A **cement** and **concrete** industry publication

Technical Report No. 66

External In-situ Concrete Paving

Report of a Concrete Society Working Group

TR66 EXTERNAL IN-SITU CONCRETE PAVING, 2007

Amendment No.1 January 2009

Page 11

Paragraph 4, line 3: *Delete*: "This can be relaxed if a B-type fabric is being used."

Page 18, Table 4

Delete: "Wear factor, *W"*
Substitute: "Wear factor, *VWF"*

Delete: "Weighted annual traffic for category (52*x *F* x *D* x *G* x *W* x 10-6)"
Substitute: "Weighted annual traffic for category (52*x *F* x *D* x *G* x *VWF* x 10^{-6})"

Delete: "Design traffic $(Y) \times (G) \times (AT)$ msa"
Substitute: "Design traffic $(Y) \times (AT)$ msa"

Page 25, Table 8

Heading *Delete* "Infrequent Loading"
Substitute "Infrequent loading on pavement edge"

Page 26, Table 9

Heading *Delete* "Infrequent Loading"
Substitute "Infrequent loading on pavement edge"

Page 27, Table 10

Heading *Delete* "Frequent Loading"
Substitute "Frequent loading on pavement edge"

Page 28, Table 11

Heading *Delete* "Frequent Loading"
Substitute "Frequent loading on pavement edge"

Page 37, Unreinforced and conventionally reinforced concrete

Paragraph 1, line 1: *Delete* "and Figure 13"

Paragraph 1, line 4: *Delete* "reinforcement".
S*ubstitute* "fabric (e.g. A142, A193, A252)

Delete "4m"
Substitute "7m"

Paragraph 1, line 5: *Delete* "third joint".
S*ubstitute* "second joint"

Page 37, Figure 13

Delete

Note. Although this Figure and Road Note 29 etc is the basis of Table 13, its presence in TR66 has been found to be confusing to readers.

Page 39, Table 13

Column 1 text row 1	*Delete* "EPRO unreinforced" *Substitute* "EPRO, no fabric"
Column 1 text row 2	*Delete* "EPRO unreinforced" *Substitute* "EPRO, no fabric"
Column 1 text row 3	*Delete* "EPRO reinforced" *Substitute* "EPRO, with fabric"

Acknowledgements

The work of preparing this report was funded by the following organisations:

Adfil	**HBG Construction Ltd**
A J Clark Concrete Flooring	**Interserve Project Services Ltd**
Bekart Building Products	**Jacobs Babtie**
BRC Weldgrip	**Kent Wire (Ispat) Ltd**
Burks Green	**Kier Engineering Services**
Cameron Taylor Bedford	**O'Keefe**
Carillion (formerly Mowlem Building)	**ProLogis Developments Ltd**
Celsa Steel	**Scott Wilson Pavement Engineering Ltd**
Cement Admixtures Association	**Shepherd Construction**
Civil and Marine Holdings	**Somero Enterprises Ltd**
Elasto Plastic Concrete (Europe) Ltd	**Twintec Industrial Flooring**
Fosseway Flooring Systems Ltd	**Wates Construction Ltd**
Galliford Try	**White Young Green**
Gazeley Properties Ltd	**Winvic**

The Concrete Society is grateful to the following for providing photographs for inclusion in the report:

Front cover:	**ProLogis Developments Ltd**
Figure 15:	**American Concrete Pavement Association**

Published by The Concrete Society

CCIP-023
Published August 2007
ISBN 1-904482-37-6

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CCIP publications are produced by **The Concrete Society** (www.concrete.org.uk) on behalf of the Cement and Concrete Industry Publications Forum – an industry initiative to publish technical guidance in support of concrete design and construction.

CCIP publications are available from the Concrete Bookshop at **www.concretebookshop.com**
Tel: +44 (0)7004 607777

Cover photo: ProLogis Swindon, 350,000 sq ft.

Printed by Alden Press, Witney, UK.

External In-situ Concrete Paving

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Glossary of Terms

Abrasion – Wearing away of the concrete surface by rubbing, rolling, sliding, cutting or impact forces.

Aggregate interlock – Mechanism that transfers load across a crack (or induced joint) in concrete by means of interlocking, irregular aggregate and mortar surfaces on each side of the crack.

Armoured joint – Joint with steel protection to arrises.

Aspect ratio – The ratio of length to breadth of a bay.

Bay – A region of a slab surrounded by joints and with no internal joints.

Bump cutting – The process of using a straight edge to remove high spots when levelling the surface of a slab during construction.

Capping layer – Layer on top of the subgrade to improve its performance, particularly under construction traffic loading. Not always present – only required on low-quality subgrades.

CBGM – Cement-bound granular material; may be used as a sub-base.

CBR – California Bearing Ratio – a measure of the load-bearing capacity of the sub-base or subgrade.

Client – The party who commissions the development and employs the main contractor to manage the construction of the development.

Contractor – See *Main Contractor* and *Paving Contractor.*

Crazing – Pattern of fine, shallow, random cracks on the surface of concrete.

Curling – Local rise at the edges of a slab due to differential drying shrinkage between the top and bottom surfaces.

Datum – A reference point, line or plane used on drawings and in surveying.

Delamination – Debonding of a thin layer of surface concrete.

Designer – See *Scheme Designer* and *Paving Designer.*

Development – The scheme or project that includes the construction of areas of external in-situ concrete paving.

Dominant joint – A joint that opens more widely than adjacent (dormant) joints in a slab with sawn joints.

Dormant joint – Sawn joint that does not open, usually because of failure of the crack to form below the saw cut; there is usually an associated dominant joint which accommodates most of the movement.

Dowel – Round or square steel bar or proprietary device used to transfer loads from one slab to the next across a joint; used to minimise differential vertical movement, while permitting differential horizontal movement.

Elevational difference – The difference in height between two points.

Equivalent surface foundation modulus – The modulus of a uniform foundation giving the same support to a slab as the actual foundation.

Fabric reinforcement – Reinforcement consisting of a prefabricated grid of bars generally spot-welded together at their intersections.

Flatness – Surface regularity of a slab over short distances, typically 300 mm.

Formed joint – Joint constructed using formwork.

FRC – Fibre-reinforced concrete. Fibres may be of steel or polymer (known as synthetic). Synthetic fibres may be macro or micro.

Free-movement joint – Joint designed to provide a minimum of restraint to relative horizontal movements caused by drying shrinkage and temperature changes in a slab, while restricting relative vertical movement.

HBM – Cement or other hydraulically bound mixture; may be used as a sub-base.

Induced joint – A joint made in the pavement by reducing the concrete section along the joint line either at the time of casting or shortly afterwards. The most usual method of producing the joint is by sawing through part of the slab depth. Alternatively, formers can be placed on the sub-base or membrane, or inserts can be pushed into the surface of fresh concrete.

Isolation detail – Detail whose aim is to minimise any restraint to a slab from fixed elements such as columns, walls, bases or pits at the edge of or within a slab.

Joint – Vertical discontinuity provided in a slab to allow for construction and/or relief of stresses. The terminology relating to various types of joint is not straightforward and reference should be made to the descriptions of individual joint types.

Large-area construction – Laying of a slab with an area of several thousand square metres in a continuous operation.

Levelness – Surface regularity over longer distance (c.f. flatness), typically 3 m, and to datum.

Load transfer capacity – The load-carrying capacity of a joint in shear.

Long strip construction – Laying of a slab in strips.

Main Contractor – The contractor employed by the client to manage the construction of the development.

MHE – Materials handling equipment.

Modulus of subgrade reaction – Measure of the stiffness of the subgrade; load per unit area causing unit deflection.

Movement accommodation factor (MAF) – The change in width which a movement joint sealant can accept in service expressed as a percentage of its original width.

Operator – The party who operates the development, and hence paving, after completion. Note the operator may not be the client and/or owner. There could be several operators in the lifetime of the paving.

Owner – The party who owns the development after it is completed. Note the owner may not be the client or operator. There may be more than one owner in the lifetime of the paving.

Panel – Sometimes same as bay but can also mean the area of a slab bounded by formed joints.

Paving or Pavement – The full construction depth of: slab; polythene membrane (if required); sub-base; capping layer (if required); and any improved subgrade material.

Paving or Pavement Contractor – The contractor or subcontractor who undertakes the actual construction of the paving.

Paving or Pavement Designer – The designer who undertakes the detailed design of the slab or paving. This may be the Scheme Designer, or it could be a specialist designer employed by the Main Contractor or the Paving Contractor.

Point load – Concentrated load from a base plate or wheel.

Power finishing – Use of machines for floating and trowelling slab surfaces.

Remedial grinding – The process of removing regions of a slab surface by abrasive grinding of the hardened concrete usually in order to achieve the required surface regularity.

Remedial texturing – The process of obtaining an improved surface texture where the correct finish has not been achieved (often because of rain damage) or where the surface texture has been removed by traffic.

Restrained-movement joint – Joint designed to allow limited movement to relieve shrinkage-induced stresses in a slab at predetermined positions.

Sawn joint – Joint in slab where a saw cut is provided to induce cracking.

Scheme Designer – The designer employed by the client or, in the case of design-and-build contracts, the main contractor, responsible for the overall architectural and structural design of the development.

Sealant – Polymeric material installed in a recess in the slab surface above a joint. The objective of the sealant is to prevent detrital material from entering the joint while permitting relative movement between the concrete on either side of the joint. Joint sealants have limited life and need to be replaced.

Slab – Structural concrete element forming the top layer of the paving which is finished to provide a wearing surface.

Slip membrane – Plastic sheet laid on the sub-base before concrete is placed, to reduce the friction between slab and sub-base. Note: other forms of membrane are sometimes used for other requirements, e.g. to contain spillage or leakage.

Slip/Skid Resistance – The ability of a slab surface to resist slipping or skidding by foot or vehicular traffic.

Specific development – A development initially commissioned by a client for a specific user. Note the client may not be the owner or operator.

Speculative development – A development commissioned by a client where the user is not known at the time of commissioning and/or construction. The client may sell a speculative development to a new owner before the operator is known.

Standard axle – Reference loading used for thickness design taken as 10.5 t based on a minimum of five axles and a gross vehicle weight of 38 t.

Sub-base – Layer (or layers) of granular or cement-bound material constructed on top of the subgrade (or capping layer, where provided). As well as contributing to the performance of the paving, the sub-base layer is also required to act as a temporary construction platform.

Subgrade – The upper strata of the soil or rock under a slab and sub-base to which all of the vertical loading is transferred.

Surface regularity – Generic term to describe the departure of a wearing surface from a theoretical perfect plane.

Tang – Shear stud or other fitting on an armoured joint to provide bond to the adjacent concrete.

Tied joint – Joint in a slab provided to facilitate a break in construction at a point other than a free-movement joint; sufficient reinforcement runs through the joint to prevent movement.

Tolerance – Permitted dimensional or level construction variation.

Wearing surface – The top surface of a slab or applied finish on which the traffic runs.

List of Figures

List of Tables

Notation

A_S	area of reinforcement
AT	total weighted annual traffic
D	number of days a facility is in use per year
$f_{cm,cube}$	concrete mean cube compressive strength
F	percentage of failed pavement bays at end of life
F_j	present traffic per day of commercial vehicle class j
G_j	growth factor for commercial vehicle class j
h	slab thickness
k_{762}	modulus of subgrade reaction measured using a 762mm diameter plate
k_D	modulus of subgrade reaction measured using a plate of *D*mm diameter
L	traffic loading over the lifetime of the pavement in millions of standard axles
M	equivalent modulus of a uniform foundation giving the same slab support as the actual foundation
$R_{e,3}$	equivalent flexural strength ratio
T	design traffic loading in millions of standard axles
VWF_j	vehicle wear factor for commercial vehicle class j
Y	design period in years

Abbreviations

ACI	American Concrete Institute
BCA	British Cement Association
BRE	Building Research Establishment
Britpave	British In-situ Concrete Paving Association
BS	British Standard
CBGM	Cement-bound granular material
CBR	California Bearing Ratio
CIRIA	Construction Industry Research and Information Association
DEFRA	Department for Environment, Food and Rural Affairs
EPR	External paving reinforcement
EPSB	External paving sub-base
EPT	External paving traffic
FRC	Fibre-reinforced concrete
ggbs	Ground granulated blastfurnace slag
HA	Highways Agency
HBM	Hydraulically bound material
HGV	Heavy goods vehicle
H&S	Health and safety
JSCE	Japan Society of Civil Engineers
MAF	Movement accommodation factor
MCHW	Manual of Contract Documents for Highway Works
MHE	Materials handling equipment
pfa	Pulverised fuel ash (fly ash)
PTR	Pneumatically tyred roller
RCC	Roller-compacted concrete
SuDS	Sustainable drainage systems
TR	Technical report
TRL	Transport Research Laboratory
UK CARES	Product certification scheme for reinforcement for concrete
XC1, XC2, XC3 and XC4	BS 8500 exposure classes for corrosion of reinforcement associated with carbonation
XD1, XD2 and XD3	BS 8500 exposure classes for corrosion of reinforcement associated with de-icing salts
XF1, XF2, XF3 and XF4	BS 8500 freeze–thaw exposure classes

1. Introduction

Large distribution centres and retail developments have become familiar features of the suburban landscape. Most towns have industrial estates, retail parks and supermarkets within and around them. Each one of these has an associated area of distribution roads, parking and delivery areas and hardstandings. This being the case, it is surprising that there is little guidance on the design and construction of these paved areas. This Technical Report is aimed at filling the gap. In some respects it is a natural extension to the extremely successful Concrete Society Technical Report 34 *Concrete industrial ground floors*,[1] which deals with internal floor slabs.

1.1 General

From many points of view, concrete is the ideal material for the construction of parking and working areas around buildings. The rigidity of concrete enables it to spread imposed loads over a sufficiently large area of the underlying soil so that any deflections are small. It provides a hard-wearing surface which drains well at low gradients and can be textured to provide skid resistance. Concrete resists spillages of diesel and other petroleum-based products. Concrete slabs also resist indentation by the dolly wheels or pads on the front legs of lorry trailers. Concrete is relatively light in colour and hence concrete parking areas are easy to illuminate. However, the light appearance also means that care has to be taken in choosing appropriate colours for lines and signs applied to the surface.

Although there are many common factors in the design and construction of internal and external slabs there are also some significant differences, some of which are listed below.

Surface regularity

Many warehouses require very tight control on the flatness and levelness of their internal floor slabs because of the operational requirements of materials handling equipment used in high racking systems. External paved areas do not require the same degree of control.

Surface finish

Many internal floors are finished by power floating and trowelling to provide a flat, smooth, hard-wearing surface suitable for vehicles with small, hard wheels. External slabs often require a textured finish that is both appropriate to vehicles with pneumatic tyres and also suitable for pedestrians.

Services

Internal floors are generally laid level. External slabs require falls and incorporation of drainage; there may also be the need to provide lighting, street furniture and routes for other services.

Loadings

Many internal floors experience high point loads from racking systems. Although there may be high point loads from parked trailers on external paving, most areas experience less intense loading from parked vehicles. Distributor roads and other areas around distribution centres and warehouses have to be designed for the frequent passage of vehicles with high axle loads and fatigue becomes an issue.

Exposure conditions

External pavements are subjected to a greater daily and annual temperature change than internal slabs in a controlled environment. External pavements are also subject to rain, frost, de-icing salts and freeze–thaw effects. The possibility of rainwater ingress to the underlying strata is not generally an issue for internal floor slabs.

Highways

There are also significant differences between paving around retail, commercial and industrial developments and highway pavements. Highway pavements experience the actions of a wide variety of vehicles which are converted for design purposes to a standard axle. Many of the paved areas of the type covered by this report are likely to experience the actions of specific types of vehicle. Even where large retail and other similar developments require provision of access and parking for both light vehicles used by the public and heavy delivery trucks, these are likely to be segregated on the actual site and there will be few, if any, areas that experience traffic from both types of vehicle. In most cases, wheel tracks from heavy goods vehicles will be much less channellised than is the case on highways.

Large areas of paving around retail developments serve only cars and similar light vehicles. This being the case, the design thickness is likely to be influenced more by practical limitations than the stresses imposed by the vehicles on the pavement or subgrade.

Another significant difference is the method of construction. Most concrete highway pavements are slipformed whereas many hardstandings are constructed by manual methods.

1.2 Scope

This report covers the design, detailing, materials and construction methods for hardstandings adjacent to industrial and commercial developments constructed from in-situ concrete. Block paving is not included as there is adequate guidance in other publications.[2,3] Rigid semi-flexible pavements of resin-modified asphalt, e.g. Densiphalt, are also outside the scope of this report. Major developments such as warehouses, storage facilities, shopping malls, bus depots and distribution centres are included, as are smaller developments such as workshops and sports and recreation facilities. The main application is to open car and lorry parks and roads which are integral with the external paving scheme. Refuelling and wash-down areas are also included.

Design and construction of unreinforced and conventionally reinforced concrete external slabs are within the scope. Although there are many examples of concrete external slabs reinforced with steel fibres and macro-synthetic fibres using design approaches based on Concrete Society Technical Report 34[1] and a Dutch CUR[4] report, there is, as yet, no consensus on design methods, and so design with these materials has not been included specifically. The Concrete Society has published guidance on the use of both steel-fibre-reinforced[5] and macro-synthetic-fibre-reinforced[6] concrete.

The loading range considered is from cars to the higher end of the heavy goods vehicle (HGV) range, i.e. a five-axle articulated lorry with a typical maximum axle load of approximately 105kN. The design method and tabulated values could be used for higher axle loads provided they can be converted into standard axles, i.e. an axle that exerts a force of 80kN.

Traditional and more modern methods of construction are described. Laser Screed techniques, large-area pours and the possibility of slipforming or roller-compacted concrete with or without surfacing may need to be considered where rapid forms of construction are dictated by the overall construction programme. The possibilities of using non-structural surfacing material are discussed.

Reference is also made to environmental considerations in terms of design to minimise the environmental impact. There is a short, but nonetheless very important, section on sustainability.

The important topics of inspection, evaluation and routine maintenance are covered.

This report does not cover internal floors (see Concrete Society Technical Report 34[1]), separate access roads which are not integral with the main paved area, roads that will be adopted by highway authorities (see Highways Agency *Design Manual for Roads and Bridges*,[7]) paving for ports or container yards, paving for airfield runways or aprons or paving subject to heavy military loading such as tanks, heavy armoured or tracked vehicles.

1.3 Terminology

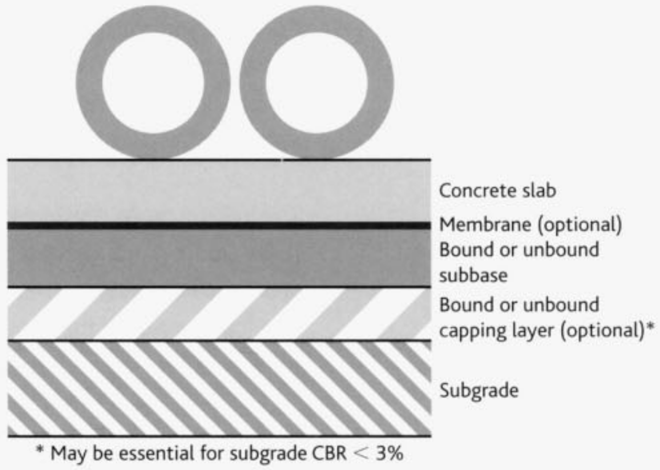
The sequence of layers which makes up a typical hardstanding is shown in Figure 1. A capping layer may be provided in some cases where the subgrade is poor (California Bearing Ratio (CBR) < 3%) and could deteriorate under the action of construction traffic.

Key terms and abbreviations encountered in paving are given in Glossary of Terms.

1.4 Operator's requirements

It is essential for the designer to gain a clear understanding of the client's or operator's expectations at an early stage in the design process. In broad terms, these can be summarised as the provision of a structurally adequate, drained, illuminated, demarcated, neat, clean, easily maintainable all-weather surface for the parking and manoeuvring of vehicles. It follows from these broad requirements that the pavement

Figure 1
Layers in a typical hardstanding.



should protect the underlying soils by distributing vehicle loads so that the stresses imposed on the subgrade are within acceptable limits and that the constructed pavement does not deform or settle.

The information required by the designer from the client at an early stage includes: the intended working life; the area of the facility, which will be dictated by the available site; the types and numbers of vehicles that will use the facility; the traffic circulation patterns; lighting and drainage requirements; and the need for any areas with special functions, services or loading.

Another consideration is the operating pattern for the facility. Some distribution centres are open for 24 hours a day and seven days a week. This being the case, there is little scope for closing down areas for maintenance or repair of services. As a consequence, there is a strong case for conservative design of areas of paving which are required for continuous operation and/or separation of services from trafficked areas. An initially more expensive design solution may turn out to be more economical in the long run when whole-life costs are taken into account.

There is also a need for the paved area to match the needs of the structure which it serves. Examples of this are the position of access ramps and suitably reinforced bays adjacent to loading bays.

1.5 Design process

The design of an external concrete pavement (Chapters 3, 4 and 5) is a relatively straightforward process. In essence, the main features which have to be decided are the slab thickness and the joint type and spacing in each direction.

Slab thickness

In this report, thickness design of unreinforced and conventionally reinforced pavements is based on equations developed by the Transport Research Laboratory (TRL)[8] from the behaviour of sections of trial concrete carriageway. Empirical equations are used to determine the required thickness of concrete slabs based on traffic loading during the life of the pavement, concrete strength, stiffness of the foundation, amount of reinforcement and (for unreinforced pavements) the number of failed bays at the end of the design life. This approach has been adopted because many facilities will have total design loads similar to those used to develop the TRL empirical equations. As the equations are based on the performance of trial sections of carriageway, they take into account the effects of fatigue, shrinkage, early thermal and differential thermal effects.

The thickness design method based on the TRL work in this report uses standardised sub-bases of either 150 mm Highways Agency Type 1 unbound mixture or 150 mm hydraulically bound granular mixture (Highways Agency, Specification for highway works[9]) on subgrades with a range of strengths as determined by the CBR. Fabric reinforcement is classified according to cross-sectional area, and traffic loading is also divided into classes according to the number of standard axles over the lifetime of the pavement.

Tabulated values of slab thickness for concrete of strength class C28/35, C32/40 and C40/50 and the two standard sub-bases for a range of subgrade CBRs are given for wheel loads that are unlikely to approach slab edges (the edge of the whole paved area) and also for slab edges that are frequently loaded. Appendix A gives a factorial equation for slab thickness (based on the TRL equations) for which the input is the CBR of the subgrade and the factors depend on the range of parameters given for the tabulated values above.

Details of increases in thickness are provided to cover the design of undowelled slabs which may be used with cement-bound sub-base only.

Other design methods which are principally used by suppliers of fibres, but some of which could also be used for design of fabric-reinforced slabs, are touched upon.

Joint spacing

The different types of joints and their function are set out in Chapter 5. Joint spacings for gravel and limestone aggregate concretes, depending on slab thickness, are suggested.

2. Design – general

As with most other construction projects it is essential that a clear idea of the expectations and requirements of the client, owner or operator of a development is obtained before proceeding with the design and construction.

