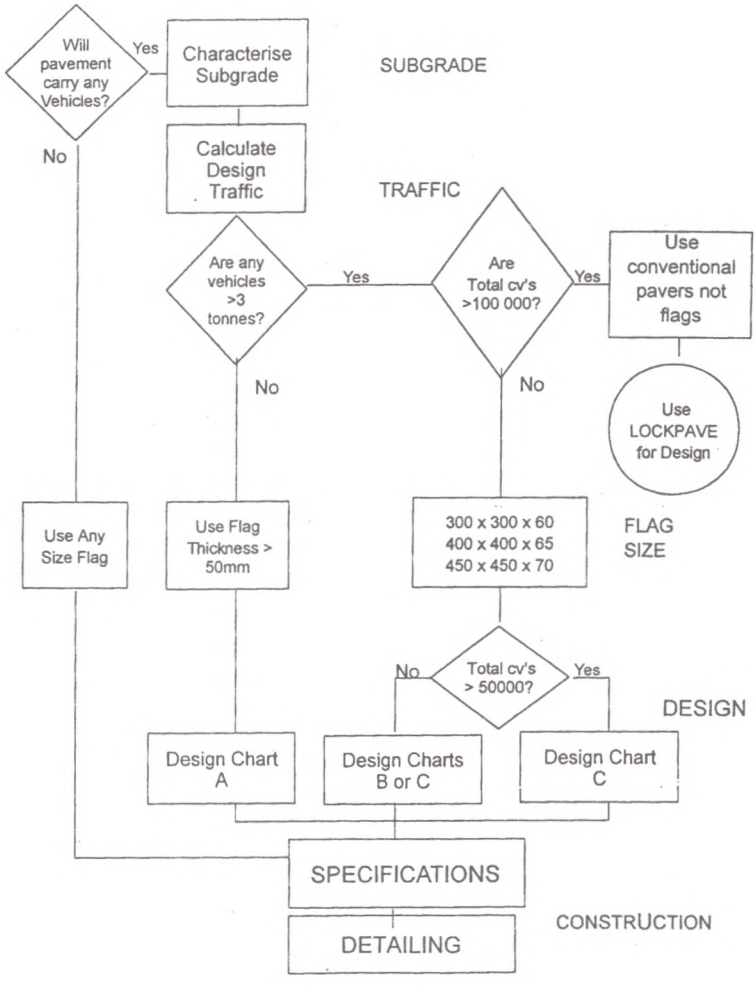

Figure 1. Flow chart for the pavement design process.

Traffic volumes depend on the design period and the design traffic. The design period of the pavement, P, is the period in years for which the pavement is planned to serve without renewal or relaying. Typical design periods range between 10 and 20 years.

For pedestrian precincts and malls the design traffic should be calculated for locations in which the traffic is concentrated e.g. entry points from the neighbouring street system.

a) *Light Vehicles* The number of light vehicles is estimated for the Design Period. This should include all vehicles having a gross weight < 3 tonnes including cars, vans and light trucks. This is then the Design Traffic.

b) *Commercial Vehicles* The Average Annual Daily Traffic (AADT) in one direction and the percentage of commercial vehicles, C (%), can be obtained from traffic surveys. The Design Traffic is then given by

$$\text{Design Traffic} = \text{AADT} \times L \times 365 \times G \times C / 100 \qquad (1)$$

Here G is a growth factor that reflects the expected percent annual increase in traffic, i, (if any) and is given by

$$G = [(1 + i/100)^P - 1]/(i/100) \qquad (2)$$

NB. Where there is no expected traffic growth (i=0) then G=P

L is a Lane or Distribution factor reflecting the distribution of traffic across the pavement. For pedestrian precincts and malls it is assumed that L=1.0 at entrances and where the traffic is channelised. Elsewhere, values of L between 0.65 and 1.0 can be assumed depending on the traffic distribution. For streets, the Lane Factor, L, shall be chosen from Table 1 as follows:

Table 1. Lane Distribution Factors

No. of lanes in each direction	Minimum Lane Factor L
1	1
2	0.85
3 or more	0.65

Where the Average Annual Daily Traffic, AADT, is not available then an estimate of the number of commercial vehicles can be based on Table 2.

Table 2. Minimum Number of Commercial Vehicles.