2.1 Managing expectations

In the case of external pavements the management of expectations may not be straightforward if the design is speculative and the developer is not going to be the operator. Nonetheless, there are several fundamental requirements which need to be established, agreed and recorded between the designer and the client for the project. The exchange of information should be a two-way process. For example, the client should be left in no doubt that some cracking may occur in concrete slabs immediately after construction, that more cracks may develop in service (see Appendix B) and also that the surface finish may change as a result of wear. A checklist for discussions with a potential client is provided in Table 1.

The normal intended working life for external pavements is considered to be in the range 30–40 years but will depend on the traffic loading and will be linked to the adjacent structure which it serves.

2.2 Methods of construction

Different methods of pavement construction are discussed in Chapter 7.

2.3 Working life of components

The concrete pavement should be designed to have the same intended life as that of the development which it serves. However, some maintenance of the pavement will be required during that period and some components may not last for the full life of the development. Owners or operators must allow for periodic maintenance and replacement of some elements, e.g. pavement markings, joint sealants, lighting components and drainage gratings. If maintenance is not possible because of 24 hour per day and 7 day per week working then a more conservative and invariably more expensive design should be provided.

2.4 Environmental considerations

External in-situ concrete hardstandings cover substantial areas of development land. It is vital, therefore, that construction materials and methods, and the impact on the site and its surroundings, are carefully assessed from an environmental and sustainability aspect. Planning conditions for the development may dictate some of the requirements.

The factors to be considered should include those listed below. Clearly there may be additional requirements for certain developments. For convenience the factors have been listed under various categories, but in many cases they will be interrelated.

Table 1
Client checklist.

1	Intended working life		
2	Vehicle usage		
		Types of vehicle	Numbers of vehicles per day of each type (both laden and unladen) Traffic growth (if any):
		Zoning	• by vehicle type • by vehicle numbers • where jockey wheels will be placed • any critical areas where greater slab thickness may be advisable
3	24-hour operation		
4	Vehicle refuelling areas		
5	Vehicle washing areas		
6	Any special abrasion resistance requirements?		
7	Hazardous or corrosive materials		
8	Drainage requirements: is some temporary ponding acceptable?		
9	Maximum gradients		
10	Surface finish in different areas Are there any 'aesthetic' requirements, e.g. where a particularly high standard of surface or finish is required or where some form of additional surfacing is to be provided?		
11	Marking, lining, street furniture and signage		
12	Inform client about the following: • Likelihood and significance of cracking both initially and in service • There are likely to be variations in colour • Surface texture will wear • Fibre-reinforced concrete is likely to have fibres in the surface and more fibres may appear as the surface abrades; steel fibres may corrode in the surface • Probable working life of components • Maintenance of surfaces, joints and drainage will be necessary		

Planning

- Consider the effect of traffic movements on the local infrastructure, both during construction and when in operation.
- Consider noise and visual intrusion, including light pollution; provide appropriate acoustic screening and landscaping.
- Consider the effects on the local drainage infrastructure of surface water runoff from the new paved area.
- Assess ecological impact, including flora/fauna surveys and relocation where necessary.
- Redevelop brownfield sites where possible.
- Consider the need for in-situ remediation and/or the retention of contaminated soil.
- Balance cut and fill to minimise import/export of materials.
- Minimise the need for retaining structures; use graded slopes where possible.
- Encourage the procurement of materials from local sources.
- Prepare a risk assessment and/or pollution control plan to minimise noise, light and emissions from the works to air, land and water, both during construction and when in service, taking into account the 24-hour nature of operations at some facilities.
- Use sustainable drainage systems (SuDS) for surface water and also for refuelling areas, vehicle washing, fuel interceptors and pollutant removal (see Section 2.6).

- ☐ Consider whole-life costs and life cycle environmental/energy impact.
- ☐ Carry out a flood risk assessment and consider the use of SuDS to take surface water flows in extreme events.

Construction

- ☐ Reuse materials wherever possible. Separate subsoil and topsoil correctly for reuse after construction. Reuse waste or surplus materials in bunds rather than removing from site.
- ☐ On poor or cohesive ground with suitable properties, consider soil stabilisation,[10,11] including the use of lime and/or cement-lime, to minimise importing fill and/or sub-base material.
- ☐ Aim to minimise construction noise, dust and vibration, including that from soil-improvement techniques.
- ☐ Minimise waste, segregate waste streams and store in accordance with the Duty of Care Regulations.[12].
- ☐ Where possible, use recycled materials/aggregates in fill, sub-base or in the concrete slab (see www.aggregain.co.uk).
- ☐ Consider the use of prefabricated components such as drainage and retaining wall units where appropriate.

Concrete slab

- ☐ Consider the use of mixer combinations or factory-produced composite cements rather than plain Portland cement in the concrete – see Section 6.2.
- ☐ Consider whether components used can be easily separated into recyclable components at the end of the life of the slab, e.g. unreinforced rather than reinforced concrete.

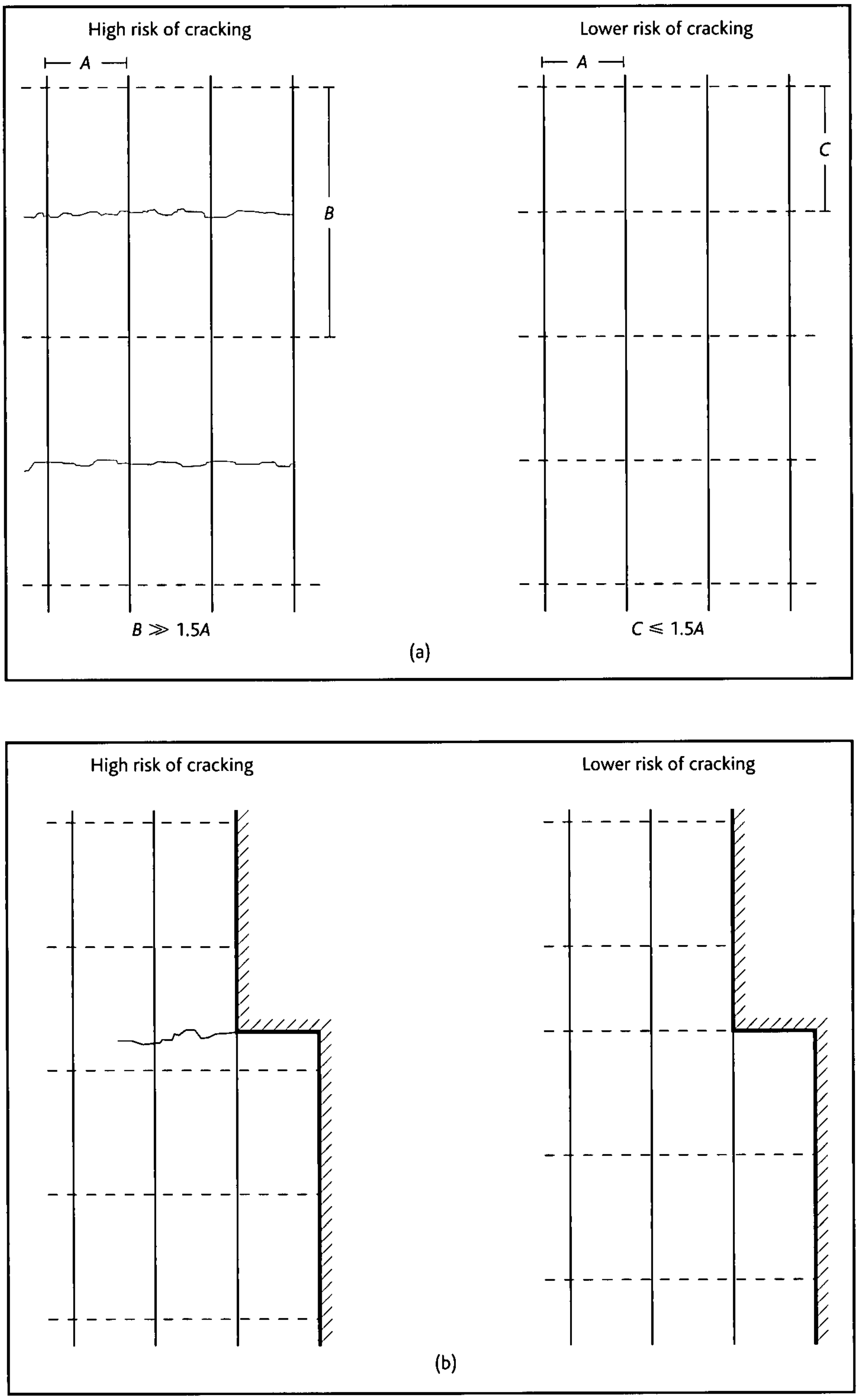
Operation

- ☐ Arrange for careful storage and handling of chemicals and materials, to avoid spillages and contamination.
- ☐ Regularly maintain drainage and wastewater handling systems, particularly in refuelling areas and areas subject to chemical spillage.
- ☐ Maintain joints between slabs and reseal as necessary, to avoid weakening the lower layers.
- ☐ When planning lighting, consider zoning or reduced lighting when areas are not in use.

2.5 Layout

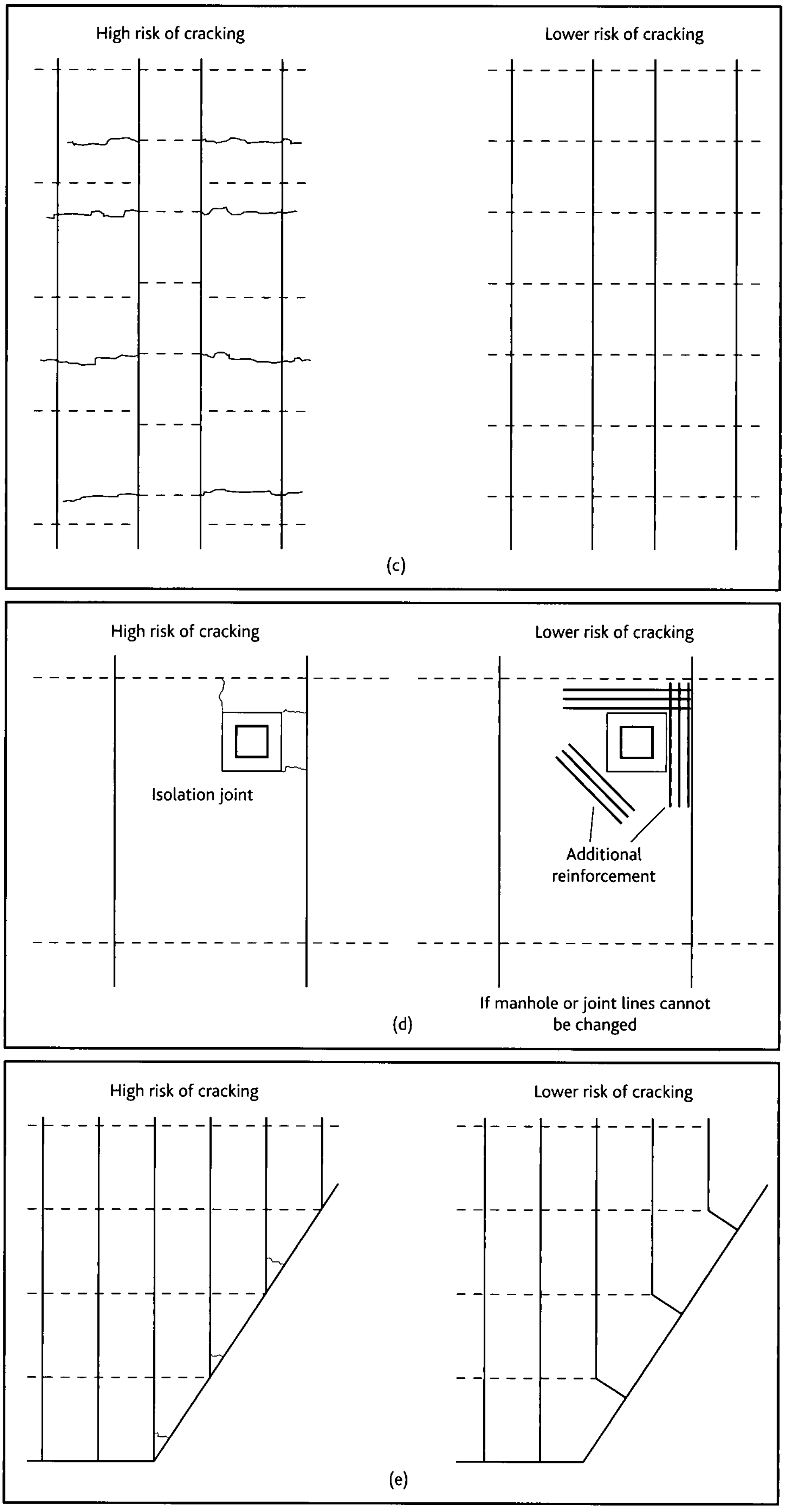
The overall external paving layout will be determined in conjunction with the client and design team to suit the proposed operations and site constraints. There should be a clear, logical arrangement with different thicknesses of construction for separate uses in different areas where appropriate. Such differences must be agreed with the client who may prefer a uniform design to facilitate future changes or when speculative development is being undertaken. Construction may also vary with changing soil conditions across larger sites (e.g. thicker slabs on poorer-quality soils; use of cement-bound granular material or treated/improved soil elsewhere; even piling in poor soils, or for very heavy loads).

Figure 2
Preferred joint layouts[d].



Note
A = bay width
B = bay length

Figure 2
Continued



Trafficked areas require good visibility and safety provision for pedestrians. Prevent tall vehicles from driving under low building projections. Vehicle tracking simulation may be needed where manoeuvring areas are constricted. Avoid tight bends and consider the widening of roadways at bends to allow for the wheel paths of turning articulated and other HGVs. The location of control/security gates, barriers, fencing and other operational requirements such as refuelling/wash-down/maintenance areas must be planned in conjunction with environmental considerations, e.g. noise constraints and any future expansion.

Subject to drainage requirements, docking heights and other such factors, paving levels should be set to minimise cut and fill, importation of materials and the height of retaining walls.

Wherever possible, below-ground service runs and access points should be placed in dedicated zones away from main trafficked routes and joints to facilitate maintenance, upgrading and replacement, and in general sympathy with the joint layout to prevent premature pavement cracking. Manholes should never be located in areas subject to very heavy repetitive traffic, e.g. the vehicle wheel tracks in access road areas.

Typically a rectangular grid of joints at appropriate centres forming bays of low aspect ratio (recommended maximum of 1–1.5) to minimise shrinkage cracking will be needed (refer to Section 5.4). This can be relaxed if a B-type fabric is being used. Nonetheless, some degree of shrinkage cracking is almost inevitable as a balance is sought between minimising cracking and maximising joint spacing to reduce maintenance. Keeping bay sizes down to say 5m reduces, but does not eliminate, cracking. The joint arrangement (including expansion joints in large paved areas) will be determined by the actual layout in conjunction with the pavement contractor's construction methodology. Alternatively the joint layout could be determined by the specialist contractor subject to specified parameters. Figure 2 illustrates certain dos and don'ts regarding joint layout to minimise cracking normally associated with high aspect ratio bays, parts of bays or awkward shapes. Joint types and required spacings are discussed in Chapter 5.

The layout in front of loading docks should be designed so that vehicle wheels or jockey wheels of vehicles using the docks are not normally positioned close to the joints.

2.6 Drainage

External paving should be laid to drainage falls, typically 1 in 60 (although 1 in 40 cross-falls and 1 in 150 long falls in sections of road may be acceptable). Steeper falls are appropriate to suit site topography and minimise cut and fill or retaining structures, provided this does not impede operations. Certain areas may require flatter falls for operational reasons, for instance some unloading areas, but this is likely to result in localised ponding unless the highest construction tolerances are achieved. Sharp or frequent changes in gradient should be avoided, particularly in trafficked areas. Avoid falls towards building entrances; if unavoidable, provide channel drains. Consider the consequences of high-intensity rainfall by provision of suitable overflows.

Drainage collection can be by proprietary channels and/or gullies with suitable gratings, preferably located away from main trafficked areas for ease of maintenance and to avoid the effects of differential settlement if they are isolated by undowelled joints. Actual drainage details must be considered carefully in conjunction with manufacturer's recommendations and construction methods, e.g. movement joints. In trafficked areas, dowelled joints may be more appropriate to avoid differential settlement and isolated narrow sections which may be subject to high braking loads. If undowelled joints are used, their low ability to transfer load must be considered when pavement design is undertaken (refer to Chapter 4).

The location of drainage routes and other services must be coordinated with the pavement layout and construction sequence (see Section 2.5). Uniform paving gradients and long distances between channels/gullies are preferable. Spacings of up to 100m between drainage channels of adequate capacity can be used provided the depth of flowing surface water during severe storms is operationally acceptable.

Surface water drainage would typically be discharged to:

- ☐ mains drains or other outfall, generally after attenuation via SuDS.
- ☐ SuDS infiltration systems such as ponds, swales, soakaways (linear or ring), subgrade infiltration or porous sub-base. The lower capacities of systems such as these may lead to a need for some attenuation.

(Note: pervious surfacing – for example blocks, and granular, porous asphalt – are not dealt with in this report.)

Foul water would normally discharge to:

- ☐ foul main drains
- ☐ specialist treatment units.

Commonly used design standards are:

- ☐ BS EN 752 *Drain and sewer systems outside buildings*[13]
- ☐ Building Regulations Part H[14]
- ☐ *Sewers for adoption* [15]
- ☐ National SUDS Working Group's *Interim code of practice for sustainable drainage systems*[16]
- ☐ CIRIA Report C609, *Sustainable drainage systems*[17]
- ☐ BRE Digest 365, *Soakaway design*[18]
- ☐ CIRIA C635, *Designing for exceedance in urban drainage – Good practice*[19].

External surface water drainage systems are typically designed for one- or two-year return period storms, but the acceptability of short-term ponding/flooding during more intense storms must be considered. Controlled flooding in designated paved areas can also be used as part of a surface water attenuation strategy, which should be developed in conjunction with the client and design team, and recorded on drawings, the operations manual and/or the health and safety file. Remote or little-used paving areas may be appropriate for this. Extra-height kerbs or other perimeter retention may be needed to contain controlled flooding. Ponding at building entrances or access routes or other key areas should be avoided. Standing water may be more problematic in small paved areas where higher-capacity drainage may be needed.

In any event, the extent of flooding and the route of surface water flows during extreme events must be considered and modified as required to ensure that water does not enter buildings on site. No site runoff should discharge onto public highways or adjacent properties.

It may be necessary to intercept existing land drainage or over-ground runoff from adjacent areas around the paving perimeter on less permeable soils and/or to provide on-site land drainage or sub-base drainage at low points over cohesive subgrades.

An appropriate type of fuel interceptor must be used for trafficked area drainage, except on certain very small developments. Runoff from refuelling facilities and certain wash-down areas should be connected to foul drains. Fuel tanker bays will need alarmed full-retention interceptors with automatic closure devices, together with local falls and/or kerbs to ensure that a major fuel spill is not allowed to flow into adjoining areas.

2.7 Design for mechanised construction

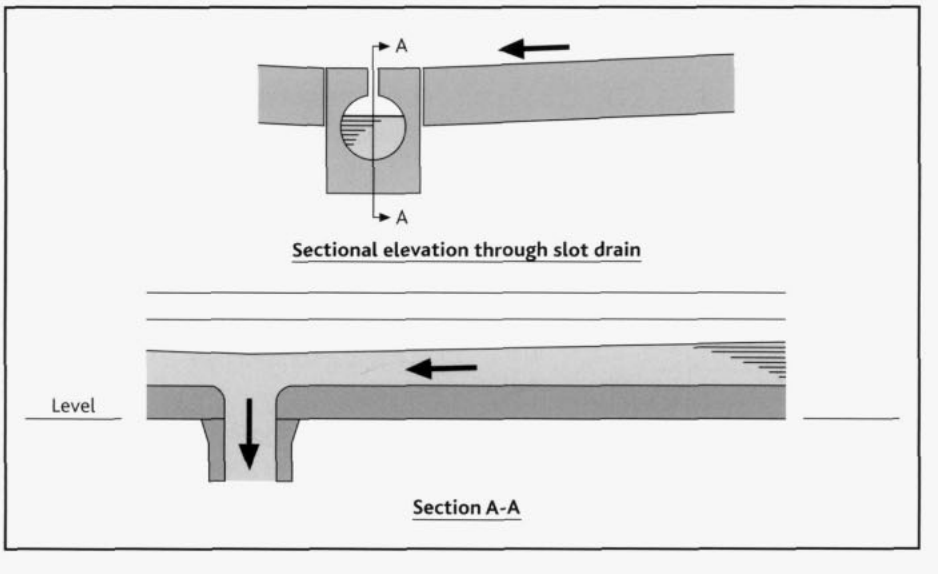
External concrete paving is laid principally by manual methods and the design and detailing of slabs have reflected this fact. Manual construction is relatively slow and thus may be inconsistent with minimising construction programmes. One aim of this report is to promote design and construction techniques that will give substantial improvements in the speed of construction of concrete paving. Over the last two decades there has been a revolution in the methods of laying industrial floors, including mechanised construction, which has produced very large reductions in the construction periods. As a result, designers have needed to modify the way in which floors are designed and detailed to suit these production methods. To improve construction productivity a similar philosophy is needed for the design and detailing of external paving, so that the potential benefits of mechanised construction can be realised.

Initially, the scheme designers will probably not know how a contractor will decide to construct the paving or if mechanised construction will be used. However, there is a wide range of factors the designers should consider at the concept stage that would significantly aid the use of mechanised construction or alternatively increase the speed of manual construction:

- Rationalise the layout of the paving, wherever possible, into simple rectangular areas and bays, and avoid complex-shaped areas and bays and acute corners.
- Use edge strips containing longitudinal drains at the perimeter of paving areas, instead of installing conventional kerbing.

- Avoid falls in two directions in paving bays. If falls in two directions cannot be avoided, make sure that the contours are parallel. Bays should preferably have simple cross-falls to shed water into trough or channel drains that are laid with longitudinal falls. Slot drains can be laid horizontally as the water flows under the influence of the internal head, as shown in Figure 3.
- Avoid the use of isolated gullies located within paving bays for drainage. Locate gullies in edge strips (as per highway practice) or use trough, slot or channel drains.
- Locate manholes outside the paving, e.g. in verges or islands.
- Rationalise the layout, spacing and detailing of joints, which should be on a regular rectangular grid.
- The paving contractor should be allowed to propose modifications to the joint layout and details if needed to suit the proposed method of construction. Permission to modify the design or details should normally be given, unless the proposed changes are considered detrimental to the performance of the paving.
- Rationalise the slab thickness design and the reinforcement details. Preferably all the paving should be of uniform thickness and have constant reinforcement details.
- Rationalise the concrete specifications used for the paving. Ideally, there should only be one specification for all the paving.
- Consider the use of unreinforced paving with no load transfer devices (e.g. no dowels) on hydraulically bound sub-base. Although this will usually result in thicker paving, and hence increased concrete volumes and material costs, the omission of reinforcement and load transfer devices will remove their material costs, fixing costs and reduce construction times. These savings will partly, or possibly even fully, offset the increased concrete costs.
- Adopt the specialist contractor design-and-construct approach, as frequently used for internal industrial floors. The scheme designer would provide the paving contractor with the loadings, possibly a nominal slab thickness and the overall outline geometry of the paving and drainage. The paving contractor would then design the slab thickness, the joint layout and the joint details, to suit the intended method of construction. In most cases these would then have to be agreed with the scheme designer

Figure 3
Drainage using slot drains laid flat.



2.8 Ramps and loading docks

The width, gradient and surface finish of ramps need to suit the vehicles using them. Typically the gradient of HGV ramps should not exceed 1 in 15. Transition gradients may be needed at the top and bottom of steep ramps to prevent vehicle overhangs or their undersides grounding.

While vehicles mostly dock at right angles to building elevations, angled loading docks may ease manoeuvring in restricted service yards.

Transition slabs providing for some relative movement may be needed adjacent to building entrances as the external pavement may settle more than the internal floor. In addition to creating an undesirable abrupt change in level at the entrance, the relative movement can cause spalling along the edges of slabs.

2.9 Street furniture and accessories

Base-plates for barriers, bollards, signposts, security fences etc. bolted to paving, must not straddle construction joints, and bolts should have suitable edge distances. Cast-in items may be stronger but they are more difficult to replace than those that are bolted down.

Consider the effect of vehicle impact on buildings, barriers and other items. Concrete kerbs (either standard or the Trief type, which is a higher safety kerb with a profile that can deflect vehicles), plinths or other barriers may be needed to protect building perimeters, roller shutter door jambs or isolated columns from impact. Allowance should be made for vehicle overhangs where appropriate.

Street furniture should be designed for ease of maintenance and replacement without disrupting traffic or the operation of the facility.

Concrete or steel wheel guides may be used at docking positions, along with buffers at chassis level to cushion lorries/docks from impact.

3. Thickness – design information

It is important to assess the quality of the ground conditions as this has a major bearing on the build-up of the construction. Designs in this Report are based on the California Bearing Ratio (CBR) of the subgrade.

3.1 Ground conditions

CBR testing involves the insertion of a 50mm diameter plunger into the ground at a constant rate (1mm per min.), while the load is recorded. The method of test is described in BS 1377-4 (laboratory) and BS 1377-9 (in situ).[20] When the test is carried out in situ, the value obtained is representative of the moisture conditions and state of compaction prevalent only at the time of the investigation. Laboratory CBR tests can be carried out on remoulded samples to determine values at a range of moisture contents and relative compactions likely to be encountered in service.

Where the subgrade CBR is less than 3%, consideration should be given to providing a capping layer.

An alternative method of assessing the subgrade is to use a plate bearing test. This test measures load and deflection of a circular plate on a foundation layer. The load is often provided by a jack reacting onto a heavy item of plant. The test is used to determine modulus of subgrade reaction, defined as the applied pressure under the plate divided by the displacement (normally 1.25mm) using a plate of 762mm diameter. Plates of other diameters can be used as there is an approximate method of conversion to give an equivalent result for a 762mm diameter plate. However, the plate diameter should generally not be less than 300mm. There is an approximate relationship between modulus of subgrade reaction and CBR (as shown in Section 4.1), used as the basis of tabulated thickness values and factorial equations.

A soil investigation should be undertaken and the report should be made available to the pavement designer. Site investigations and methods of test should be carried out in accordance with BS 5930,[21] BS EN 1977-1[22] and BS 1377.[20] The responsibility for the scope, commissioning, execution and interpretation of the soil survey should be clearly established. The scope of the survey needs to take into account that loading effects can extend well into and possibly beneath the subgrade or filled area.

Materials at deep levels can affect the long-term settlement of the paving. The long-term settlement may be much larger than the elastic deformations under loading and hence there could be differential settlements which could affect the structural performance of the slab and surface slopes and drainage.

3.2 Sub-base

The sub-base is a layer of granular or hydraulically-bound material constructed on top of the formation: it has three main purposes. First, it provides a working platform for construction activities. In this respect it is important that it does not rut excessively under construction traffic. Second, it provides a relatively smooth surface for the construction of the pavement. Third, it supports the slab and helps to spread the load from pavement to the subgrade.

In the context of design, it is the third function which is important. The property used in the design method in TRL Research Report 87,[8] and which is also the basis of the method used in this report, is the equivalent surface foundation modulus. This is the modulus of a uniform foundation giving the same support to the slab as the actual foundation. The equivalent surface foundation modulus is thus dependent on both the subgrade and the thickness and nature of the sub-base.

For simplicity, the design method in this report uses only two 'standard' sub-bases as shown in Table 2.

Table 2
Details of standard sub-bases.

Sub-base	Description
EPSB1	150 mm Highways Agency Type 1
EPSB2	150 mm Cement-bound granular mixture (CBGM)

Note
i. EPSB = external paving sub-base.
ii. Type 1 material is to Highways Agency *Specification for Highway Works*,[19] MCHW1, Clause 803.
iii. CBGM is CBGM A or CBGM B C8/10 to Highways Agency *Specification for Highway Works*,[19] MCHW1, Clauses 821 and 822.

A relationship between subgrade CBR and equivalent surface foundation modulus for the two standard sub-bases has been developed as shown in Appendix D. This means the inputs to the design procedure, although still based on TRL RR87,[8] are simplified to CBR and sub-base type.

Note that Britpave adopts the four foundation classes from TRL 615[23] in its hardstanding design handbook.[24]

3.3 Loading

Traffic loading, in terms of the total number of commercial vehicles expected to use the pavement during its lifetime, is an important factor for pavement design. The traffic on the paved area should be considered under different operational areas in terms of present and future loading when appropriate, in order to optimise the pavement thickness design. Areas subjected to light vehicles and cars can be considered separately to areas subjected to medium and heavy commercial vehicles.

In UK practice, road pavement structural wear is estimated using wear factors based on vehicle axle loads. The wear factor for a vehicle is a means of expressing its effect in relation to the effect of a standard axle of 80kN. Design traffic load is normally expressed in terms of millions of standard axles (msa) during the lifetime of the pavement.

Vehicle wear factors (VWFs) for a range of different commercial vehicle classes are given in Highways Agency *Design Manual for Roads and Bridges*,[7] Volume 7 (HD24/06) and can be summarised as shown in Table 3.

The structural wear associated with lighter traffic such as bicycles, cars and light goods vehicles is considered to be negligible.

Table 3
Vehicle wear factors.

Commercial vehicle class	Vehicle wear factor for new construction
Buses and coaches	3.9
2-axle rigid	0.6
3-axle rigid	3.4
4-axle rigid	4.6
3- and 4-axle articulated	2.5
5-axle articulated	4.4
6-axle articulated	5.6

To determine the design traffic loading T, the number of standard axles for each commercial vehicle class is obtained by multiplying the wear factor for that class by the number of vehicles in that class likely to use the facility (or particular part of a facility) and adding together the results. Hence the design traffic loading is given by:

$$T = D \times Y \times 10^{-6} \times \sum_{j=1}^{N} (F_j \times G_j \times VWF_j) \qquad \text{(Equation 1)}$$

where Y = design period in years
F_j = present traffic per day of commercial vehicle class j
G_j = growth factor for commercial vehicle class j
VWF_j = vehicle wear factor for commercial vehicle class j from Table 3
D = number of days worked in a year.

Table 4 offers a convenient way of calculating design traffic loading. It may be necessary to undertake the calculation for different parts of a facility if there are marked differences in use. In Table 4, the growth factor G is the anticipated increase in traffic using the facility or part of the facility and it can be assessed by using Table 5.

For convenience, in this report traffic loading, for thickness design purposes, is considered to fall into one of six ranges as shown in Table 6.

Table 4
Method of calculating design traffic.

Category		Daily number, F	Days in working week, D	Growth factor, Table 5, G	Wear factor, W	Weighted annual traffic for category ($52^* \times F \times D \times G \times W \times 10^{-6}$)
OGV1 and PSV	Buses and coaches				3.9	
	2-axle rigid				0.6	
	3-axle rigid				3.4	
	4-axle rigid				4.6	
OGV2	3- and 4-axle articulated				2.5	
	5-axle articulated				4.4	
	6-axle articulated				5.6	
		Total weighted annual traffic (AT)				
		Design period (Y)				
		Design traffic (Y) × (G) × (AT) msa				

Note
* Or number of working weeks in year.

Table 5
Traffic growth factors.

Years	Percentage annual compound traffic growth				
	1	2	3	4	5
10	1.05	1.09	1.15	1.20	1.26
20	1.10	1.21	1.34	1.49	1.65
30	1.16	1.35	1.59	1.87	2.21
40	1.22	1.51	1.89	2.38	3.02
50	1.29	1.69	2.26	3.05	4.19

Table 6
Details of traffic classes.

Traffic class	Million standard axles over life of pavement
EPT0	No HGVs
EPT1	Up to 1
T1	2 to 5
T2	6 to 10
T3	11 to 15
T4	16 to 20

Note
i. EPT = external paving traffic.
ii. Traffic categories T1 to T4 are the same as those in the Britpave concrete hardstandings design handbook.[24]

3.4 Concrete strength

The thickness design method in TRL RR87[8] is based on a mean cube compressive strength at 28 days which is taken in this report as 7MPa above the characteristic strength.

The tabulated values given in Chapter 4 and the factorial approach to pavement thickness design described in Appendix A use the concrete strength classes C28/35, C32/40 and C40/50 which are commonly used in pavements. The concerns about the freeze–thaw durability of C40/50 non-air-entrained concrete outlined in Section 6.4.2 should be considered. If pavement thicknesses for other concrete strengths are required they can be assessed using the method in TRL RR87[8] which is summarised in Appendix C.

Using a higher-strength concrete has the advantage that this should result in a thinner slab to carry the same amount of traffic or alternatively more traffic may be carried for the same thickness of slab.

3.5 Reinforcement

Fabric

Reinforcement, in the form of fabric, is provided in the pavement mainly to control cracking. It is positioned towards the top of the slab. Where the plastic method of design is used (see Section 4.2), the reinforcement would be placed in the bottom of the slab and additional reinforcement at the top may be considered for crack-control purposes. The reinforcement classes shown in Table 7 cover the common standard fabric sizes that are used as a basis of the tabular and factorial approaches.

The lighter fabric sizes are classed as unreinforced partly for simplicity and partly because they fall well below the range included in the trials on which the equations in TRL RR87[8] are based.

Table 7
Details of reinforcement classes.

Reinforcement class	Fabric designation
EPR0	Unreinforced, A142, A193, A252
EPR1	A393, (B385)
EPR2	(B503), (B785)

Note
i. EPR = external paving reinforcement.
ii. EPR1 corresponds to Reinforcement Class R2 in the Britpave concrete hardstanding design handbook.[24]
iii. Square (A) fabrics are preferred and hence only classes EPR0 and EPR1 have been used in tabulated thickness designs.
iv. Although some of the lighter fabrics have been included in class EPR0 for simplicity in thickness design, they will have the advantage of increasing joint spacing (see Table 13 and Figure 13) and reducing future maintenance requirements when compared to unreinforced slabs.
v. A fabrics are square meshes with the same bar size and spacing in both directions
vi. B fabrics are structural meshes with main reinforcement in one direction and minimum reinforcement in the other. When used, these fabrics should be used in reinforced slabs of aspect ratio less than 1.5.
vii. C fabrics are long meshes with reinforcement nominally only in one direction; the transverse wires are only to hold the fabric together. These fabrics should be confined to use in situations such as roads constructed by the long strip method where the bay aspect ratio is greater than 1.5. The width of the strip should be as for an unreinforced slab.

Fibres

The trials, on which the design equations in TRL RR87[8] are based, did not include steel fibres or macro-synthetic fibres. This being the case, the use of fibres in concrete is not covered by the design processes described in Section 4.1. Some indication of the design methods which are currently used by fibre suppliers for external pavements and some of which can also be used for fabric reinforcement is given in Section 4.2.

3.6 Tolerances

Tolerances are given in Section 7.3. The design equations in TRL RR87[8] and in this report for unreinforced and conventionally reinforced pavements are based on the nominal thickness of trial sections of road and were developed empirically from their performance in service. Thus tolerances are already taken into account when deriving nominal design pavement thickness using the equations.

4. Thickness design

Thickness design methods for unreinforced and reinforced concrete have been established for many years. However, there is no single universally adopted design procedure for fibre-reinforced external paving. The following sections discuss the principles involved.

4.1 Unreinforced and conventionally reinforced concrete

Basis of thickness design

The tabulated values and factorial equations discussed below are based on the equations given in TRL RR87[8] which are set out in Appendix C. The TRL RR87 procedure is the most widely used method of designing concrete pavements which are either unreinforced or which include fabric reinforcement (in the top of the slab). The method has the advantage that, because it is an empirical method based on the performance of sections of pavement in service, it automatically includes the effects of fatigue, temperature and shrinkage. Pavements reinforced with fabric (generally in the bottom of the slab) can also be designed using some of the methods described for fibre-reinforced concrete in Section 4.2.

One of the parameters that influences the required pavement thickness is the support given to the slab by its foundation. To take account of the support provided by the foundation, the TRL RR87[8] equations use the equivalent surface foundation modulus of the subgrade and sub-base acting together. Equivalent foundation modulus is defined as the modulus of a uniform foundation giving the same slab support as the actual foundation.

In the preparation of the present report, it was considered that CBR is the most useful and easily measured starting-point. To simplify matters, standard sub-bases of 150mm Type 1 granular material and 150mm hydraulically bound material (HBM) were chosen and the equivalent surface foundation moduli of these sub-bases on subgrades with a range of CBRs from 3 to 30% were determined. The method of determining these equivalent foundation moduli is described in Appendix D.

Once the foundation moduli of the standard sub-bases on a range of subgrade CBRs had been determined, this made it possible to calculate pavement thickness using the TRL RR87[8] equations with CBR as the starting-point.

There is an approximate relationship between CBR and modulus of subgrade reaction determined by plate bearing test. Hence the results of plate bearing tests could also be used as the starting-point for pavement thickness design. The approximate empirical relationship given in Highways Agency *Interim Advice Note 73/06 (Draft HD25)*[25] is as follows:

$$CBR = 6.1 \times (k_{762})^{1.733} \times 10^{-8}\% \qquad \text{(Equation 2)}$$

where k_{762} = modulus of subgrade reaction measured using a 762mm diameter plate. If a plate of diameter other than 762mm is used, k_{762} can be obtained using the relation:

$$k_{762} = (0.079 + 0.001209D) \times k_D \qquad \text{(Equation 3)}$$

where k_D = modulus of subgrade reaction measured using a plate of diameter D (mm). However, the diameter of the plate should generally not be less than 300mm.

The TRL RR87[8] equations are based on the performance of sections of trial carriageway and, in their original form, gave the number of standard axles which would lead to a defined failure condition. These failure criteria are given in Appendix B.

Slab thickness – factorial approach

Analysis of the slab thicknesses given by the basic equations in TRL RR87[8] has shown that they can be approximated by the factorial equation:

$$\text{Slab thickness} = A \times CBR^{-0.0378}\ \text{(mm)} \qquad \text{(Equation 4)}$$

for CBR in the range 3–30% and where A is a factor depending on concrete strength, amount of reinforcement, sub-base stiffness, traffic loading and whether or not the edge of the paved area is loaded frequently. Values of the factors are given in Appendix A.

Tabulated slab thicknesses

Many hardstandings experience less than one million standard axles during their lifetime. This traffic loading represents say 27 three- and four-axle articulated vehicles or 15 five-axle articulated vehicles crossing a particular section of pavement seven days per week 52 weeks per year over a 40-year lifetime. Most hardstandings are also reinforced with a fairly light square fabric or, less commonly, unreinforced.

For simplicity, slab thicknesses for common situations have been tabulated in Tables 8 to 11 for subgrade CBRs in the range 3–30%. For subgrade CBRs less than 3% a capping layer should be provided. Tables 8 (Type 1 sub-base) and 9 (HBM sub-base) are for the situation where wheels are likely to travel infrequently along edges of the paved area and Tables 10 and 11 cover the case when pavement edges are frequently loaded. The tabulated values are based on the TRL RR87[8] equations but are rounded to the nearest 5mm above and subject to a minimum thickness of:

- 150mm when no HGVs use the facility or when the sub-base consists of 150mm HBM
- 175mm when HGVs use the facility and the sub-base consists of 150mm HA Type 1.

Slabs with undowelled joints

Slabs with undowelled joints should only be used on hydraulically bound sub-bases (EPSB2). Where undowelled joints are to be used, the slab thickness indicated in Table 9 for dowelled slabs should be increased by 40mm. This increased slab thickness applies also to slabs with undowelled joints where wheels frequently travel close to the edge of the paved area.

Slabs with jockey wheel loading

Areas of slab which experience frequent loading from trailer dolly wheels require particular consideration. The contact area of each of the four jockey wheels is approximately 10 × 88mm and each exerts a static force of around 3.5t. Some trailers have pivoting base plates rather than jockey wheels and these are generally

150 × 225mm in size and exert a static force of around 7t.[26] It is suggested that jockey wheel loads should be considered as static loads and designed using the methods given in Concrete Society Technical Report 34[1] with the static loading increased by 50% to make allowance for the impact effect of dropping the trailer.

Worked design example

An example of design is given in Appendix E.

4.2 Fibre-reinforced concrete

General

Many thousands of square metres of fibre-reinforced concrete warehouse floors and areas of external concrete paving have been successfully constructed in the UK over the past five to ten years. The applications to date principally use steel fibres but there are also examples of polymer macro fibre-reinforced slabs.

Fibres at normal dosages do not improve the tensile strength of concrete. However, improvements in ductility and hence in post-cracking behaviour can be achieved if an appropriate type of fibre is used at a suitable dosage. The use of fibres also means that it is not necessary to place and fix fabric reinforcement and possibly thereby simplifies the construction process. It should be noted that fibres may protrude from or become detached from the surface and that corroded steel fibres may be visible in the surface.

The effect of macro-synthetic fibres in transferring loads across cracks and sawn joints is not well understood.

Design methods

At the present time (2007), there is no single universally adopted design procedure for fibre-reinforced external paving, although a method has been published by the Centre for Civil Engineering Research and Codes (CUR)[4] in the Netherlands. Design of fibre-reinforced paving is often carried out by the suppliers of the fibres; in this situation it is essential that it is clear which party takes design responsibility. Different fibre suppliers have adopted different procedures, some of which are summarised below. Whichever method is used, it is necessary to include partial factors of safety which recognise the possible effects of fatigue under repetitive loading and take into account the effects of temperature and shrinkage.

Elastic methods of design

As discussed earlier, the design of ground-supported slabs and the provision of the nominal amounts of fabric reinforcement are largely empirical and are based on monitoring of the behaviour of trial sections of carriageway. A simple approach adopted by some fibre suppliers is to first carry out a conventional design and replace the area of fabric reinforcement with an equivalent amount of fibre while keeping the slab thickness unchanged. The required dosage of fibre is determined using standard bending theory such that the fibre-reinforced cross-section has the same post-cracking bending moment capacity as the fabric-reinforced cross-section. (Some fibre suppliers publish tables relating the equivalent flexural strength for their products to the concrete strength and dosage rate.) One limitation with this approach is that the various beam tests used to determine the post-cracking properties of the fibre-reinforced concrete yield different results. Given the empirical approach used for determining the amount of fabric, the method is probably reasonable and the resulting fibre dosage is probably realistic. For some projects the selected fibre dosage has been confirmed by direct comparison in laboratory tests between the performance of small slabs reinforced with fabric or fibres.

Plastic method of design

An alternative is to use a plastic design approach, as given in the Third Edition of Concrete Society Technical Report 34 (TR 34), *Concrete industrial ground floors*.[1] Although TR 34 is specifically intended for internal industrial floors, some fibre suppliers adopt the same design approach to determine the required thickness of slabs for external paving, applying an increased load factor to the wheel load to account for repeated applications. This approach has been adopted for a number of contracts in the UK; one supplier indicates that it has been used for more than 250,000m^2 of ground-supported slabs. Typically, fibre dosages are around 35kg/m^3 for steel fibres and 5kg/m^3 for macro-synthetic fibres. The method could also be used for fabric-reinforced external slabs, though in this case the fabric resisting the loading would be in the base of the slab and it may also be necessary to consider the provision of crack-control fabric in the top.

The thickness design equations in TR 34 are based on plastic analysis and assume the use of steel fibres (or correctly located steel fabric reinforcement) in the concrete. The report suggests that the thickness equations should be equally valid for macro-synthetic fibres. The bending moment capacity of a fibre-reinforced ground-supported slab is a function of the equivalent flexural strength ratio, $R_{e,3}$, determined from the Japanese JCI-SF4 beam test.[27] This approach has been confirmed by large-scale slab testing. To ensure adequate ductility, the assumption in TR 34 is that the fibre-reinforced concrete has a minimum $R_{e,3}$ value of 0.3.

For dowel-jointed fibre-reinforced concrete slabs, with an $R_{e,3}$ value of 0.3, calculations by one fibre producer have shown that the thickness values in Tables 8–11 provide a calculated factor of safety (slab capacity/(1.6 × wheel load)) greater than 2. This is based on a wheel load of 40kN with a partial safety factor of 1.6, but does not explicitly take account of stresses due to thermal or shrinkage effects.

Similar analysis has been carried out for slabs with undowelled joints. Based on the assumption that a wheel load acting close to a joint is similar to a load acting close to a free edge the analysis has shown that an increase of 20mm over the values in Tables 8–11 provides a calculated safety factor in excess of 2 for an $R_{e,3}$ value of 0.3. This again considers wheel loads only and takes no direct account of thermal or shrinkage effects. Sawn-induced joints or other joints without any dowels or fabric would be provided at the basic joint spacing of 5m as for the EPRO condition.

TR 34 does not make any mention of the creep of concrete containing macro-synthetic fibres, a phenomenon which is currently not well understood. It is therefore suggested that a cautious approach should be adopted when designing slabs subjected to high concentrated loads. TR 34 suggests that, in the absence of information from the supplier, it should be assumed that the shear capacity of macro-synthetic fibre-reinforced concrete is the same as that of plain concrete.

4.3 Roller-compacted concrete

General

Design of roller-compacted concrete (RCC) pavements follows a similar procedure to that for conventional concrete pavement design in that subgrade and sub-base properties, RCC flexural strength, loading and loading repetitions must be considered.

Design methods

For the hardstandings and paved areas covered by this publication, RCC slabs can be designed by using the method described above for unreinforced slabs. A method commonly used for the design of heavy-duty pavements in RCC involves a determination of flexural stress in the pavement and consideration of fatigue effects caused by repetitive wheel loads. Full details are available from the Portland Cement Association in the USA.[28]

Table 8

Thickness for slabs with dowelled joints and infrequent loading on pavement edge – on 150mm HA Type 1 sub-base.