APPLICATION	No. of cv's per day
Residential	1
Shopping areas	10
Malls & Precincts	20

The number of cv's indicated by Table 2 is the absolute minimum number for which a flag pavement should be designed even if traffic counts predict lower vehicle movements. However, Table 2 is no substitute for accurate traffic data. The lane distribution factor, L, should not be applied to any traffic estimate based on Table 2.

If the Design Traffic given by equation 1 exceeds 100 000 commercial vehicles then the use of concrete flags is not appropriate and conventional small element concrete segmental pavers each having a gross plan area of less than 0.09 m^2 should be selected. In such cases, the pavements should be designed using the Design Guide for Residential Accessways and Roads, T45, 1997 or the LOCKPAVE computer program [8].

Having defined the traffic, the design procedure then follows well-established mechanistic principles. Essentially, mechanistic procedures attempt to predict the in-service behavior of a pavement and to design each pavement element to achieve satisfactory performance throughout the planned life of the pavement. For flag pavements the problem is twofold:

1. To specify the flag dimensions and strengths so that they will not crack under traffic.
2. To choose a suitable type and thickness of basecourse to support the flags for the predicted traffic intensity.

3.2 Choice of Flag

It was decided to restrict the design guide to the use of square flags only. This made it possible to use the theoretical analyses developed by Bull and published by PCPKA [5,6] to determine the relationships between slab dimensions and the strength needed to resist vehicle loads. Here the plan dimensions, thickness and tensile strength of a flag were chosen in combination to ensure that the flag would not crack under traffic. The flag sizes were a subset of those covered by British Standard 7263, 1994. For these flag sizes and for the traffic loads and intensities covered by the design guide the theoretical values of flexural strength needed to prevent cracking were calculated. This were expressed as Characteristic Breaking Loads and had values slightly slightly less than those set out in BS 7263. Accordingly, it was decided conservatively to adopt the British values in the new guide. These are set out in Table 3. Other flag properties were selected to be consistent with the Australian/New Zealand Standards for pavers.

Table 3. Flag Properties

Application	Vehicle Traffic	Nominal Size (mm)	Thickness (mm)	Characteristic Breaking Load (kN)
Pedestrian Pavements	Nil	Any	Any	5
Pedestrian and Light Vehicles Only (LV)	LV Only	Any up to 450 x 450	50	8
Pedestrian & Commercial Vehicles (cv), Streets	< 100,000 cv's	300 x 300 400 x 400 450 x 450	55 65 70	13.8 15.5 18.8
AS/NZ Standard	NA	NA	NA	4456.5

Concrete flags are required to comply with the minimum strengths set out in Table 3 for all categories of use. In the case of dimensions, no restriction is placed on the flag dimensions for pavements subject to purely pedestrian traffic but for pavements carrying light vehicles a minimum thickness of 50 mm is required. For pavements carrying commercial vehicles restrictions are placed on both the plan dimensions and minimum thicknesses. Deviation from these dimensions is not permitted where commercial vehicles are to be carried. The tolerances on flag dimensions are required to be in accordance with AS/NZ 4456.3.

3.3 Choice of Basecourse Type and Thickness

Both unbound granular materials such as crushed rock and cement-bound materials are commonly used under flags. The design procedure permits the use of both of these materials up to traffic levels of 50000 cv's. For higher traffic intensities only cement-bound base is recommended. Analyses similar to those used in the LOCKPAVE design procedure were used to calculate the thickness of basecourse required to support the flags. This required that the flag surface be modeled by an appropriate modulus. Conservatively, a modulus value of just 400 MPa was adopted based on accelerated trafficking tests of flags conducted in Britain at TRL [3]. Using this value it was possible to compute the thickness of granular base necessary to prevent unacceptable rutting in the trafficked pavement or, alternatively, to calculate the thickness of cement-stabilised material to avoid fatigue cracking in the base. These thicknesses are presented as functions of the traffic volumes and subgrade strengths in Figures 2, 3 and 4. For light vehicles the theoretical thicknesses of bound and unbound base were found to be similar and, for simplicity, the thicknesses plotted in Figure 2 are envelopes of those for both bound and unbound base materials.