HA TYPE 1 SUB-BASE – INFREQUENT LOADING							
Concrete strength class*	Traffic load (msa)	CBR (%)					
		3	4	5	6	6–10	10–30
150mm HA Type 1 sub-base EPR0 (unreinforced, A142, A193, A252 fabrics)							
C28/35	0	150	150	150	150	150	150
C28/35	1	175	175	175	175	175	175
C28/35	5	185	180	180	180	175	175
C28/35	10	210	210	210	205	205	200
C28/35	15	230	230	225	225	220	220
C28/35	20	245	240	240	235	235	230
C32/40	0	150	150	150	150	150	150
C32/40	1	175	175	175	175	175	175
C32/40	5	175	175	175	175	175	175
C32/40	10	195	195	190	190	190	185
C32/40	15	215	210	210	205	205	200
C32/40	20	225	225	220	220	220	215
C40/50	0	150	150	150	150	150	150
C40/50	1	175	175	175	175	175	175
C40/50	5	175	175	175	175	175	175
C40/50	10	175	175	175	175	175	175
C40/50	15	185	185	180	180	180	175
C40/50	20	195	195	190	190	190	185
EPR1 (A 393 fabric)							
C28/35	0	150	150	150	150	150	150
C28/35	1	175	175	175	175	175	175
C28/35	5	175	175	175	175	175	175
C28/35	10	195	195	190	190	190	185
C28/35	15	215	210	210	210	210	205
C28/35	20	225	225	225	220	220	220
C32/40	0	150	150	150	150	150	150
C32/40	1	175	175	175	175	175	175
C32/40	5	175	175	175	175	175	175
C32/40	10	180	180	180	175	175	175
C32/40	15	195	195	195	195	190	190
C32/40	20	210	210	205	205	205	200
C40/50	0	150	150	150	150	150	150
C40/50	1	175	175	175	175	175	175
C40/50	5	175	175	175	175	175	175
C40/50	10	175	175	175	175	175	175
C40/50	15	175	175	175	175	175	175
C40/50	20	185	180	180	180	180	175

Note

* Strength classes C28/35 and C32/40 are air-entrained. The concerns about durability of strength class C40/50 without air-entrainment should be considered (see Section 6.4.2).

Table 9

Thickness for slabs with dowelled joints and infrequent loading on pavement edge – on 150mm HBM sub-base.

HBM SUB-BASE – INFREQUENT LOADING							
Concrete strength class*	**Traffic load (msa)**	**CBR (%)**					
		3	**4**	**5**	**6**	**6–10**	**10–30**
150mm HBM sub-base EPR0 (unreinforced, A142, A193, A252 fabrics)							
C28/35	0	150	150	150	150	150	150
C28/35	1	150	150	150	150	150	150
C28/35	5	180	175	175	175	170	170
C28/35	10	205	205	200	200	200	195
C28/35	15	225	220	220	220	215	210
C28/35	20	240	235	235	230	230	225
C32/40	0	150	150	150	150	150	150
C32/40	1	150	150	150	150	150	150
C32/40	5	165	165	160	160	160	155
C32/40	10	190	190	185	185	185	180
C32/40	15	205	205	205	200	200	195
C32/40	20	220	215	215	215	210	210
C40/50	0	150	150	150	150	150	150
C40/50	1	150	150	150	150	150	150
C40/50	5	150	150	150	150	150	150
C40/50	10	165	165	160	160	160	155
C40/50	15	180	180	175	175	175	170
C40/50	20	190	190	185	185	185	180
EPR1 (A 393 fabric)							
C28/35	0	150	150	150	150	150	150
C28/35	1	150	150	150	150	150	150
C28/35	5	165	165	160	160	160	155
C28/35	10	190	190	190	185	185	185
C28/35	15	210	205	205	205	205	200
C28/35	20	225	220	220	220	215	215
C32/40	0	150	150	150	150	150	150
C32/40	1	150	150	150	150	150	150
C32/40	5	150	150	150	150	150	150
C32/40	10	175	175	175	175	170	170
C32/40	15	195	190	190	190	190	185
C32/40	20	205	205	205	200	200	200
C40/50	0	150	150	150	150	150	150
C40/50	1	150	150	150	150	150	150
C40/50	5	150	150	150	150	150	150
C40/50	10	155	155	150	150	150	150
C40/50	15	170	165	165	165	165	160
C40/50	20	180	180	175	175	175	175

Note

For slabs with undowelled joints, the above slab thicknesses should be increased by 40mm.

*Strength classes C28/35 and C32/40 are air-entrained. The concerns about durability of strength class C40/50 without air-entrainment should be considered (see Section 6.4.2).

Table 10
Thickness for slabs with dowelled joints and frequent loading on pavement edge – on 150mm HA Type 1 sub-base.

HA TYPE 1 SUB-BASE – FREQUENT LOADING							
Concrete strength class*	Traffic load (msa)	CBR (%)					
		3	4	5	6	6–10	10–30
150mm HA Type 1 sub-base EPR0 (unreinforced, A142, A193, A252 fabrics)							
C28/35	0	150	150	150	150	150	150
C28/35	1	175	175	175	175	175	175
C28/35	5	210	210	205	205	205	200
C28/35	10	240	240	235	235	230	230
C28/35	15	260	255	255	255	250	245
C28/35	20	275	270	270	265	265	260
C32/40	0	150	150	150	150	150	150
C32/40	1	175	175	175	175	175	175
C32/40	5	195	195	190	190	190	185
C32/40	10	225	220	220	215	215	210
C32/40	15	240	240	235	235	235	230
C32/40	20	255	250	250	250	245	240
C40/50	0	150	150	150	150	150	150
C40/50	1	175	175	175	175	175	175
C40/50	5	175	175	175	175	175	175
C40/50	10	195	195	190	190	190	185
C40/50	15	210	210	205	205	205	200
C40/50	20	225	220	220	220	215	215
EPR1 (A 393 fabric)							
C28/35	0	150	150	150	150	150	150
C28/35	1	175	175	175	175	175	175
C28/35	5	195	190	190	190	190	185
C28/35	10	220	220	220	220	215	215
C28/35	15	240	240	240	235	235	235
C28/35	20	255	255	255	250	250	245
C32/40	0	150	150	150	150	150	150
C32/40	1	175	175	175	175	175	175
C32/40	5	180	175	175	175	175	175
C32/40	10	205	205	205	200	200	200
C32/40	15	225	225	220	220	220	215
C32/40	20	240	235	235	235	230	230
C40/50	0	150	150	150	150	150	150
C40/50	1	175	175	175	175	175	175
C40/50	5	175	175	175	175	175	175
C40/50	10	180	180	180	180	180	175
C40/50	15	200	195	195	195	195	190
C40/50	20	210	210	205	205	205	200

Note
*Strength classes C28/35 and C32/40 are air-entrained. The concerns about durability of strength class C40/50 without air-entrainment should be considered (see Section 6.4.2).

Table 11
Thickness for slabs with dowelled joints and frequent loading on pavement edge – on 150mm HBM sub-base

HBM SUB-BASE – FREQUENT LOADING							
Concrete strength class*	Traffic load (msa)	CBR (%)					
		3	4	5	6	6–10	10–30
150mm HBM sub-base EPR0 (unreinforced, A142, A193, A252 fabrics)							
C28/35	0	150	150	150	150	150	150
C28/35	1	150	150	150	150	150	150
C28/35	5	205	200	200	200	195	195
C28/35	10	235	230	230	225	225	220
C28/35	15	255	250	250	245	245	240
C28/35	20	270	265	260	260	260	255
C32/40	0	150	150	150	150	150	150
C32/40	1	150	150	150	150	150	150
C32/40	5	190	190	185	185	185	180
C32/40	10	215	215	215	210	210	205
C32/40	15	235	230	230	230	225	225
C32/40	20	250	245	245	240	240	235
C40/50	0	150	150	150	150	150	150
C40/50	1	150	150	150	150	150	150
C40/50	5	165	165	165	160	160	160
C40/50	10	190	190	185	185	185	180
C40/50	15	205	205	200	200	200	195
C40/50	20	220	215	215	210	210	205
EPR1 (A 393 fabric)							
C28/35	0	150	150	150	150	150	150
C28/35	1	150	150	150	150	150	150
C28/35	5	190	190	185	185	185	180
C28/35	10	220	215	215	215	210	210
C28/35	15	235	235	235	230	230	230
C28/35	20	250	250	250	245	245	245
C32/40	0	150	150	150	150	150	150
C32/40	1	150	150	150	150	150	150
C32/40	5	175	175	175	170	170	170
C32/40	10	205	200	200	200	195	195
C32/40	15	220	220	215	215	215	210
C32/40	20	235	230	230	230	230	225
C40/50	0	150	150	150	150	150	150
C40/50	1	150	150	150	150	150	150
C40/50	5	155	155	150	150	150	150
C40/50	10	180	175	175	175	175	170
C40/50	15	195	195	190	190	190	185
C40/50	20	205	205	205	200	200	200

Note
*Strength classes C28/35 and C32/40 are air-entrained. The concerns about durability of strength class C40/50 without air-entrainment should be considered (see Section 6.4.2).

5. Joints and joint spacing

Joints may be formed during the casting process, or induced by a saw cutting green or hardened concrete. Joints are formed in wet concrete at the edges and ends of strips. Occasionally extra joints are required, such as day joints (at the end of a day's work) and sometimes when work has to be stopped because of bad weather or a breakdown in concrete supply or concreting plant. Joints at the long edges of construction strips tend to be referred to as longitudinal joints and the joints perpendicular to these, which cross the strips, as transverse. These terms derive, in part, from highway construction where the longitudinal joints run along the direction of the carriageway.

The method of construction may lead to some joints being referred to as longitudinal and some as transverse and they may be formed in one direction and saw-cut in the other but on paved areas there is a case for an equal weight of reinforcement in both directions.

Information on spacing and layout of joints is given in Section 5.5.

5.1 Function of joints

Tensile and compressive stresses will be induced in concrete by restrained thermal and moisture-related contraction and expansion effects. The thermal changes can result from the heat of hydration of the concrete or from exposure to the environment. Changes in moisture content of the concrete may result in shrinkage or expansion, but shrinkage is the predominant result of moisture movement. Joints are provided in pavements to reduce the stresses generated by thermal and moisture changes and to allow horizontal movement. As the heat of hydration movements occur in the first few days after construction, joints need to be provided at an early stage – usually within 24 hours of casting.

Correctly located and detailed joints:

- reduce tensile and compressive stresses in the pavement
- reduce the risk of cracking within bays
- accommodate thermal and shrinkage movements in the pavement
- provide load transfer from bay to bay
- reduce the effect of the joints on ride quality
- minimise the occurrence of stepping across joints
- reduce damage to arrises/joint edges.

However, the concrete at joints and edges tends to be weaker than that in the centre of bays. It is often necessary to make provision for additional load transfer at joints. Load transfer across formed joints is provided by dowels and at induced joints is provided partly by any reinforcement or dowels which cross the joint and partly by the interlock of aggregate from the concrete surfaces on each side of the joint where there is only limited opening of the joint.

5.2 Types of joint

5.2.1 Introduction

This report generally follows the terminology of Concrete Society Technical Report 34[1].

Free movement joint (plain) – which may be sawn or formed; no dowels or reinforcement are provided in the joint.
Free-movement joint (contraction) – which may be sawn or formed; dowel bars are provided.
Free-movement joint (expansion) – which will always be formed; dowel bars are provided.
Restrained-movement joint – which may be sawn or formed; dowel bars are provided at formed joints; fabric may cross sawn joints.
Tied construction joint – which is a formed joint to permit a break in construction such as a day joint; dowel bars are provided.
Isolation detail – which is formed around a fixed element (building, manhole cover, lighting mast base); no dowels or reinforcement are usually provided across the joint.

5.2.2 Free-movement joint

All free-movement joints permit horizontal movement while, with some forms of load transfer, restricting relative vertical movement between bays (generally plain joints carry a risk that they will not provide load transfer or restrict relative vertical movement). They are provided to reduce stresses imposed by pavement shrinkage and contraction but can also accommodate some expansion, provided that some shrinkage has already taken place. They also help to control curling. The in-slab reinforcement does not continue across the joint but dowels or other means of achieving load transfer are provided.

Free-movement joints may be formed at the time of casting, induced by an embedded stress-raiser or by a single saw cut at an early age (within 24 hours of laying the concrete).

Formed free-movement – contraction joint

Formed free-movement joints are constructed using formwork along the sides of strips or transversely at a planned break in construction. Load transfer is provided by de-bonded dowels which can be plain round or square bars as shown in Figure 4. The de-bonding sleeves on square bars are designed to be compressible on the sides to permit lateral movement. The sleeves on both square and round bars should fit tightly and should be of sufficient stiffness to restrict vertical movement.

Induced free-movement – contraction joint

Dowel bars with a sleeve for de-bonding are supported off the sub-base using bent fabric cages firmly fixed to the underlying material as shown in Figure 5 or by other suitable means. The dowels provide vertical load transfer across the joint. The supporting cage is cut along the joint line prior to concreting, or the bars (other than the dowels) perpendicular to the joint in the supporting cage are discontinuous but joined by plastic sleeves.

Figure 4
Formed free-movement – contraction joints.

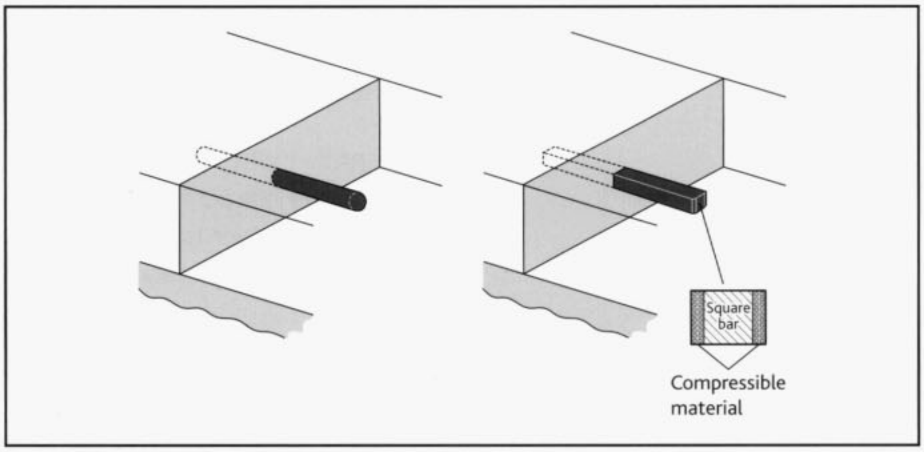
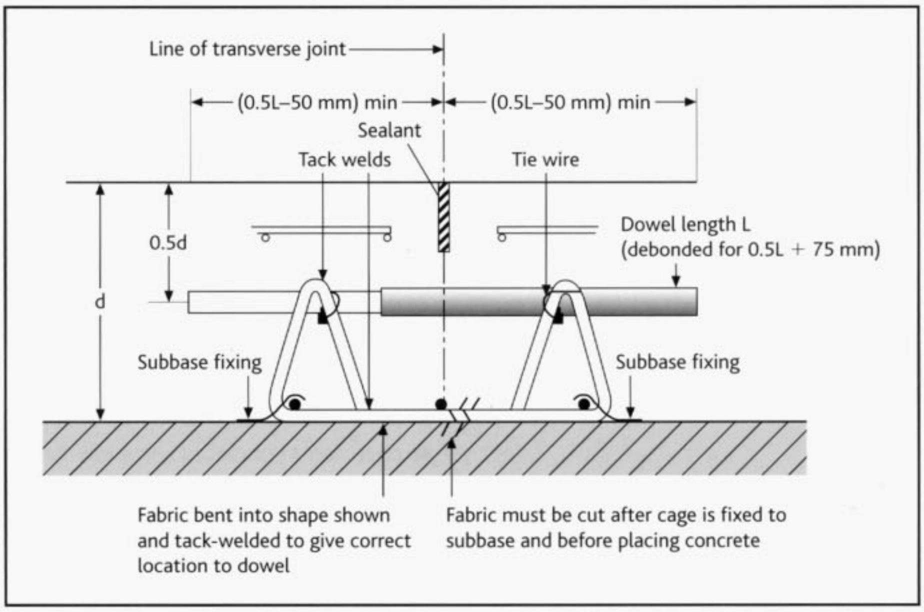


Figure 5
Sawn free-movement – contraction joint.



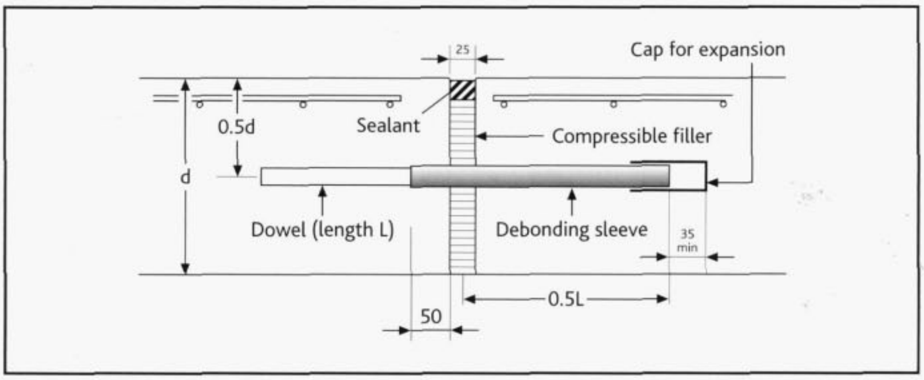
To induce a crack, a rigid triangular-section stress raiser is placed on the sub-base at the intended joint position. Once the concrete has been placed and finished, a wet-formed slot is made directly above the stress raiser or a proprietary plastic joint is cast into the surface directly above the stress raiser. As an alternative, a saw cut can be made to about one quarter depth. A crack should form between the stress raiser on the bottom and the groove or saw cut in the top as the concrete hardens and this forms the movement joint. This method of joint formation is subject to misalignment of the upper and lower stress raisers causing the crack to run parallel to, rather than connecting to, the stress-raiser and is not recommended.

A single saw cut can be used to induce a crack and form a joint. The saw cut is made as soon as the concrete is strong enough for the operation to be undertaken without damaging the joint edges. Saws are available which can cut green concrete but the operation is usually carried out within 24 hours of casting. Timing will depend on ambient conditions. The cuts are usually made with a 3 or 4mm wide blade to a depth of at least one quarter of the slab depth. Cutting to a depth greater than one third of the slab depth can result in a reduction of aggregate interlock. Fabric overlaps should be avoided at sawn joint positions.

Free-movement – expansion joint

An expansion joint is a formed free-movement joint which is able to accommodate expansion in addition to contraction. This is accomplished by using a compressible filler board between adjacent areas of slab for the full slab depth as shown in Figure 6.

Figure 6
Free-movement – Expansion joint.



In many cases, shrinkage is the predominant factor and expansion joints may not be necessary in external paving. However, they are needed for:

- large areas
- pavements concreted in winter as the subsequent expansion may exceed shrinkage
- pavements concreted using low-heat cements as the contraction after heat of hydration may be less than the subsequent expansion due to ambient effects
- thin pavements (say less than 200mm deep) that can experience raised temperatures from ambient effects over a significant proportion of their depth.

Expansion joints should be avoided if at all possible in aggressive situations such as waste-transfer stations.

There is no aggregate interlock across expansion joints and the joints are wider, hence the dowels play an important role in load transfer. The dowels also have to be capped with compressible material at one end so that expansion is not hindered.

5.2.3 Restrained-movement joint

Restrained-movement joints can be formed or saw-cut. They permit limited movement to occur at the joint which provides some relief to in-plane stresses induced by overall shrinkage and thermal movement and also helps to control curling. Any reinforcement in the slab continues across the joint. Vertical load transfer is provided by aggregate interlock and also by reinforcement which crosses the joints and dowel bars provided in formed restrained-movement joints.

Restrained-movement joints may be formed at the time of casting, induced by an embedded stress-raiser or by a single saw cut.

Formed restrained-movement joint

Formed restrained-movement joints, as shown in Figure 7, are constructed using formwork. The in-slab reinforcement does not continue through the joint and hence dowel bars are used. These are inserted through holes in the formwork and a means of aligning them properly and maintaining the alignment must be provided. Some contractors prefer to drill and grout the anchor bars once the first pour has hardened. This can lead to better accuracy in the alignment of the dowels.

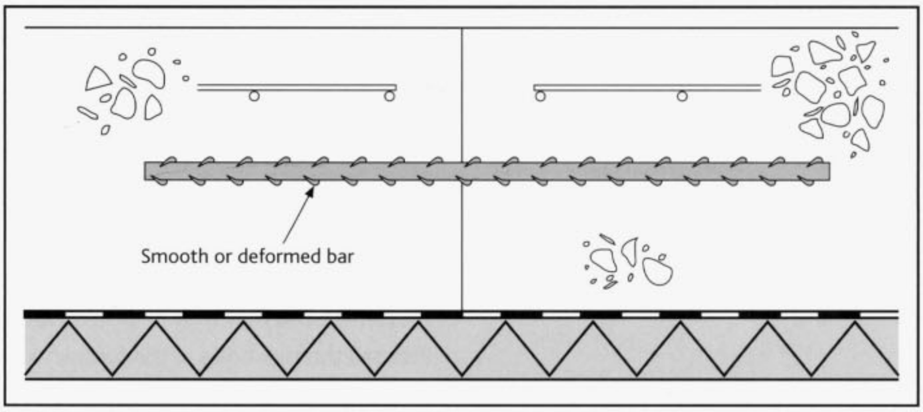


Figure 7
Formed restrained-movement joint.

Induced restrained-movement joint

Whether the crack is induced by casting-in stress-raisers or by saw cut, the in-slab reinforcement and aggregate interlock provide the load transfer across the joint and no dowel bars are provided. Joints are sawn as soon as the concrete has gained sufficient strength that the joint edges are not damaged. A typical sawn restrained-movement joint is shown in Figure 8.

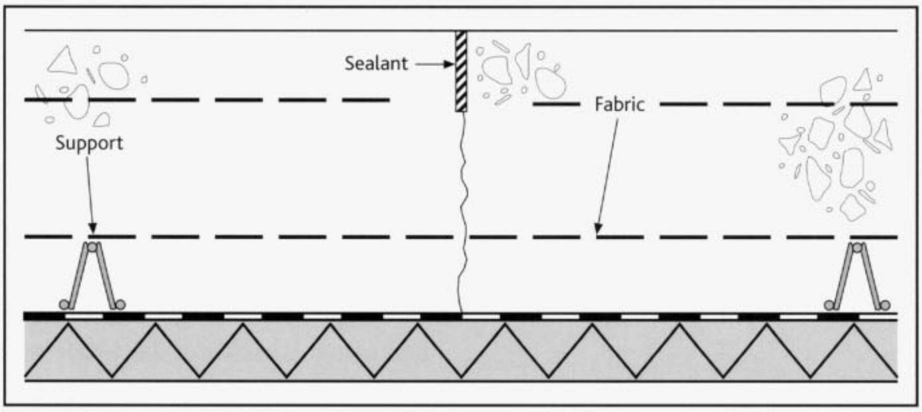


Figure 8
Sawn restrained-movement joint.

5.2.4 Tied construction joint

Tied construction joints are used when a break in construction is required other than at a free-movement joint. The aim is to provide full continuity with no relative movement. In reinforced paving, the dowels should be of deformed high-yield bars with adequate anchorage lengths. The area of the dowel bars per metre run should be not less than the slab reinforcement area provided in that direction and also not less than as shown in Table 12. Tied construction joints will not relieve strains due to overall pavement

Table 12
Joint dowel details.

Joint type	Slab thickness (mm)	Filler board thickness (mm)	Dowels			
			Type and diameter	Overall length (mm)	Minimum debonded length (mm)	Centres (mm)
Free-movement joint – plain	All	–	–	–	–	–
Restrained-movement joint	All	–	R12 or T12	900	0	600
Free-movement joint – contraction	All	–	R25	500	300	300
Free-movement joint – expansion	Up to 240 Over 240	25 25	R25 R32	600 600	365 365	300 300
Tied construction joint	All	–	T20	900	0	300

Note

i. The tabled information is based on Maynard.[29]

ii. A specification for filler boards can be obtained from Highways Agency *Manual of contract documents for highway works*,[9] MCHW1, Clause 1015.

iii. Tied joints may be tied by reinforcement instead of dowel bars. See Table 13.

iv. Dowels for contraction and expansion joints should:

a. be specified to BS EN 13877-3[30]

b. have their ends sawn and not cropped (cropping leaves a lip at the end of the bar)

c. be straight and perpendicular to the joint face to ensure joint movement can occur

d. be debonded (where required) with a tight-fitting sleeve and have end caps to permit expansion to occur when used in expansion joints.

movement but they may help to control curling. In this case also, the dowel bars are inserted through holes in the formwork. Alignment is not so important in this case, as no movement across the joint is required but they should still be held firmly in place during concreting operations. A completed tied joint is shown in Figure 9.

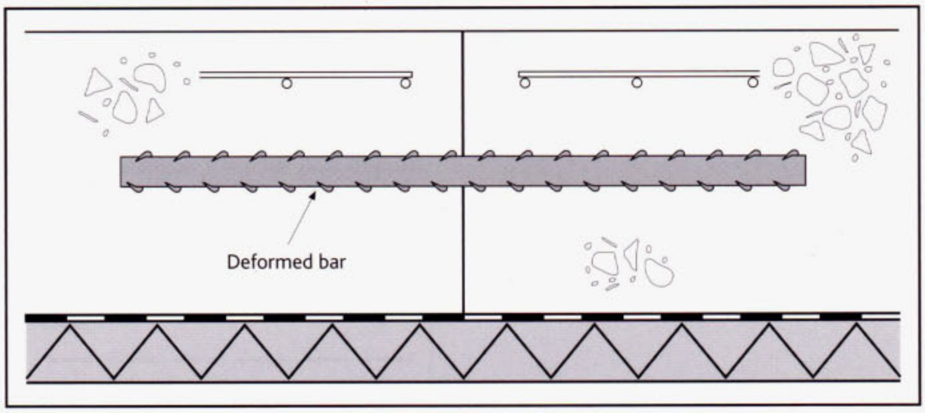


Figure 9
Tied joint.

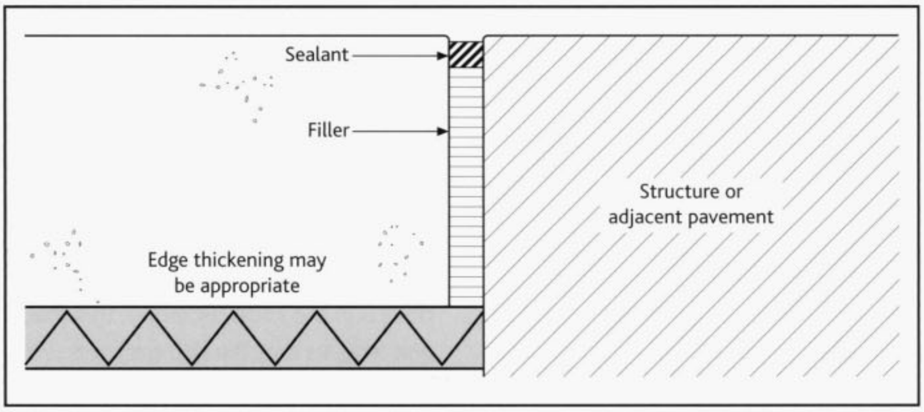
5.2.5 Isolation detail

Isolation joints are provided to prevent fixed items from exerting restraint. The fixed item might be a building foundation, a precast strip drain, a manhole, a lighting column base or even a section of slab which has previously been constructed in a different direction. Examples of the latter are at the entrance to a site where the slab may abut a concrete carriageway or at the entrance of a building where the slab may be cast against the internal floor slab.

Edge thickening may be required in situations where traffic is able to run close to or across the isolation detail.

A typical isolation detail is shown in Figure 10.

Figure 10
Isolation detail.



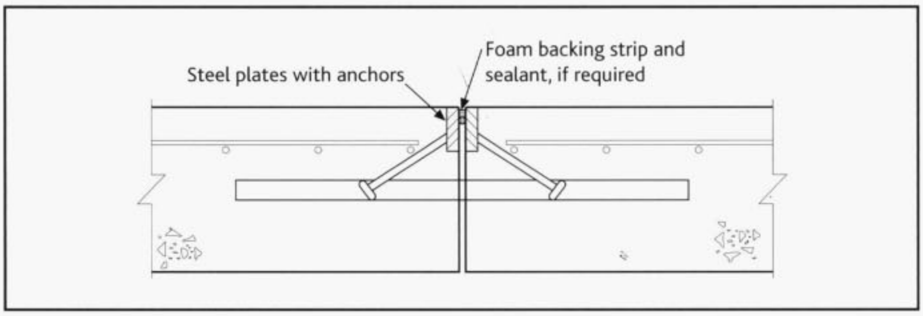
5.2.6 Edge nosing

Some pavement contractors and designers specify or use a nosing trowel on formed joints to give a rounded arris. Joints finished with a nosing trowel have clean well-formed edges that have a much lower risk of spalling under the action of traffic. However, it is a difficult operation to perform well and rounded edges form depressions along the joint lines in which water may collect. The depressions may also have an adverse effect on ride quality.

5.2.7 Armoured nosing

Most external pavements are subject to rubber-tyred vehicles and so armouring of joints is not usually necessary. However, armouring may be necessary in applications such as waste-transfer stations and close to ramps and loading bays where the pavement is trafficked by both hard-wheeled rubber-tyred vehicles and fork-lift trucks. A typical armoured joint detail is shown in Figure 11.

Figure 11
Armoured joint.



5.3 Dowels and other load transfer devices

5.3.1 Provision of dowels

Table 12 lists details for dowels and filler board thickness for the different joint types.

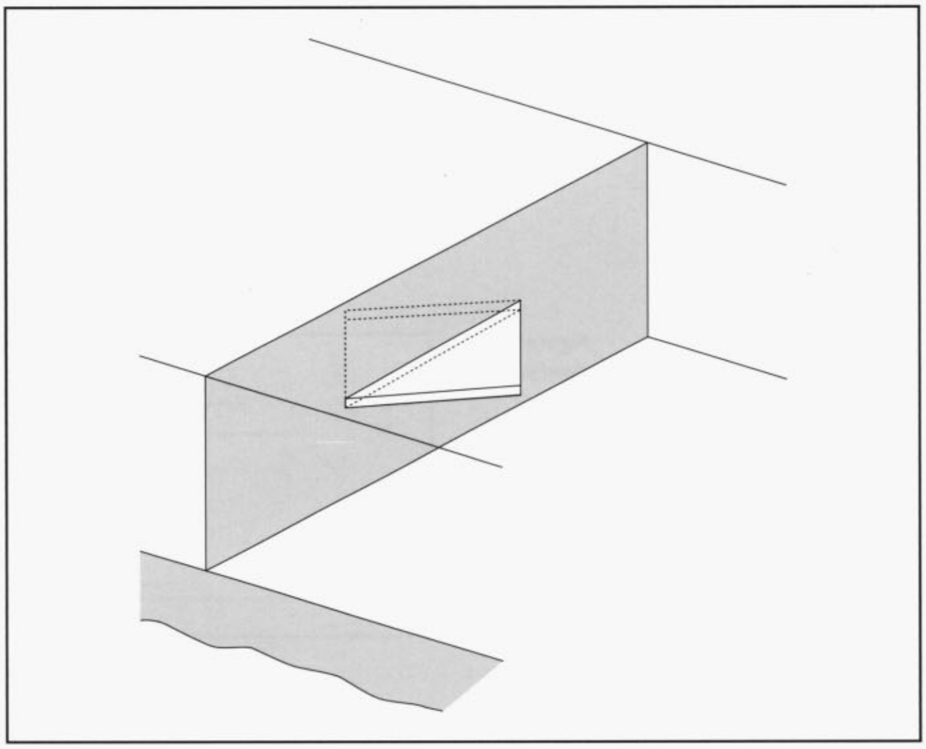
It is essential that dowels are fixed perpendicular to the joint plane (i.e. both vertically and horizontally) and that they remain in that position while the concrete is placed and until it has hardened. If dowels are not fixed correctly or are disturbed during concreting, there is a risk that the joint will not function correctly and that a crack will form close by or that an adjacent restrained-movement joint will open to a greater degree. The end dowel next to a joint at right angles should permit horizontal movement to avoid trapping the corner and causing cracks. This can be achieved by using a square dowel with compressible material as shown in Figure 4 or by omitting the last dowel in one direction.

There may be advantages in constructing unreinforced concrete pavements without dowels in the joints. However, this should only be done on hydraulically bound sub-base and requires that the slab thickness is increased as described in Section 4.1.

5.3.2 Diamond plates

Diamond-shaped flat steel plates can be used in place of dowels. They are positioned with their diagonal along the line of the joint as shown in Figure 12. This means that the slab is not restrained in the direction perpendicular to the joint or along the joint once the joint has opened slightly due to shrinkage. Diamond plates have the advantage that they can be used close to intersections of joints. Requirements for plate dimensions and spacing are given in ACI 302.1R.[31]

Figure 12
Diamond plate at joint.



5.4 Proprietary joint systems

A range of proprietary products is available to facilitate the process of constructing functional joints. These range from simple devices to align dowel bars and diamond plates on shutters and dowel support baskets to complete prefabricated joints. The use of these products can speed up the construction process and also assist greatly in the production of accurate joints.

5.5 Joint spacing

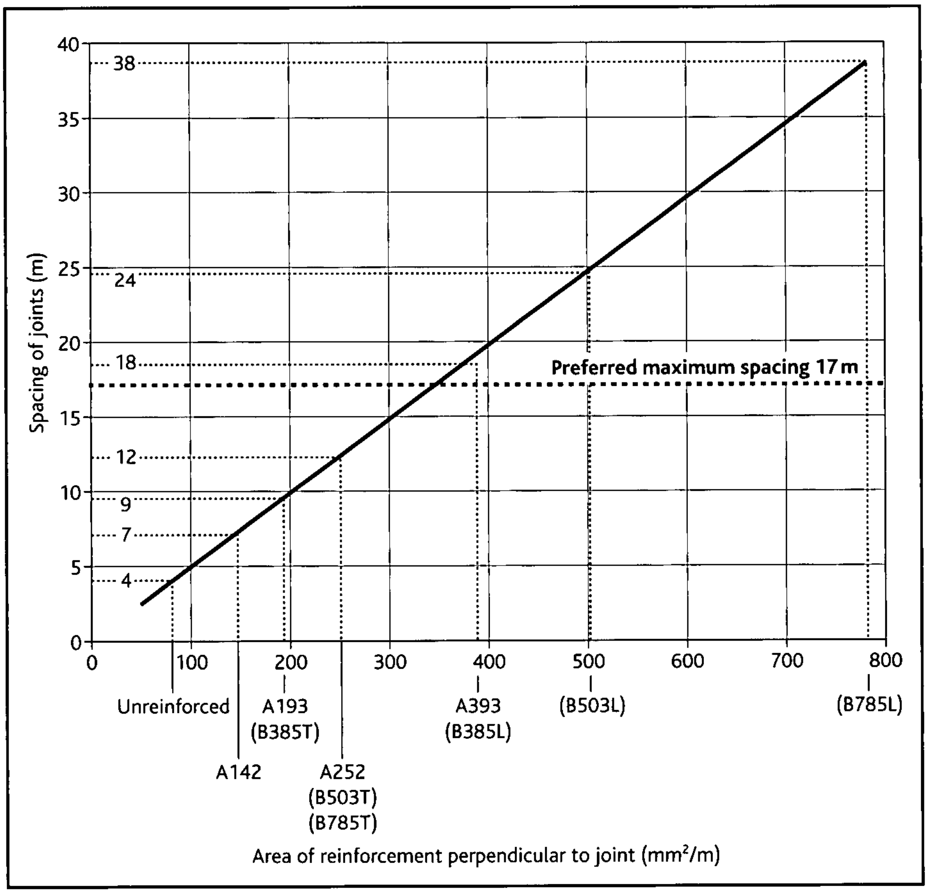
Some advice in relation to joint layout is given in Figure 2. In particular, the bay aspect ratio should not exceed 1.5 when the slab is unreinforced or when A fabric reinforcement is used.

Unreinforced and conventionally reinforced concrete

Suggested spacings for the various joint types are provided in Table 13 and Figure 13 which is based on Road Note 29.[32] Joints are to be provided at the centres shown in both directions. For example, for a 200mm thick slab with gravel aggregate and EPRO reinforcement, restrained movement joints would be provided at 4m centres in both directions and for every third joint in each direction the restrained movement joint would be replaced by a free-movement–contraction joint. An idealised example of joint spacing is shown in Figure 14. If C fabrics are used, the joint spacing in the direction of lesser reinforcement should be taken as that for an unreinforced slab. Joint spacings are often rationalised to avoid cutting standard fabric sheets.

Figure 13

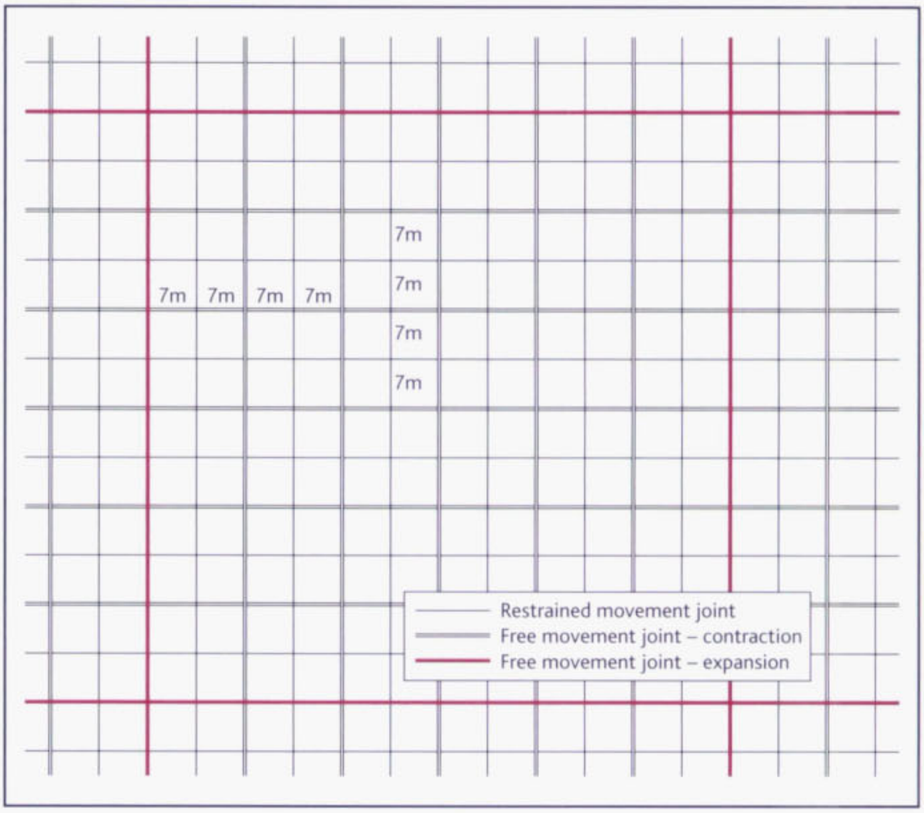
Spacing of free-movement joints (developed from Figure 13 of Road Note 29[32]).



Britpave[24] notes that joint spacing in reinforced-concrete slabs should be restricted to approximately 17m as the joint movement in longer bays may affect the long-term performance of the joint sealant. It also notes that bays longer than around 9m can be prone to cracking at points intermediate to the joints and that while these cracks do not adversely affect the performance of the pavement if the correct reinforcement and joint spacing have been specified, they could be considered unsightly by some operators.

Figure 14

Idealised joint layout for gravel aggregate concrete slab of thickness 200mm reinforced with EPRO square fabric.



Note

i. Free- movement joint – expansion spacing for cold weather construction.
ii. Bay sizes could be rationalised so that sheets of fabric do not have to be cut.

Fibre-reinforced concrete

It is not at present possible to develop a theoretical relationship between joint spacing and $R_{e,3}$ value for steel-fibre-reinforced floors. TR 34[1] gives guidance on the spacing of joints in ground-supported slabs and their capacity to transfer loads. However, it gives no guidance when using macro-synthetic fibres. Nevertheless, fibre suppliers have suggested, based on their experience gained from constructing external slabs, that joints should be provided as shown in Table 14. As for joint spacing in slabs with fabric reinforcement, the joint spacings indicated are dependent on achieving the concrete mix requirements described elsewhere and on good curing.

Table 13

Suggested joint spacing for unreinforced and conventionally reinforced concrete.

Paving type	Joint type	Maximum spacing of joints (m)			
		Paving thickness (mm)			
		Gravel aggregate		Limestone aggregate	
		≤200	>200	≤200	>200
EPR0 unreinforced: With no ties or load transfer at joints	Free-movement joint – plain	4	5	5	6
	Free-movement joint – expansion:				
	Cold-weather construction	80	100	100	120
	Construction at other times	180	200	200	240
EPR0 unreinforced: With ties or load transfer at joints	Restrained-movement joint	4	5	5	6
	Free-movement joint – contraction	8	10	10	12
	Free-movement joint – expansion:				
	Cold-weather construction	80	100	100	120
	Construction at other times	160	200	200	240
EPR0 reinforced: Fabric continuous between contraction joints	Restrained-movement joint	7	9	9	11
	Free-movement joint – contraction	14	18	18	22**
	Free movement joint – expansion:				
	Cold-weather construction	84	108	108	110
	Construction at other times	168	216	216	220
EPR1 reinforced:	Restrained-movement joint	N/R*	N/R*	N/R*	N/R*
	Free-movement joint – contraction	18**	21**	22**	25**
	Free-movement joint – expansion:				
	Cold-weather construction	90	105	110	125
	Construction at other times	180	210	220	250
EPR2 reinforced:	Restrained-movement joint	N/R*	N/R*	N/R*	N/R*
	Free-movement joint – contraction	24**	25**	25**	25**
	Free-movement – expansion:				
	Cold-weather construction	96	100	100	125
	Construction at other times	192	200	200	250

Note

i. Table based on Maynard[10] and Knapton[11]

ii. Isolation joints are recommended when paving abuts fixed items such as precast slot drains or buildings.

iii. Bay proportions: the length to width of unreinforced and nominally reinforced slab bays should ideally be 1.0 and should not exceed 1.5.

iv. It is essential that the concrete mix requirements given elsewhere are adhered to strictly and that slabs are well cured.

* N/R = not required, but fine cracks within bays could occur.

** Mid-bay cracking may occur.

Table 14

Suggested joint spacing for fibre-reinforced concrete.

$R_{e,3}$	Maximum joint spacing (m)	Comments
0.3	5	Could be without dowels but an increase in slab thickness would be required (see above)
0.4	9	Dowelled joints
0.5	17	Dowelled joints

Note

Check joint spacings are acceptable to the fibre producer.

6. Materials

The specification of the materials used and how they are used in the construction of external in-situ concrete paving are important in achieving the design requirements specified and its intended working life.

6.1 Foundation

6.1.1 Sub-base

Type 1

In an unbound sub-base, the top 150mm should be of material meeting the requirements for Type 1 sub-base as detailed in the Highways Agency *Manual of contract documents for highway works*, MCHW1, Clause 803.[9]

Type 2

Type 2 sub-base material as detailed in the same Series of Highways Agency *Manual of contract documents for highway works*,[9] should generally not be used for the upper 150mm layer of any sub-base because of its potentially poor grading. If Type 2 material is to be used in the top 150mm layer of sub-base, the grading must be such that the required degree of compaction can be achieved with the available plant and such that it can form a suitable and stable running surface for construction traffic. Type 2 can be used for the lower layers of any sub-base or could be used as capping.

Crushed concrete

Crushed concrete may be used as a Type 1 or Type 2 material provided that it meets the requirements of the Highways Agency *Manual of contract documents for highway works*,MCHW1, Series 800.[9]

Hydraulically bound mixtures (HBMs)

There are a number of different ways of producing HBMs for use in pavement construction. These are:

- mix in-plant using batching by mass
- mix in-plant using volume batching
- mix in place.

Requirements for HBMs including cement-bound granular materials (CBGMs) are given in Highways Agency *Manual of contract documents for highway works*, MCHW1, Series 800[9] and in Parts 1 to 5 of BS EN 14227.[34] HBM should be CBGM A or CBGM B, C8/10 to Highways Agency *Specification for Highway Works*, MCHW1, Clauses 821 and 822.[9]

6.1.2 Slip membrane

A membrane may be provided to reduce the friction between the sub-base and the slab. The most common membrane is 1200 gauge plastic sheet with an appropriate British Board of Agrément certificate. Alternatively, the plastic sheet may conform to Packaging and Industrial Films Association standards and/or the Building Regulations.

6.2 Paving concrete constituents

6.2.1 Cements and combinations

Any cement or combination listed in BS EN 206-1[35] and Parts 1 and 2 of BS 8500[36] can be used in concrete for pavements subject to the guidance given below. Cements or combinations containing fly ash can require higher dosages of air-entraining admixtures to achieve the specified air content. However, air content variation is not solely caused by the concrete constituents. Changes in consistence and ambient and/or concrete temperature can also affect air content.

Weather conditions can also play their part in choice of the appropriate cement or combination. The different rate of hydration associated with the use of fly ash (pfa) and ground granulated blastfurnace slag (ggbs) could be an advantage in periods of hot weather but should be carefully considered in colder periods due to the longer period before finishing operations can start and slower strength gain.

The specifier is advised to discuss his requirements with the concrete producer prior to commencement of construction.

Portland cement (CEM I)

Portland cement concretes can usually be air-entrained consistently when good production control is in place. In low temperatures Portland cements may be required so that finishing operations are not delayed. In high temperatures Portland cement concretes may stiffen too rapidly and may not give sufficient time to provide the specified textured finish.

Mixer combinations

Mixer combinations (CEM I with fly ash or ground granulated blastfurnace slag, or factory-produced composite cements) may be beneficial in warm weather to reduce the risk of rapid stiffening of the concrete. Normally, ggbs content should be limited to a maximum of 55% otherwise more rigorous curing procedures would have to be adopted. Highways Agency *Manual of contract documents for highway works*, MCHW1, Table 10/2, Clause 1001[9] limits the fly ash content of a combination to 25% and the ggbs content to 35% because of concerns about freeze–thaw attack on all but the strongest concrete.

Sulfate-resisting cement

Sulfate-resisting cement conforming to BS 4027[37] is generally not required for paving and is becoming more difficult to obtain in bulk. Suitable combinations of CEM I and fly ash or ggbs, or equivalent factory-produced composite cements, are commonly used to provide sulfate resistance.[36]

Portland limestone cements

There is little information or current UK experience of the use of Portland limestone cement in industrial paving.