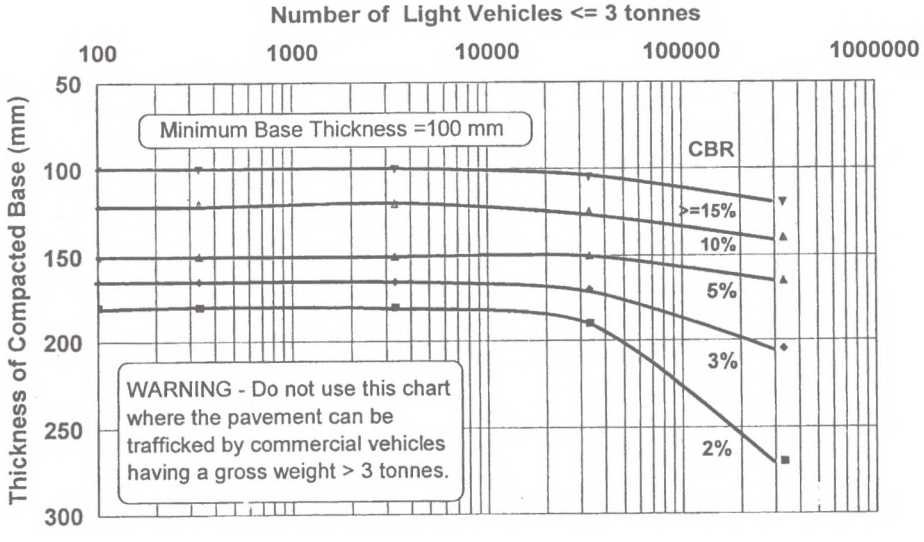

Figure 2. Design Chart A for pavements carrying light vehicles (<3 tonnes) only

Where the pavement is to carry commercial vehicles the subgrade strength is expressed as a representative soaked CBR value based on laboratory tests. For pedestrian areas and pavements subject only to light traffic the CBR may also be estimated from soil classification data or by selecting presumptive values from Table 4.

Table 4 Presumptive Subgrade Strengths

Soil Type	Unified Soil Classification	Presumptive Subgrade CBR (%)
Gravel	GP, GW, GM	20%
Sand	SM, SW, SP	10%
Silt – well drained	ML	5%
Silt – poorly drained	ML	2%
Sandy clay – well drained	SC	6%
Sandy clay – poorly drained	SC	2%
Highly plastic clay – well drained	CH	5%
Highly plastic clay – poorly drained	CH	2%

Where the subgrade CBR is less than 4% the use of a select subgrade material (capping layer) or subgrade stabilisation with lime and/or cement is required.

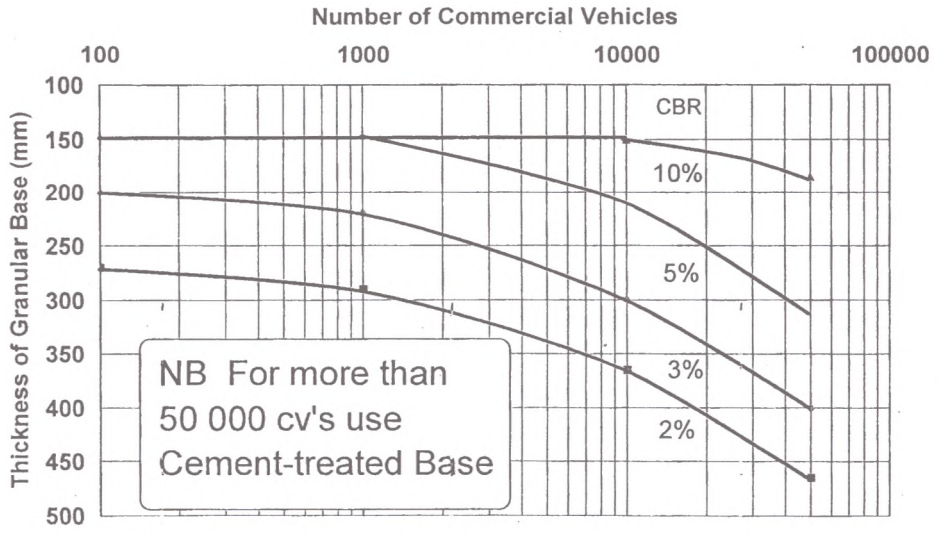

Figure 3. Design Chart B for Granular Base pavements carrying Commercial Vehicles