6.2.2 Aggregates

All aggregates for paving concrete should be freeze–thaw resistant. Requirements are given in BS 8500.[36] Aggregates should conform to BS EN 12620[38] and PD 6682-1[39] with the exception that Los Angeles Abrasion requirements may be relaxed in some circumstances. In some parts of the country there is a long history of successful use in pavement concrete of aggregates which do not meet the full requirements of the standards, particularly in respect of Los Angeles Abrasion category. In these circumstances, the Los Angeles Abrasion requirement can be relaxed.

In the case of exposed aggregate finishes, grading, flakiness index and polishing resistance should also be specified. Requirements for a range of situations are given in Highways Agency *Design manual for roads and bridges*, Volume 7, Section 5, Part 1, (HD36/06).[7]

Recycled concrete aggregates may be suitable for use in industrial paving provided it can be demonstrated that they have the required freeze–thaw and wear resistance characteristics.

6.2.3 Admixtures

Admixtures are chemicals added to concrete, usually in relatively small amounts, in order to modify the properties of the fresh or hardened concrete. They are usually supplied as a solution and dispersed as the batching and mixing progresses.

Almost all types of admixtures are covered by European or national standards that require them to meet basic performance requirements. The main standard is BS EN 934-2.[40]

The main admixture types are:

- dispersing (plasticising/water reducing)
- set modifying (accelerating/retarding)
- air entraining
- viscosity modifying
- special purpose (water resisting, under water, shrinkage reducing, corrosion inhibiting).

Some of the more specialised admixtures are not covered by BS EN 934-2 but by BS 8443.[41]

6.3 Specification and supply of paving concrete

Concrete should be specified and supplied in accordance with BS EN 206-1[35] and BS 8500[36] under which the purchaser specifies the concrete. However, in practice, it is usually the designer who decides most of the requirements and passes them to the contractor. There are a number of methods by which concrete can be specified to BS EN 206-1 and BS 8500. Designed or designated concretes are most appropriate for external paving.

For designed concretes, the specifier chooses the mix parameters required for the work. For designated concretes, the specifier chooses a concrete designation from a list of typical applications given in Table A.13 of BS 8500 Part 1. The ready-mixed concrete producer is responsible for producing the chosen designated concrete subject to the strength, minimum cement content, maximum water/cement ratio and cement type requirements of Table A.14 of BS 8500 Part 1.

6.4 Paving concrete properties

6.4.1 Strength

For most purposes, a strength class C28/35 with air entrainment should be specified, as this gives the greatest possible range of options for the contractor in purchasing the concrete and is the minimum class (with air entrainment) to provide resistance to freeze–thaw attack when de-icing salts are present. Some exposure classes may require higher strength as discussed below.

6.4.2 Durability

Exposure classes

The relevant BS EN 206-1[35] and BS 8500-1[36] exposure classes for external paving are:

a. Applicable to both reinforced and unreinforced paving
   - ☐ Freeze–thaw = **XF4** (or **XF3** in the unlikely circumstance that there is no possibility of exposure to de-icing salts including salt carried in on the wheels of vehicles).

b. Applicable to reinforced paving only
   - ☐ Carbonation-induced corrosion = **XC3/4**.
   - ☐ Corrosion induced by chlorides other than sea water (e.g. de-icing salts) = **XD3** (but see below).
   - ☐ Corrosion induced by chlorides from sea water:
     - **XS1** – Pavements close to sea and subject to airborne spray but not in direct contact with sea water.
     - **XS3** – Pavements subject to direct splashing by the sea, e.g. marine promenades.

Table 15 illustrates whether various possible specifications meet the requirements for these exposures. The designated concretes do not meet XD3 exposure classification and neither does a C28/35 air-entrained designed concrete. Although these concretes are theoretically unsuitable for reinforced paving because of the possibility of reinforcement corrosion, there are many millions of square metres of reinforced paving constructed of C28/35 air-entrained concrete which have performed very satisfactorily over many years. In general, external industrial paving is reinforced to control cracking and not for structural purposes. This report takes the practical view that for industrial paving, reinforcement to the degree shown in Section 3.5 is only for crack control and that C28/35 air-entrained concrete has been demonstrated by experience to be durable under XD3 exposure. In these circumstances, PAV2 and RC40/50XF are also considered to meet XD3 exposure. This view is reinforced by a note in section A.4.3 Of BS 8500-1 which states that because pavements and hardstandings often have an intended working life less than 50 years, consideration could be given to relaxing the requirements related

Table 15
Summary of parameters for possible paving concretes with 20mm freeze–thaw-resisting aggregate.

	Designated concretes		Designed concretes						
	PAV2	RC40/50XF*	C28/35	C32/40[1]		C40/50*			
Strength class	C28/35[2]	C40/50[2]	C28/35	C32/40		C40/50			
Maximum water/cement ratio	0.55[2]	0.45[2]	0.55	0.50		0.45		0.40	
Minimum cement content (kg/m³)	300[2]	340[2]	320	340		360		380	380
Minimum air content (%)[3]	3.5[2]	None	3.5	3.5		None		None	None
Permitted cement types[4]	A,B	A,B	A,B	A	B	A	B[5]	A	B[5]
Meets exposure class:									
XF4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
XC3/4 (nominal cover mm)[6]	Yes (50)	Yes (50)	Yes (50)	Yes (50)	Yes (50)	Yes (50)	Yes (50)	Yes (50)	Yes (50)
XD3 (nominal cover mm)[6]	No[3]	No[7]	No[7]	No	Yes (65)	Yes (65)	Yes (60)	Yes (60)	Yes (55)
XS1 (nominal cover mm)[6]	No	Yes (55)	No[8]	Yes (55)	Yes (55)	Yes (50)	Yes (50)	Yes (50)	Yes (50)
XS3 (nominal cover mm)[6]	No	No[9]	No	No	Yes (65)	No	Yes (60)	Yes (65)	Yes (55)

Note
1. There may be difficulty in achieving strength class C32/40 with air-entrained concrete with some aggregates.
2. Specifying a PAV2 or RC40/50XF should provide these limiting values.
3. Roller-compacted concrete is not air-entrained.
4. Group A consists of CEM I, CEMIIA and CEMIIB-S.and Group B consists of CEMIIB-V and CEMIIIA.
5. Note that Section 6.2.1 limits ggbs content for cement to 55% for use in hardstandings.
6. The nominal reinforcement cover values listed in brackets in the table are based on the nominal covers listed in BS 8500-1,[36] taking 15mm as the fixing tolerance, but subject to a least value of nominal cover of 50mm.
7. See Section 6.4.2 for slabs reinforced only for crack control; least value of nominal cover of 50mm.
8. Yes for cement or combination Group B with 60mm cover.
9. Yes for cement or combination Group B with 65mm cover.
* There is concern about the freeze–thaw durability of non-air-entrained concrete in hardstandings subject to de-icing salts (most hardstandings).

to corrosion of reinforcement due to chlorides. If however, an area of paving is reinforced for structural purposes and/or reinforced with relatively high percentages of reinforcement (for example as a continuously reinforced concrete pavement), designed concrete meeting XD3 and XF4 requirements should be used.

BS EN 206-1 Table F.1[35] recommends 4% (minimum 3.5%) air-entrainment for XF1, XF2 and XF3 exposure classes. BS 8500-1[36] is more ambivalent. Section A.4.3 notes that "consideration should be given" to using the air-entrained option for pavements and hardstandings because it has superior resistance to freeze–thaw attack. On the other hand Table A.8 which gives limiting values for composition and properties of concrete to resist freezing and thawing' permits the use of a non-air-entrained C40/50 concrete for XF4 conditions, which implies that it may be used for paving.

CIRIA Report C559[42] concludes:

> "Experience in practice has revealed no freeze–thaw problems in the UK with C50 non-air-entrained concrete. However, it is noted that many specifiers have continued to require air-entrained concrete for the most extreme parts of exposure class XF4, e.g. pavements, and therefore some caution is advised. It is recommended to permit the option of C50 non-air-entrained concrete for vertical elements e.g. abutments and walls, but require air-entrained concrete for horizontal surfaces exposed to high water saturation, freezing and de-icing salts."

In view of the lack of experience concerning the long-term durability of C40/50 non-air-entrained concrete in paving subject to freeze–thaw and de-icing salts, it is recommended in this report that in areas of normal risk of freeze–thaw damage and application of de-icing salts, C28/35 or higher-strength class air-entrained concrete should be used, although their may be difficulty in producing higher-strength air-entrained concrete in some parts of the UK. In mild, lowland areas where de-icing salts are not used, there may be a case for the use of C40/50 non-air-entrained concrete (RC40/50XF).

It is reported[43] that field performance over many years in harsh climates has shown that roller-compacted concrete without air entrainment has adequate durability to freeze–thaw exposure.

6.4.3 Consistence

Industrial paving is generally manually laid and so the consistence (workability) will need to be significantly higher than that of concrete laid by a paving machine. The consistence specified by the concrete purchaser should be suitable for the proposed method of construction. For manual laying methods it is recommended that the purchaser should specify a minimum slump class S2 (note that the default slump class for RC40/50XF is S3). The manual laying of concrete of slump class S1 would be very difficult and if such concrete is ordered there would always be a high risk that uncontrolled water would be added to the concrete on site to increase the consistence, hence decreasing strength and durability. Unnecessarily high-consistence concrete should not be ordered, as this would increase the risk of bleeding and its attendant problems of poor surface finish and durability.

For machine-laid paving where the concrete is much stiffer, compaction index is the appropriate measure of consistence. Highways Agency *Manual of contract documents for highway works, Notes for Guidance*, MCHW2, Clause 1005[9] suggests compaction index in the range 1.37–1.29 for single-layer construction.

6.4.4 Mechanical resistance

The resistance of the surface of concrete to abrasion will depend on the following factors.

Concrete quality

The concrete quality will be satisfactory provided that the guidance on the concrete specification and aggregates given above is followed AND that any water added to the concrete on site does not lead to the specified maximum water/cement ratio being exceeded. BS EN 206-1[35] permits addition of water at delivery in special cases where this is done

- under the responsibility of the producer
- to bring the consistence to the specified value

and provided that the limiting values permitted by the specification are not exceeded and the quantity of additional water is marked on the delivery ticket. Concrete with the lowest water content consistent with placing and finishing requirements will give optimum mechanical resistance provided that it is effectively cured.

Fibres

Abrasion resistance can be improved by the addition of polypropylene micro-fibres. Steel fibres have been used to give enhanced impact resistance and to provide a surface which is more resistant to the passage of tracked vehicles.

Finishing

The methods of finishing to achieve a satisfactory durable surface are discussed in Chapter 8.

6.5 Concrete testing

Slump

It is recommended that Identity Testing for consistence be undertaken frequently by suitably trained operatives. Sampling and testing should be carried out in accordance with BS EN 12350.[44] On many contracts the majority of loads would be checked. This requirement can be relaxed if the consistence as delivered is found to be well controlled. The allowable limits for slump test results are given in BS 8500.[36]

BS 8500 permits a truck driver to add water in a controlled manner to bring the consistence within the required range provided that the additional water does not lead to a contravention of any maximum water/cement ratio requirement. Clearly, this should only be done within normal time limits after batching and only when the truck is first ready to discharge and not part way through discharge of a load.

Compressive strength

Under BS EN 206-1[35] and BS 8500,[36] the responsibility for conformity testing lies with the producer. However, it is recommended that some Identity Testing for strength be undertaken by the purchaser of the concrete. A rate of one sample per 50 to 100m^3 of concrete delivered is suggested. Site sampling and Identity Testing of concrete should be undertaken strictly in accordance with the requirements of BS EN 206-1,[35] BS 8500,[36] BS EN 12350,[44] and BS EN 12390 *Testing hardened concrete*.[45] Results could be open to challenge and potentially worthless unless the testing is carried out by suitably trained personnel and these standards are followed rigorously.

An alternative would be to carry out strength testing on cores as set out in BS EN 13877-2.[30] However, it would have to be made clear in the contract documents that this is the method of assessing strength compliance. However, as this method of assessment takes into account the influences of workmanship on site and maturity, conformity of the ready-mixed concrete supplied can only be based on samples taken from the delivery truck. The cores could also be used for checking thickness compliance using the method given in BS EN 13863-3.[46] Suitable tolerances for external paving are suggested in Section 7.3.7 of this report.

Air content

It is recommended that testing of air content to BS EN 12350-7[44] is carried out frequently at the start of concrete supply. In many cases this means the majority of loads should be checked. This frequency of testing can be relaxed once it has been established that the air content is well controlled. If the concrete is pumped, the air content should be established after passing through the pump, but clearly this air content measurement can not be used to dispute the air content of the concrete at delivery.

6.6 Steel reinforcement

Steel reinforcement should be obtained through suppliers registered under an accredited quality scheme, such as UK CARES.

Fabric

Steel fabric is the most commonly used reinforcement for paving and should be specified to conform to BS EN 10080[47] and BS 4483.[48] Fabric can be supplied with 'flying ends' – that is, without the end cross-wire – to ease congestion at overlaps. The standard size of welded fabric sheets is 4.8 m × 2.4m but larger sizes can be obtained by special order.

Bars

Conventional bar reinforcement is not commonly used in paving slabs except where a localised increase in load capacity is required. Where such reinforcement is required, bars should be specified to conform to BS EN 10080[47] and BS 4449.[49]

Dowel bars

Round bars are not covered in BS EN 10080[47] or BS 4449.[49] Dowel bars should be specified to BS EN 13877-3[30] but note that this standard only covers bars with diameters of at least 16mm and does not cover square bars.

6.7 Fibres

Steel fibres

Steel fibres should conform to Part 1 of BS EN 14889.[50]

Polymer fibres

Part 2 of BS EN 14889[50] covers polymer fibres.

Macro-synthetic fibres

Macro-synthetic fibres are generally greater than 0.3mm in diameter and the Standard notes that they are generally used where an increase in residual (post-cracking) flexural strength is required.

Micro-synthetic fibres (non-structural)

Some fibre suppliers have test results and/or Agrément certificates to show that concrete containing their polypropylene micro-fibres can pass a BS freeze–thaw test (BS 5075-2[51] now superseded). Due to the absence of any extensive long-term research and experience of fibres influencing freeze–thaw resistance, it is difficult to give any definitive guidance. As there are many fibre types and their performances may vary, pavement designers are strongly recommended to consult fibre suppliers regarding the evidence of long-term performance of particular fibres. If, following discussions with fibre suppliers, it is decided to use micro-synthetic fibres for enhancement of freeze–thaw resistance, the concrete specification requirements should also be established with the fibre supplier.

Micro-synthetic fibres can reduce the incidence of plastic shrinkage cracking (see Concrete Society TR22[52]), but their crack control effectiveness in hardened concrete is very small. They do not fulfil any structural role.

6.8 Joint sealants

Joint sealants should comply with Highways Agency *Manual of contract documents for highway works* MCHW1, Clause 1017.[9]

6.9 Use of recycled materials

Recycled aggregates may be used in the sub-base or in concrete provided that they meet the specified requirements.

7. Construction

Internal floor construction is not usually on the 'critical path' of the construction programme. However, this is not the case for the construction of the external concrete paving. Choosing the right construction methods appropriate to the development and planning the works must be undertaken with due consideration.

7.1 Planning/programme

7.1.1 General

On many modern large distribution or retail developments the area of external concrete paving can be equal to or greater than that of the internal floor area of the building. Clients now usually require that these developments are constructed in short timescales. These short timescales do not give any problems for the internal floor construction because indoors (protected from the weather) where there are no falls and few obstructions, large areas can be constructed very quickly using mechanised methods.

Traditional construction methods for external paving can lead to slower rates of progress and as a result the construction of the paving may be on the 'critical path' of the construction programme. There is thus a need to significantly improve the construction productivity of external concrete paving, by developing simple uncomplicated and 'buildable' designs and by carefully rethinking the construction process.

In the past, external concrete paving was quite often the last major item to be constructed in the development of a facility. However, it is now usually necessary to start the construction of the paving early in the construction programme to make sure that it will be constructed within the contract period. There are distinct advantages in the construction of the paving at a much earlier stage, provided the operations are planned correctly. The completed paving provides a good running surface for construction traffic and a good surface for cranes and access equipment such as scaffolds and scissor lifts working on the adjacent structure. The paving can also be used as a platform for storing construction materials under relatively clean conditions and with easy access. However, the loading should be monitored to make sure that it does not exceed the design capacity of the slab.

The paving should not be constructed until all of the service runs beneath the pavement are in place. Alternatively, service corridors could be left for later infill. Services can be laid through hydraulically bound mixtures (HBM) as they provide a good clean working platform and allow easy plant access. There is also the possibility that construction activities could damage or contaminate the paving if it is heavily trafficked. Heavy plant can inflict significant damage to a new concrete surface, especially if stones are trafficked onto the surface. Tracked plant can destroy a concrete surface before it comes into its intended use.

When mechanised methods are being used, best economy results if the whole area is made available at one time. There are additional advantages if the drainage and service manholes lie outside the paved area.

There are benefits in installing an HBM layer at an early stage in the development. It provides a good over-site environment and a good running surface for vehicles in addition to leading to thinner pavements, as noted in Chapter 4. In this case also, services have to be installed prior to the construction of the HBM layer. The design needs to take into account the fact that, in many cases, construction loads could be greater than those experienced in service and hence there is a need for good liaison between the designer and the contractor.

Increasing the manpower and plant resources available for construction is one way of increasing the rate of progress of the traditional construction of hardstanding, but this may not give any improvements in construction productivity.

7.1.2 Responsibilities

Work on the sub-base and formation and the concrete pavement may be contracted to separate parties. Their separate responsibilities should be clearly identified. The sub-base may be placed early in a contract to provide a running surface for deliveries and plant servicing other construction activities on the site. This being the case, the integrity and level of the finished sub-base should be established before it is handed over to the pavement contractor.

7.1.3 Plant access requirements

If the sub-base surface is to be extensively used as a temporary running surface for site traffic, care is needed to ensure that the traffic does not damage the subgrade and/or sub-base. If used for temporary traffic it may be necessary to increase the thickness of the sub-base or provide a capping layer where the subgrade CBR is low. The condition of the sub-base and subgrade should be checked prior to the construction of the concrete slab and any damaged areas or contaminated areas made good.

7.1.4 Foundation treatment

Pavements may be constructed either on natural ground or on fill. In both cases there is a requirement that they provide uniform support. Any soft spots in natural ground should be excavated and replaced. The replacement material should be placed and compacted to achieve properties similar to those of the surrounding soil. Excavations for drains and other services should also be backfilled in a similar manner.

7.2 Foundation

7.2.1 Fill and capping

Imported or site recycled material used to replace unsuitable material or to raise ground level must be stable. Grading and moisture content of fill material must be such that the material can be adequately compacted. Details of fill materials and compaction plant and procedures are given in Highways Agency *Manual of contract documents for highway works*, MCHW1, Clauses 608 and 613 to 615.[9]

7.2.2 Sub-base

Sub-bases should normally be constructed from stable, well-graded frost-resistant Type 1 material or hydraulically bound material. In both cases they should comply with, and be laid in accordance with, the Highways Agency *Manual of contract documents for highway works,* MCHW1, Series 800.[9]

Any final trimming of the surface should leave the sub-base homogeneous and well compacted. Sand may be used for closing any coarser-grained patches on the surface of the sub-base but it should not form a layer any more than 5 mm thick.

The finished surface of the sub-base should be "well closed and free from movement under construction plant and from ridges, cracks, loose material, potholes, ruts or other defects" as required by the Highways Agency *Manual of contract documents for highway works,* MCHW1, Series 800.[9]

The Highways Agency *Design Manual for Roads and Bridges,* Volume 7, Section 2, Part2 (HD25/94)[7] requires a bound sub-base for concrete highway pavements. However, bound sub-bases are not commonly used for paving at industrial premises. There are some advantages in the use of bound sub-bases. They can provide a good working platform for the construction of the concrete paving, which is particularly important when reinforcement is to be included. Saving in pavement thickness can also be made when a bound sub-base is used (refer to Chapter 4). A broad range of recycled and secondary materials may be used in the production of hydraulically bound sub-bases.

7.2.3 Membrane

If a separation membrane above the sub-base is required, it is important that it is laid without creases. Overlaps of at least 300 mm should be provided at the edges and the ends. Care should be taken to prevent damage to the membrane during construction operations. Any damaged areas should be cut out and replaced, providing the 300 mm overlap at the patch edges.

7.3 Pavement

7.3.1 Construction methods

Details of various methods of pavement construction are given in Table 16. Currently relatively few areas of industrial paving at warehouse and retail developments are constructed using mechanised methods, and generally manual construction methods are used, although the use of mechanised methods of construction is increasing. This is different from the situation of concrete pavements for highways and airports where mechanised construction is very common. An increase in the use of mechanised construction is required to increase production rates and productivity.

Laser Screed techniques, which have been in successful use for internal industrial ground floors for many years, are being used for external paving. More compact equipment is now available which makes the use of this technique more feasible for smaller projects than was previously the case.

Table 16
Comparison of methods of construction.

Method	Advantages	Disadvantages	Comments
Manual laying			
Hit and miss bays	Simple. Low mobilisation costs. Requires minimal plant. Area at risk of weather damage can be very low. Easy to finish	Very low production rate. Lots of formed joints. Labour-intensive	Too slow for most uses.
Narrow strips (up to 5 or 6 m)	Simple method. Quicker than hit and miss laying. Low mobilisation costs. Requires minimal plant. Area at risk of weather damage relatively low. Easy to finish	Relatively low production rate. Many formed joints	Common method of laying external paving
Wide strips (over 6 m)	Simple method. Quicker than narrow strips	Area at risk of weather damage could be high. More difficult to finish. May require sawn centre longitudinal joints. May require more specialist plant. Can lead to difficulty in achieving tolerances	Could be used to speed up production over that of narrow strips
Large bays	Simple method. High production rate	Area at risk of weather damage could be very high. More difficult to finish	
Machine laying			
Laser Screed large bays	Rapid production rates. Plant readily available	May be difficult to finish on large areas. Difficult to achieve good brushed finish. Exposure to weather risks high	Faster laying rates if no fabric reinforcement or load transfer devices. May need on-site batching plant to realise full benefits of increased production rates
Slipforming between fixed forms	Rapid production rates. Easy to finish	High mobilisation and plant costs. Low availability of suitable plant. Needs special concretes. Needs to be laid by specialist contractors	Would only be suitable for very large areas of paving. Faster production rates if no reinforcement and no load transfer devices. Slipformers prefer air-entrained concrete because of lubricating effect. May need on-site batching plant to realise full benefits of increased production rate
Roller-compacted concrete	High production rate. No reinforcement	Surface characteristics are different – not as aesthetically pleasing as a brushed surface	Needs large area. Semi-dry concrete. External compaction effort. Widely used in USA and beginning to be used in UK. Should be considered for heavily loaded areas or areas subject to impact loads (waste transfer stations)

Roller-compacted concrete (RCC) can be used for industrial paving. RCC is a zero slump concrete, placed by a modified asphalt paving machine, and compacted using conventional vibrating rollers.

As a general guide for mechanised laying:

- ☐ RCC becomes economic for areas greater than 5000m^2.
- ☐ Slipform paving becomes economic for areas above 5000m^2.
- ☐ Laser Screed construction becomes economic for pour areas above 1000–1500m^2 with production rates of around 4000m^2 in an 8-hour shift.
- ☐ Construction using smaller walk-behind Laser Screeds becomes economic for areas above 500m^2 with production rates up to 2000m^2 in an 8-hour shift.

7.3.2 Machine lay

Laser Screed

Laser Screed techniques have been widely used in the construction of industrial floors and are just as capable of being employed on external projects. Some additional considerations are however required.

The Laser Screed comprises a four-wheeled tractor unit on which is mounted a telescopic boom with a screed head up to 3.8m wide. Concrete is discharged from the concrete truck in strips 5m wide and up to 50m long. The Laser Screed works from one side to the other across this concrete face, cutting, levelling and compacting in one pass. When the machine reaches the end of the face, it returns to the left-hand side and starts again. The process is known as mechanised large bay construction. Production rates in excess of 4000m^2 per day are quite realistic. Logistics are therefore more critical than for smaller hand-laid areas. Below are some areas for consideration.

- ☐ Large-area external pours pose significant risks in the exposure to adverse weather conditions. It is important that good weather forecasts are obtained and consulted prior to starting large-area external pours. If adverse weather is forecast, the pour should be postponed or measures put in place to mitigate the risk of damage to the newly laid concrete.
- ☐ Sufficient ground should be prepared in advance of the concrete pour so that good rates of productivity are maintained.
- ☐ Sufficient and consistent concrete supplies are required to reduce the potential for cold-joint formation.
- ☐ Consideration should be given to joint and reinforcement detailing to facilitate rapid mechanised construction.
- ☐ Pavement drainage and falls should be designed to facilitate mechanised construction.
- ☐ The nature of textured surface finishes should be agreed.
- ☐ Obstructions can disrupt the process and should be avoided.

Mechanised large bay construction continues to evolve. Recently, a walk-behind Laser Screed has been introduced. This also employs the principle of using a laser beam to control the height of the screed head but the method of working is somewhat different. Production rates of 2000m^2 in an 8-hour shift are not uncommon.

Another recent advance is the introduction of computer software that, in conjunction with a robotic control station, has the ability to provide curved and contoured surface profiles. This same equipment can be used to control the cutting of the sub-base using a grader or dozer. The same data are then used to direct the Laser Screed, ensuring a constant depth slab and minimising material wastage.

Slipform construction

Industrial paving can be constructed using slipform paving machines. This would be undertaken by specialist contractors. A slipform paving machine effectively extrudes a long strip of concrete paving onto the sub-base. No formwork is needed and good control of the surface profile is possible. The same considerations discussed above for mechanised laying using a Laser Screed machine also apply to construction using a slipform paving machine. Slipforming requires the use of well-controlled and cohesive concrete of low workability. Thus the supply of the concrete should be the responsibility of the specialist slipforming contractor. Slipform paving in long strips is relatively easy to protect against the weather by tenting and it is easy to insert a stop-end at the onset of heavy rain.

7.3.3 Hand lay

Strip

The long strip method of construction requires more edge formwork than large pours and also leads to a greater length of formed joints. Timber forms have been found to give better control than steel. The method is less susceptible to wet-weather problems as it is relatively easy to provide covers for recently poured areas. The use of forms permits the production of a rounded upper edge to the slab at the joint.

Thin/wide bay

Thin bays. These are bays/long strips up to 5 or 6m wide, that require no induced longitudinal joint.

Wide bays. These are bays/long strips that are over 6m wide. They may require one or more induced longitudinal stress relief joints, depending on the bay width, slab depth and reinforcement detailed. Wide bays could be machine laid or manually constructed using a long vibrating beam, e.g. a 'razorback' screed.

7.3.4 Roller-compacted

As is the case with other forms of mechanised construction, the sub-base must be capable of carrying construction equipment without deformation. RCC has the same basic constituents as conventional concrete, but with much lower water content, giving a mix stiff enough to be compacted by vibratory rollers. Site mixing of concrete is recommended in order to maintain continuity of supply while satisfying the high output of the paving equipment.

Compaction of RCC is monitored by use of a nuclear density meter and continues until the required density has been achieved. Adherence to a strict curing regime is required and if a sprayed curing membrane is applied, it must be uniform and void-free.

Joints to control cracking can be wet-formed or saw-cut.

The resulting RCC surface is not as smooth as a slipformed or panned finish, so a common use of RCC is for industrial hardstandings where traffic speeds are low and a high-strength pavement is required.

7.3.5 Ramps

Ramps are usually constructed using conventional concreting techniques with side forms. The concrete needs to be sufficiently stiff to enable the top surface to be constructed without sagging or running. As ramps are likely to be used by fork-lift trucks, a tamped finish is not suitable.

Table 17
Plant and equipment for different pavement construction techniques.

Method	Forms	Placing	Compaction	Finishing
Walk-behind Laser Screed	Edge forms of steel or timber to pour perimeter	Straight from the concrete truck	Will compact up to 250mm slab. Beyond this, supplementary poker vibration required	Brush finish, long handled brush
Laser Screed	Edge forms of steel or timber to pour perimeter	Straight from the concrete truck	Laser screed will compact up to a 300mm slab	Brush finish, long handled brush
Slipforming	Not required	Depends on machine type	By slipform machine	Brush finish, applied transversely
Roller-compacted concrete	Not used	High-compaction. asphalt paver	Vibrating steel drummed roller. Pneumatically tyred roller (PTR)	Curing agent sprayer. Joint cutter
Hand lay	Side and end forms of steel or timber	Straight from the concrete truck	Poker. Vibrating beams	Brush finish applied transversely

7.3.6 Plant and equipment

The items of plant and equipment generally used in each of the forms of construction are set out in Table 17.

7.3.7 Tolerances

The following are considered to be minimum acceptable standards for trafficked areas. Modern construction methods are capable of achieving closer tolerances. Closer tolerances may be required on pedestrian areas.

Top surface levels: ±15mm from the design level. The ±6mm range in the Highways Agency *Manual of contract documents for highway works*, MCHW1, Clause 702 and Table 17[9]) is too onerous for industrial paving and is not necessary at the slow traffic speeds involved in many situations. An additional requirement is that there should be no ponding.

Surface regularity: Not more than 10mm deviation under a 2m straight edge using the method in Annex C of BS 8204-1[53] (does not apply at changes in gradient). Steps at joints to be not greater than 5mm.

Top of sub-base level: Ideally +10 to −30mm, as per the Highways Agency *Manual of contract documents for highway works,* Series 700 specification.[9] This may be unacceptable in some circumstances, i.e. in cases where the thickness of the paving is critical. An alternative range could be +0 to −40mm.

Pavement width: +50 to −25mm of the design width.

Setting out: Within 25mm of the specified location shown on the contract drawings.

Slab thickness: −20mm to +35mm. (Note: Good control of the sub-base and concrete surfaces is required to meet these tolerances.) BS EN 13863-3 [46] provides a method for determining the thickness of slabs from cores. BS EN 13877[30] suggests tolerance categories.

Ramps: Surface level on uniform inclines, within ±10mm of straight line drawn between actual base level and actual top level. Surface regularity, ±10mm under a 2m straight edge using the method in Annex C of BS 8204-1.[53]

7.3.8 Curing

No matter which method of construction is adopted, it is extremely important that the surface of the newly constructed slab is protected from loss of moisture. Rapid loss of moisture can cause plastic shrinkage cracking and may also result in a dusty surface. These problems can be controlled by appropriate curing measures. However, there are some practical difficulties. If a spray-applied curing compound is to be used it cannot be applied until the concrete has lost its free surface water and the textured finish to the surface has been produced. Plastic shrinkage cracks may have already started to form at this stage. The concrete is at most risk of plastic shrinkage cracking during the period between initial compaction and surface levelling to the application of curing. Wind is a major factor in the formation of this type of cracking and therefore even if a slight wind is present, it may be necessary to introduce other protective measures. One possibility is to cover the surface with a well-secured polythene sheet after the surface has been floated and to apply curing membrane immediately after production of the brushed finish or other surface texture. The use of micro-synthetic fibres in the concrete can reduce the incidence of plastic shrinkage cracking.

7.4 Working in adverse weather

7.4.1 Weather considerations

By its nature, external paving is constructed in exposed locations and is subject to the vagaries of the elements. As with many other construction operations, forward planning is the secret of dealing with adverse weather conditions. In the UK, prolonged periods of high or low temperature are unusual but the same cannot be said of wet weather. Nonetheless, for any particular geographical location within the UK, there are likely to be several days each year on which high or low temperature conditions could adversely affect concreting operations. One simple but effective expedient is to obtain local weather forecasts and delay or bring forward concrete pours, if the programme permits. From a wider perspective, it would be advantageous if the external paving was not the last activity on site, leaving no room for programme slippage, since the quality of paving can be significantly affected by adverse weather.

7.4.2 Wet weather

Wet-weather problems

The main effect of wet weather is to make concrete finishing and the production of a textured surface very difficult or impossible. Concrete has to be reasonably stiff to accept a textured finish. Heavy rain can make the surface so wet that it will not retain the texture. In some cases, it can be so bad that the surface is left weak and liable to dusting. Heavy rain can also cause pock-marks in a previously finished surface.

Control measures

There is little that can be done to protect a large area of paving from the rain. The best solution is to check the weather forecast and avoid placing on days when prolonged or heavy rain is expected. It may be possible to protect finished areas with polythene sheeting but it is necessary to secure the sheet and deal with any runoff. It should be noted that sheeting may result in marks on the concrete. Long strip pours can be tented.

Areas which are affected by rain can often be satisfactorily planed and textured.

7.4.3 Hot weather

The adverse effects of hot weather are not simply related to high temperature. An extremely hot day with high humidity and little wind may not be as demanding as a cooler day with a stiff breeze and low humidity. This is because the latter situation results in greater rate of evaporation of water from concrete surfaces.

Hot-weather problems

Hot weather can affect concrete at all stages from production through to hardening and beyond. Most of the adverse effects are a consequence of the increased rate of hydration and movement of moisture either within the concrete mass or from an exposed surface. Moisture movement is of particular concern in external slabs because of their high surface area to volume ratio.

High temperature affects both the initial consistence of concrete and the rate at which consistence reduces. Loss of consistence is due to both loss of moisture from evaporation and the increased rate of the hydration reaction. Lower consistence at site means that there may be difficulty in achieving adequate compaction which can have an effect on both strength and durability. Another consequence of higher temperature is that there is less time available between mixing the concrete and initial set. This can lead to formation of cold joints and difficulties in finishing.

Loss of water from the surface of a slab under hot, dry conditions, particularly if there is an accompanying wind, can result in severe plastic shrinkage cracking.

Control measures

There is not much that can be done in the UK in relation to the upper temperature of concrete delivered to site although measures to reduce temperature are undertaken routinely in hot climates. However, it does make sense to commence concreting operations in the early morning when ingredients of the mix are coolest and to order concrete from the nearest batching plant to minimise transit times. There could be a clear advantage in using the services of a mobile batching vehicle provided that the quality of concrete is not compromised. This gives the maximum amount of time for concreting operations on site before the concrete starts to set. It also gives the best possibility of matching the rate of delivery to operations on site as it eliminates the possibility of delivery trucks being delayed by traffic. Otherwise, the dispatch of trucks from the batching plant should be coordinated with the placing rate to avoid trucks having to wait at site.

It is also worth considering the use of a cement or combination with lower heat evolution or using admixtures to retard set or to increase initial consistence.

The placing and curing operations should be carefully planned with the aims of:

- ☐ reducing any delay so that loss of consistence is minimised
- ☐ making sure that the delivered concrete has the correct consistence and temperature before discharge
- ☐ placing the concrete as near as possible to its final position
- ☐ being able to start the finishing operations when the concrete is in the correct condition
- ☐ initiating and maintaining curing so that there is always sufficient surface moisture to prevent plastic shrinkage cracking.

7.4.4 Cold weather

Concrete can suffer permanent damage if it is allowed to freeze before it has gained sufficient strength. BS 8110-1[54] notes that the temperature of concrete should not be permitted to fall below 5°C until it attains a compressive strength of 5MPa.

Cold-weather problems

The main problem arising from cold weather is the possibility of the formation of ice crystals in the concrete and the breakdown of the surface. Subsidiary problems include slower gain in strength, extended setting times and the fact that bleed water may not evaporate from the surface.

If freezing occurs while the concrete is still in the plastic state, the expansion of the water and ice crystals causes such severe damage that the concrete is unusable. If freezing occurs after set but before the concrete has gained sufficient strength, the paste–aggregate bond is weakened and the strength of the concrete is reduced. The associated increase in porosity reduces durability and abrasion resistance.

Control measures

Planning ahead is essential if a spell of cold weather is not to come as an unpleasant surprise. The required materials should be available and personnel should be briefed on the measures to be taken. In most parts of the UK the first frosts can be expected in November and can be a risk until late April or early May. In the more northerly regions the frost season is somewhat longer and preparations should be in place over a longer period.

The use of cement types or combinations which are slow to set and gain in strength should be avoided during cold weather. Aggregates and water may need to be heated before mixing. It may be advisable to batch concrete with a lower slump than normal to minimise the tendency for bleeding.

As with hot-weather concrete, transit times should be kept to the minimum as, even if concrete has been produced at the right temperature, it can cool significantly during the journey to site. One contributing factor is the speed of revolution of a mixer truck drum and temperature losses can be minimised by not revolving the drum more than is absolutely necessary during delivery.[55]

BS EN 206-1[35] requires a minimum concrete temperature of 5°C at time of delivery. It is worth checking whether the ready-mixed concrete supplier is able to meet this requirement and what measures are in place to comply.

At site, all snow, ice and frost should be removed from the area of the pour. The sub-base must not be in a frozen condition. It may be necessary to place insulating mats on the sub-base for several days before the pour. If the sub-base has become frozen, it may be possible to thaw it using industrial heaters.

Once the concrete has arrived on site, the aim is to place it quickly and then to maintain an adequate temperature until it has gained sufficient strength to withstand freezing conditions. This can be achieved by using insulated mats. When the concrete has reached the required strength the insulation should be eased off the surface and removed gradually to avoid thermal shock. Water curing is not a good idea in near-freezing temperatures as the saturated concrete could suffer damage.

Further information on constructing external slabs in cold weather is contained in a Britpave/Highways Agency report.[56]

8. Surface texture

The production of an acceptable surface texture is not just dependent upon the equipment or the concrete placing gang. It begins with the specifier and continues through all those who are involved with the various processes up until the final stage. This includes the detailer, the author of the specification and bill of quantities, the main contractor's estimator and purchaser, the ready-mixed concrete supplier and the concrete paving contractor.

8.1 General

As is the case for roads, the surface texture of external paving is important in relation to providing good ride quality and skid resistance in wet weather. One significant difference for industrial paving is that traffic speed is lower, but on the other hand there may be a lower provision of crash barriers to contain skidding vehicles and less separation between vehicles and buildings. Wheel noise is important on roads but at the lower vehicle speeds that apply to most parts of external paved areas, this is not a consideration.

Skid resistance of a concrete surface is derived from the introduction of a macro-texture, as opposed to a micro-texture, i.e. a surface that has a noticeable profile rather than just having the excess surface laitance removed.

The paving contractor should endeavour to produce a good standard of uniform finish. However, designers and clients should appreciate that a very high standard of uniformity of texture cannot be produced consistently in practice especially over large areas and there may well be differences between pours constructed on different days. They should also be aware that the surface finish may wear away under the influence of traffic.

8.1.1 Finish specifications and assessment

Most finishing specifications are derived from one of the five main specifications used in the industry. These are as follows:

- ☐ Clause 6.2.7 'Surface finish' from BS 8110[54]
- ☐ Highways Agency *Manual of contract documents for highway works*, Series 1000, Clause 1026 'Finished surface requirements' and Clause 1029 'Texturing of hardened concrete' and Series 1700, Clause 1708 'Concrete-surface finish'[9]
- ☐ Clauses 210 to 520 of section E41 of the *National Building Specification*[57]
- ☐ Clauses 4.6.2 of the *National Structural Concrete Specification*[58]
- ☐ Defence Estates Specification.[59]

Particular attention should be given to the achievement of a good ride quality, by careful control and accuracy during the laying process, skid-resistant surface through correct choice of materials and finishing technique, and the overall appearance of the surface. In fibre-reinforced concrete some fibres will be on the surface and, if steel, may corrode. In general, ridges which are a result of a textured finish should not impede the flow of water across the surface – that is, ridges should be aligned with surface falls. A chevron pattern or lines straight across at an angle should be adopted on ramps so that the ridges do not trap water. The specification of finish needs to take into account all users of the surface. Some finishes may be suitable for large rubber-tyred vehicles but not mechanical handling plant such as fork-lifts. The finish may also need to be suitable for pedestrian access by members of the public.

One of the main difficulties with specifying a surface texture is that the appearance of a finish cannot be described easily in words. Assessing the quality of concrete surface finishes is a matter of opinion since it is visual and subjective rather than measurable and objective. Not surprisingly, there is often controversy and disagreement as to whether or not a particular finish that has been achieved is poor, satisfactory, good, or perhaps the best that could be achieved in the circumstances. This being the case, there is a lot to be said for keeping the requirements for external paving simple and for using completed projects as examples of the type of surface required.

8.1.2 Concrete mix design for achieving a good surface texture

This is covered in Chapter 6. To achieve a good surface texture, the concrete should not bleed excessively and there will need to be adequate thickness of surface mortar in which to produce the texture. Good textures cannot be produced on harsh or unclosed surface layers.

8.1.3 Trial bays

Ideally, trial areas of paving should be constructed to assess the proposed method of obtaining the required surface texture. If the construction of the paving is to be a highly mechanised operation using specialist equipment, it may not be practical to undertake trial bays prior to the main installation. If it is required to set a visual standard for the work, this could be done by reference to a previous project. An alternative is to construct a trial bay by hand-lay methods and finish it to achieve the specified texture. Any sample panel constructed should be of a realistic size and ideally should have the same width as the typical paving bays. The trial bay offers a benchmark against which the rest of the work can be judged.

8.2 Worked finishes

This report is concerned with those finishes where the concrete surface itself is worked either while it is still in its plastic stage or after it has hardened. Finishes that are applied as a separate layer on top of the concrete are not covered. The most common worked finishes are discussed in the following sections and a summary is given in Table 18. Different finishes are illustrated in Figure 15.

Achieving a consistent texture on fresh concrete is difficult because it can depend on so many factors. Among these are:

- the consistence of the concrete which can vary substantially between loads
- the capacity and rate of bleeding of the concrete and the time at which it occurs

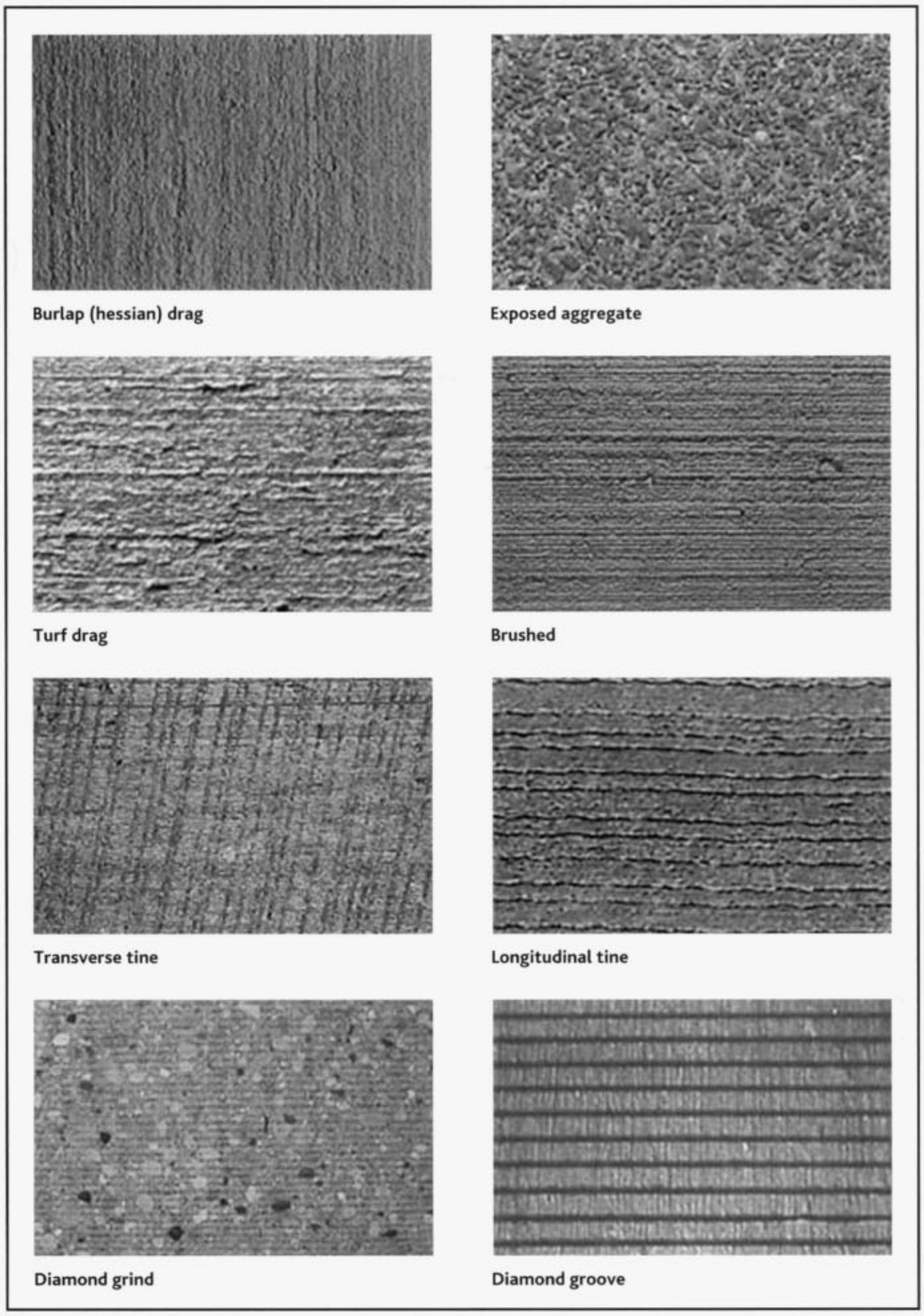
Table 18
Comparison of common finishing techniques.