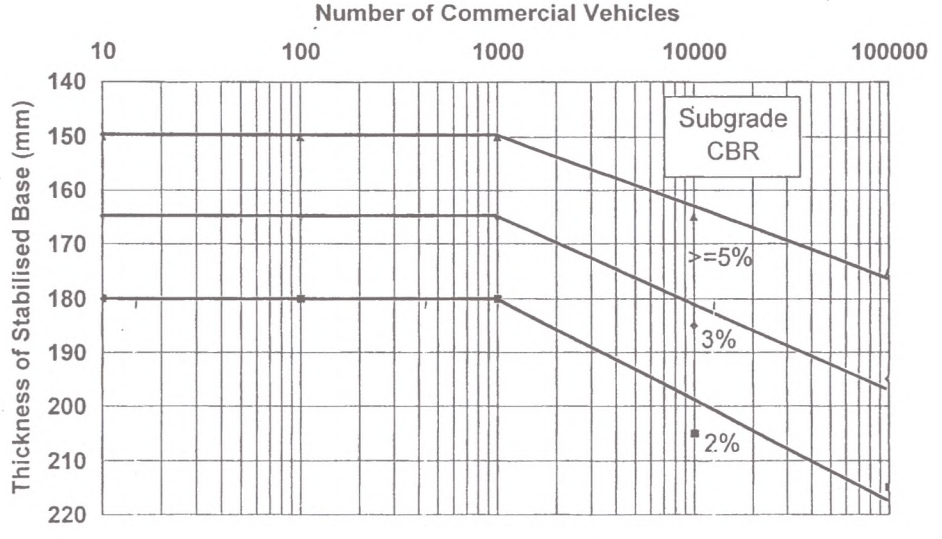

Figure 4. Design Chart C for Stabilised pavements carrying Commercial Vehicles

4. SPECIFICATION AND DETAILING

From Figure 1 it will be seen that the final stages in design are specification and detailing. This is because experience has shown that more projects fail because of poor execution than because of poor design. For this reason, specification and detailing should be considered an integral part of the design process. In particular, care should be given to specifying the pavement materials. In the new guide both the bound and unbound basecourse materials are specified to be of identical quality to those required under small element pavers. Details are given elsewhere [9]. Care must also be given to the placement of these materials as inadequate compaction has historically been a source of failure in segmental pavements. Specifically, the base should be compacted to not less than 98% of modified maximum dry density to AS 1289 for granular base and to not less than 96% of modified maximum dry density for cement-stabilised base.

Following European practice, the normal bedding course requirements for segmental paving have been made more stringent where flags are to be used. For particle sizes of 150 μm or more the grading are based on well-proven grading requirements for concrete block pavements [9,10]. However, where the pavement is to carry commercial vehicle traffic, the proportion of material smaller than 0.075 mm is required not to exceed 2%. This has been chosen to lie within the range recommended in Britain (see above). Noting that, in Europe, considerable emphasis was placed on the need for good drainage of flag pavements, adequate provision for draining the bedding sand is also a key requirement.

In terms of detailing, the new design procedure builds on "T46-Concrete Segmental Pavements – Detailing Guide" published by the Concrete Masonry Association of Australia. Some notable features include the requirement that lipping between adjacent flags to be below 3mm and that joint widths lie within the range 2 to 4mm. Flags may be laid in either stack or stretcher bond. These are required to be orientated so that the continuous joint lines run across rather than along the direction of trafficking and so that any cut flags are placed away from trafficked areas. Details are provided for edge restraints, vehicle crossings, manholes and other surface intrusions and for drainage.

5. CONCLUDING COMMENTS

Experience has shown that many problems in flag pavements stem from a failure of designers to properly consider the effects of traffic. In reality, few pavements are completely free of traffic. For this reason a central feature of the new design method has been to ensure that the designer is required to confront traffic considerations at an early stage of design and to identify whether the traffic comprises light or commercial vehicles. A well-proven mechanistic procedure that has been used for nearly 15 years in the design of CBP has been combined with theoretical studies and trafficking test data from Europe to produce new design curves. Minimum requirements for assumed traffic volumes have been specified and restrictions on the size and strength of the flags and the types of basecourse material have been imposed depending on the traffic volumes. These restrictions are intended to lead to conservative design. The need for good specifications that are sometimes stricter than those customarily used for CBP has been strongly emphasised. Overall, however, it should not be forgotten that flags can never provide the levels of performance that are now routinely

expected from small element CBP. Accordingly flags must be used with caution where traffic is to be carried.

6. ACKNOWLEDGEMENTS

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