Method of finish	Advantages	Disadvantages	Comment
Tamping	Simple method	Difficult to control texture. Too rough for mechanical handling equipment. Suitable for narrow bays only. Slow. Hard work for operatives	Not a preferred method
Brushing	Simple method. Texture suitable for MHE	Degree of texture can be difficult to control. Timing of finish critical. Difficult to use on large bays. Risk of rain damage	A good method of finishing. Correct equipment must be used. May wear away quickly in service
Floating	Simple method. Can be used on large bays. Can be used as preparation for other methods	POOR SKID RESISTANCE with heavy panning. Risk of delamination with air-entrained concretes	Method not recommended except as preparation for another method or for smaller bays
Proprietary floats	Floats with grooves can provide skid resistance	Square grooves can pick out aggregate and this could be seen as a blemish	–
Trowelling	–	VERY POOR SKID RESISTANCE. Risk of delamination with air-entrained concretes	Method not recommended
Hessian (burlap) drag	Can be used behind slipform	Not appropriate for steel or macro-synthetic fibre concrete	Use in external paving is pretty rare
Exposed aggregate – using retarders	Can be used on large bays. Can give a good texture	May be weather-sensitive. Need to get rid of liquid produced when washing down. Sharp aggregate could be an H&S issue	Effective method for large bays. Sometimes used in pedestrian areas
Exposed aggregate – open shot blasting	Can be used on large bays. Not weather-sensitive. Can be used on rain-affected bays. Can give a good texture	Messy method. Possible H&S issues. More difficult to control texture than with enclosed blasting. Sharp aggregate could be an H&S issue. More expensive than providing a texture at concreting stage	Not a preferred method due to potential dust problem. Not appropriate for steel fibre-reinforced concrete
Exposed aggregate – enclosed shot blasting	Can be used on large bays. Not weather-sensitive. Can be used on rain-affected bays. Can give a good texture	Sharp aggregate could be an H&S issue. More expensive than providing a texture at concreting stage	Effective method for large bays. Possible remedial measure. Not appropriate for steel fibre-reinforced concrete
Concrete plane	Can produce a good skid-resistant texture. Not weather-sensitive. Can be used on rain-affected bays	Relatively slow method. More expensive than providing a texture at concreting stage	The texture can be made to be similar to a brush texture. A good remedial method of finishing for rain-affected bays. More common as a finishing method in Europe than in Britain
As-rolled roller-compacted concrete	Simple method. Rapid completion of large areas	Sensitive to heavy rain. Open-textured finish	Surface texture similar to asphalt

- the time after placing at which the finishing operations are performed
- the ambient conditions
- the mechanics of the equipment used and the way in which it is applied across the surface.

From the above, the timing of the finishing is of critical importance. Ideally, the finish should be applied when any surface bleed water has gone and the surface is starting to stiffen. If the finish is applied too early, bleed water may be worked into the surface layer, weakening it and leading to a risk of rapid surface wear. If the finish is applied too late, the concrete could be too stiff to produce sufficient texture depth, and drag marks could be left on the surface. These considerations do not apply to textured finishes which are produced on hardened concrete and this can give them a distinct advantage in some circumstances.

Figure 15
Illustrations of different finishes as shown on *http://www.pavement.com*



8.2.1 Tamped finish

Tamped finish is produced, after the concrete surface has been struck off, by raising and lowering the compacting beam or a tamping beam at regular, closely spaced intervals. This typically gives a surface with ridges at spacing of around 20–30mm and around 5mm high but the finish achieved is highly dependent on the skill of the operatives. Ridges are normally aligned at right angles to the direction of travel of vehicles using the paving and preferably also to assist drainage on areas with a fall. Chevron patterns are used on ramps, with the lower end of the tamp mark on the ramp edge to assist drainage.

Tamped finishes are not generally recommended because of difficulty in achieving an even distribution of parallel ridges within a single pour and uniformity of effect from pour to pour. This is because the finish achieved is highly dependent on the consistence and bleed characteristics of the concrete, the length of time since placing and the ambient conditions. However, tamped finishes do have an application in some utilitarian situations when the concrete is laid in narrow strips. A tamped texture may not be appropriate when paving is trafficked by small hard-wheeled vehicles and equipment and it can be difficult for pedestrians.

Floating, whether by hand or machine, can be the first-stage operation in the production of a finished pavement slab. The purpose is to close the surface, remove gross blemishes and bring the pavement within the required flatness tolerances. Floating is not intended to produce a wearing surface but is often a preliminary operation in producing a textured finish. Hand floating with a wooden trowel may be the only option for small or irregularly shaped areas.

8.2.2 Floated and trowelled finishes

Float finishes

Prior to the introduction of power tools, a floated finish was that produced by a large, generally wooden or sometimes metal, hand float moved over the surface when the concrete was still plastic. This produced a flattish slightly textured surface which often contained float marks. Nowadays, the operation is carried out using powered machines fitted with either a large circular pan or large flat metal floats. The timing of machine floating is similar to that of hand floating. Machine floating produces a similar surface to hand floating, with a slightly textured surface often with circular swirl marks from the floating operation. This operation is sometimes called panning. Power floating can sometimes lead to surface delamination of air-entrained concretes.

Another method of floating, namely skip floating, can be carried out on a wet concrete surface to produce a smooth matt appearance. A large, long, narrow float on the end of a knuckled handle is pushed or pulled over the surface of the wet concrete with the leading edge always higher than the rear edge, whichever way it is moving. Skip floats are also known as easy floats or bull floats. The resultant finish tends to have a smooth texture similar to that produced by either hand or power floating, but it usually exhibits slight ridges between each pass of the float. Another problem which seems to be associated with skip floating is that of reinforcement ripple when the surface of the concrete has slight depressions along the line of the top reinforcement, often giving it a quilted appearance. Care is needed in the timing of skip floating. If skip floating is undertaken too early, bleed water may be worked into the surface thereby weakening it and giving a risk of rapid surface wear.

A Laser Screed finish is similar in appearance but a brush attachment can be used to provide texture.

Trowelled finishes

Trowelling follows floating to provide a direct finished wearing surface. When carried out correctly on concrete of the appropriate class, trowelling leaves a smooth, very dense and almost glass-like surface which is generally not appropriate for external paving. Power trowelling of air-entrained concretes is not recommended due to the risk of surface delamination.

8.2.3 Other textured finishes

Textured finishes usually introduce a pattern of fine parallel ridges on the concrete surface. As with tamp marks, the ridges should be at right angles to the direction of motion of vehicles and preferably along the direction of drainage on the slab surface. However, on a surface draining to slot drains, the natural laying direction is parallel to the drains. This being the case, drag finishes will produce small ridges across the drainage path.

Brushed finish

A brushed finish is obtained by pulling a brush over the surface of the fresh concrete, after the surface has been levelled. The type of finish obtained will depend upon the coarseness of the brush bristles and the length and shape of the tufts. Coarse texture is given by stiff-bristled brooms, softer bristles giving medium and light textures. Brushes can have plastic bristles or steel tines of varying gauge and density. Normal manual sweeping brooms produce an unsatisfactory texture for finishing concrete surfaces and should not be used; rather, a purpose-made brush should be used. Such brushes generally have steel bristles or tines and long heads to reduce the number of passes. A commonly used piece of equipment for producing a brush finish is the combined skip float and brush. In use, the skip float is pushed across the bay using the long handle. When the skip float has reached the bay edge the handle is turned which lifts the skip float and lowers the brush head onto the concrete. The brush is then drawn back across the bay. Care is needed with the timing of the use of this equipment. If it is used too early bleed water can be worked into the surface, thus weakening it, and pieces of coarse aggregate may be 'plucked' out of the surface by the brush.

Brushed finishes are suitable for areas trafficked either by vehicular or foot traffic and are also suitable for many types of mechanical handling plant. Brushing transverse to the direction of the traffic either by hand or machine using a stiff brush has been used widely. Its disadvantage is that it is difficult to control the frequency of the striations and the profile of the texture. Hand or mechanical brush finish usually gives striations which are 1.5–3mm deep.

Many of the above comments on the difficulty of obtaining a uniform finish apply particularly to brush finishes. Therefore it must be appreciated that the aesthetic appearance of a brushed finish on large areas may be disappointing.

National Building Specification Clause 230[57] requires a brushed finish to produce a "lightly textured surface". Highways Agency *Manual of contract documents for highway works*, Volume 1, Clause 1031,[9] requires the surface macro-texture to be measured using the volumetric patch technique described in BS EN 13036-1.[60] The requirements are shown in Table 19. The value of 1.0mm for macro-texture depth measured in this way may be greater than necessary for hardstandings, values of 0.5–0.75mm being more the norm.

Brushed finishes are relatively shallow and may quickly wear away under service traffic.

Table 19
Macro-texture depth.
(as given in Table 10/8 of Highways Agency *Manual of contract documents for highway works, Volume 1, Specification for highway works*[9]

Note
i. The typical texture specified for and produced on industrial paving will not be as rough as that on a public highway and it may not meet the texture requirements of the HA specification.

Time of test	Required macro-texture depth (mm)		
	Basis of assessment	Specified value	Tolerance
i. Between 24 hours and 7 days after the construction of the slab or until the slab is first used by traffic	An average of 10 measurements	1.00	±0.25
ii. Not later than 6 weeks before the road is opened to public traffic	An average of 10 measurements	1.00	±0.25 −0.35

Turf drag finish

Turf drag surface finish is produced by trailing an inverted section of artificial turf across the surface on a device that controls time and rate. Striations are 1.5–3mm deep depending on the number of blades in the mat.

Hessian (burlap) drag finish

Hessian or burlap drag surface finish is produced by trailing moistened coarse hessian across the surface on a device that controls time and rate. Striations are 0.5–1mm deep.

Tine finish

Tine surface finish is generally produced using a mechanical device with a tine head (metal rake) that moves across the surface. Texture depends on the tine spacing and regularity. Striation depths are typically in the range 3–6mm with width of up to 3mm.

8.2.4 Exposed aggregate finishes

An exposed aggregate finish, in itself, may not give the necessary degree of skid resistance and the micro-texture of the aggregate needs to be taken into account. For example, some limestone aggregates can develop a polished surface with very low skid resistance. There are requirements for minimum polished stone value and flakiness index for coarse aggregate in Highways Agency *Design manual for roads and bridges*, Volume 7, Section 5, Part 1, (HD36/06).[7]

Abrasive blast finish

National Building Specification[57] guidance note on clause 420 states: "Blasting will not improve the appearance of poor quality concrete and will accentuate irregularities and blemishes." The depth of exposure is dependent on the aggregate size and grading. Blasting a 20mm gap-graded aggregate concrete may expose the aggregate to a depth of 6mm but for a normally-graded aggregate, only around 3mm is likely to be achieved. The cover to any reinforcement should be increased to compensate for the surface loss.

Abrasive blast finishes can be divided into three categories (see C&CA *Appearance Matters 8*,[61], which shows pictures of the finishes):

- light blast, to expose the edges of some coarse aggregate particles
- medium blast, to expose some course aggregate particles
- heavy blast, to expose the large coarse aggregate particles.

Heavy blast is the appropriate category for external paving surfaces. This can be achieved by either open shot blasting or preferably enclosed shot blasting. The abrasive medium is delivered to the surface in a jet of air and removes a thin surface layer. The depth of removal can be controlled depending on the abrasive type and grade and the power of the machine. Ideally an enclosed system should be used where the detritus is removed. Blasting should not be used on steel-fibre-reinforced concrete as it may partly expose fibres in the surface.

Using retarders

A set retarding agent is applied to the surface of the plastic concrete. After a suitable interval, when the bulk of the concrete has hardened but before the retarded surface concrete has gained sufficient strength, the surface is brushed and hosed down to remove the mortar fines. This produces a texture similar to that produced by medium abrasive blasting. Care has to be taken to contain the water used in the process and to dispose of it in a suitable manner.

8.2.5 Grinding and grooving

The thickness of slab initially constructed may have to be increased to take account of the layer to be removed by grinding or grooving.

Power grinding

Power grinding is a finishing technique intended to provide a durable wearing surface. Once the concrete has been compacted, levelled and floated, for example with a skip float, it is allowed to harden. The surface is then ground with a low-speed grinder with closely spaced saw blades to remove 1–6mm of laitance and aggregate. The blade assembly cuts tiny grooves (160–200 grooves/m width) in the pavement surface, providing texture as it levels out surface irregularities.

Diamond grooving/planing

Surface retexturing correctly undertaken using a concrete plane will produce a grooved surface not dissimilar from a brush finish. Grooves are typically 3mm wide and 6mm deep at spacing up to 20mm.

9. In-service assessment

External in-situ concrete pavements, if correctly designed and constructed, should have a long service life and require only limited maintenance. However, some changes in the condition of the pavement over time and some maintenance, especially at joints, are to be expected.

9.1 Monitoring of condition

General

It is strongly recommended that routine monitoring be undertaken at intervals to assess the condition of the pavement at a point in time and to also assess the rate of change in condition. This latter aspect is very important because if there is a rapid rate of deterioration in the condition of the paving it could signify that there may be a problem with the paving and further more detailed investigations are required.

It is recognised that in many cases the users of the paving and the premises which it serves are not necessarily the owners of the paving. However, it is still important that users monitor the condition of the paving because it can affect the efficiency and function of their business. Many tenancy agreements lay the responsibility for repairs on the tenant. Thus it is in the interest of the tenant to monitor the condition and maintain the paving in good condition.

If there is to be a significant change in loading and/or traffic intensities on the paving, or a rapid rate of deterioration is found from the regular monitoring, a structural assessment of the paving may be required. Guidance on the detailed assessment of concrete pavements is given in the Britpave/Highways Agency *Concrete pavement maintenance manual*.[62]

It is recommended that surface condition, drainage, joints, cracking and vertical movement should be checked and the condition recorded during regular monitoring.

Surface condition

Wear and abrasion

Evidence of any loss of surface texture or surface mortar due to wear should be recorded. Some loss of texture or surface mortar is to be expected over time, particularly in heavily trafficked areas, and should not be regarded as unusual. It is relatively common in very heavily trafficked areas of industrial concrete paving to find after several years that the upper surface mortar layer has been lost, giving an exposed aggregate type finish. If there is evidence of rapid or very extensive loss of surface, further investigations may be required because rapid or extensive abrasion could signify problems with the concrete quality at the surface, e.g. inadequate curing, water added to the concrete or non-compliant concrete. The normal brush finish on paving is intended for traffic from wheels with pneumatic tyres and even under this type of traffic some wear will occur. If brush-finished concrete paving is heavily trafficked by vehicles with small hard wheels (of the type that usually run on power-trowelled interior industrial floors), rapid abrasion of the surface is to be expected. Damage can also occur at locations where jockey wheels of trailers are dropped onto the surface.

Freeze–thaw damage

Freeze–thaw damage often becomes apparent as small localised patches of shallow spalling or 'shelling-off' of the upper mortar layer. Eventually, damage may lead to the partial or complete loss of the surface mortar layer and in the worst cases deep pitting of the surface. Freeze–thaw damage may continue indefinitely. If the correct concrete is specified and placed, no significant areas of freeze–thaw damage should occur on concrete paving. If there is evidence of extensive freeze–thaw damage, further investigations are required into the concrete specification and the concrete actually supplied and laid.

Drainage

During the inspection the condition of the pavement drainage should be checked to see if it is working correctly and that it is not blocked with dirt and debris. Also the inspection should check that the gully pots are not full and that slot or trough drains are free-flowing. The inspection should also ascertain if any ponding of water is occurring on the surface. Ponding could be a result of blocked drains, inadequate falls as constructed or settlement of the paving. If ponding indicates that settlement could have occurred, further investigation may be needed, e.g. a level survey and ground investigation.

Joints

Joints are the aspect of paving that require the most maintenance and thus regular monitoring of their condition is very important. Joint sealants must be replaced as necessary so that the joints remain sealed. Unfilled/unsealed joints can lead to surface water percolating down into the sub-base and subgrade, leading to a possible deterioration in the support to the paving. In addition, unfilled joints filled with detritus give an increased risk of joint edge damage.

Cracking

Most cracking that occurs in concrete paving is due to restrained contraction and will not normally affect the performance of the paving. Sometimes the edges of wider cracks may break down under the action of traffic. Some types of cracking could be indicative of other problems, e.g. overloading, poor support, excessive deflections. Table 20 provides some information on the assessment of cracks. Further guidance on the causes of cracking is given in the HA/Britpave *Concrete pavement maintenance manual* [62] and Concrete Society Technical Report 22.[52]

Vertical movement

If significant vertical movement or differential vertical displacement is apparent at joints or cracks, further investigations should be undertaken. Excessive vertical movements at joints or cracks may lead to localised structural failures around the joint or cracks.

9.2 Maintenance and repairs

General

Over its lifetime, concrete paving will require periodic maintenance and possibly repairs. Users of the paving should regularly monitor the condition of the paving and undertake maintenance as and when required. If regular maintenance is delayed or not undertaken there will be an increased risk that repairs will be needed. Regular maintenance is invariably more cost-effective than undertaking infrequent but expensive repairs.

Table 20
Assessment of cracking in conventionally reinforced concrete paving.

Crack type	Crack width	Crack edge damage present	Evidence of vertical movement at crack	Probable causes	Further investigation required	Repairs required
Longitudinal	Narrow	No	No	Restrained contraction	No	No
	Wide	Yes	Yes	Restrained contraction and deflection	Yes	Possibly
Transverse, in middle ⅓ of bay	Narrow	No	No	Restrained contraction	No	No
	Wide	Yes	Yes	Restrained contraction and deflection	Yes	Possibly
Transverse, near joint	Narrow	No	No	Restrained contraction, inoperative contraction joint, misaligned dowels	Monitor	Possibly
	Wide	Yes	Yes		Yes	Yes
Corner cracking	Narrow	No	No	Load-induced failure, poor support, slab too thin	Monitor	Possibly
	Wide	Yes	Yes		Yes	Yes
Cracking close to edges	Narrow	No	No		Monitor	Possibly
	Wide	Yes	Yes		Yes	Yes
Random cracking	Narrow	No	No	Plastic shrinkage, restrained contraction	No	No
	Wide	Yes	No		No	Fill cracks

Note
i. The longitudinal direction is parallel to the long dimension of the bay and/or direction of placing.
ii. The transverse direction is parallel to the short dimension of the bay and/or at right angles to the direction of casting.
iii. Narrow cracks are 1.5 mm or less in width.

Cleaning

Paving should be periodically swept to prevent the accumulation of dirt and debris that could block drains and potentially cause damage to joints and cracks. Drainage channels and gulley pots should also be periodically cleaned out.

Joints

Joints require regular inspection and should be refilled/resealed where necessary. It is important that joints are filled to prevent the accumulation of dirt and debris in the joint. There is a much higher risk of damage to the edges of movement joints if the joint sealant is not maintained. Edge damage may require nosing-type repairs, see the Britpave/Highways Agency *Concrete pavement maintenance manual*.[62]

Surface texture

If the surface texture deteriorates and becomes inadequate for skid-resistance purposes, e.g. due to wear of the surface, the surface of concrete paving can be retextured by mechanical methods, i.e. by using a concrete plane or enclosed shot blasting machine. If retexturing is to be considered, trial areas should be undertaken first for agreement of the method and texture. Any retexturing will clearly affect surface appearance.

Cracking

Some cracking may need repairs – see Table 20. In some cases it will be necessary to replace cracked bays in their entirety. Cracks in conventionally reinforced slabs do not necessarily need to be repaired immediately but should be monitored. Cracks in fibre-reinforced slabs may need more urgent attention where it is necessary to maintain the tying action of the fibres. The effect of the steel fibres could be lost by corrosion if the cracks are not sealed.

Repair methods

Detailed guidance on repair methods is given in the Britpave/Highways Agency *Concrete pavement maintenance manual*.[62]

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Appendix A. Slab thickness – unreinforced and conventionally reinforced pavement – factorial approach

A.1 Slabs with dowelled joints and infrequent wheel loads at pavement edge

The basic equations in TRL RR87[8] outlined in Appendix C are for the situation, which occurs in highways, where wheels can run close to the edge of the carriageway slab. As this means that the loads are close to the 'unsupported' edge there are higher stresses and hence slabs need to be thicker. TRL RR87[8] also gives details of reductions in thickness which apply where there is a tied shoulder giving support to the edge of the road slab. These reductions have been applied in the derivation of the factors applicable to the equation given below as this reflects the situation for most hardstandings where only limited traffic occurs at the edge of the paved area.

Examination of the values generated by the equations in Appendix A has shown that a simplified factorial approach is possible. The factorial equation for slabs where the joints are dowelled and there is only limited traffic on the pavement edge, and for CBRs in the range 3–30% is:

$$\text{Slab thickness} = A \times \text{CBR}^{-0.0378} \text{ (mm)} \qquad \text{(Equation A.1)}$$

rounded up to the next 5mm but not less than:

- 175mm for sub-base EPSB1 with traffic categories EPT1, T1, T2, T3 and T4
- 150mm for sub-base EPSB1 with traffic category EPT0 and sub-base EPSB2 with all traffic categories

where values for A are given in Table A.1.

A.2 Slabs with dowelled joints and frequent wheel loads at pavement edge

The TRL RR87[8] equations give slab thicknesses for the situation where wheels can run close to the pavement edge, i.e. roadways without tied shoulders. Figure 7 of TRL RR87 shows the decrease in slab thickness which can be achieved if a tied shoulder is provided (i.e. no wheels can run near pavement edges). The decrease in thickness is given by:

$$\text{Decrease in slab thickness for tied shoulder} = 0.0658h_{NS} + 12.5 \qquad \text{(Equation A.2)}$$

where h_{NS} is the slab thickness given by the TRL procedure.

The factors in Table A.1 are for the situation where wheel loading occurs only occasionally close to the pavement edge. Reversing the TRL RR87 equation leads to a requirement to **increase** the results of the factorial equation thicknesses when wheel loads are anticipated close to pavement edges (say within 1.5m) by:

Table A.1
Factors to be used in the factorial thickness equation for slabs with dowelled joints and infrequent loading on the pavement edge and for subgrade CBRs in the range 3–30%.

INFREQUENT LOADING									
Traffic class	**Concrete strength class**								
	C28/35			C32/40			C40/50		
	Reinforcement								
	EPR0	EPR1	EPR2	EPR0	EPR1	EPR2	EPR0	EPR1	EPR2
	Factor A for 150 mm Type 1 sub-base (EPSB1)								
EPT0	150 mm slab			150 mm slab			150 mm slab		
EPT1	175 mm slab			175 mm slab					
T1	194						175 mm slab		
T2	218	204	194	201	194				
T3	238	223	206	219	206	194	194		
T4	252	238	220	233	220	203	202	194	
	Factor A for 150 mm HBM sub-base (EPSB2)								
EPT0	150 mm slab			150 mm slab					
EPT1							150 mm slab		
T1	184	169		166					
T2	212	199	184	196	184	166	170	166	
T3	231	218	202	213	201	186	185	175	166
T4	245	232	215	226	215	199	197	187	173

Additional note
Except where specifically shown, the above values are factors to be used in Equation B.1 and not slab thicknesses.

Note
For:
Sub-base classes see Table 2
Traffic classes see Table 6
Reinforcement classes see Table 7.

$$\text{Increase in pavement thickness} = (0.0704h + 13.4)\text{mm} \qquad \text{(Equation A.3)}$$

where h is the slab thickness given by the factorial equation (A.1).

This increase in thickness has been used to derive the A factors given in Table A.2 which can be used in the same factorial equation A.1.

A.3 Slabs with undowelled joints

Slabs with undowelled joints should only be used on cement-bound sub-bases (EPSB2). Where undowelled joints are to be used, the slab thickness indicated by Equation A.1 should be increased by 40mm.

Table A.2

Factors to be used in the factorial thickness equation for slabs with dowelled joints and frequent loading on the pavement edge and for subgrade CBRs in the range 3–30%.

FREQUENT LOADING									
Traffic class	Concrete strength class								
	C28/35			C32/40			C40/50		
	Reinforcement								
	EPR0	EPR1	EPR2	EPR0	EPR1	EPR2	EPR0	EPR1	EPR2
	Factor A for 150mm Type 1 sub-base (EPSB1)								
EPT0	150mm slab			150mm slab			150mm slab		
EPT1	175mm slab			175mm slab					
T1	217	202		201			175mm slab		
T2	248	233	217	230	216	201	202	194	
T3	269	254	236	249	236	219	218	207	194
T4	284	270	251	263	250	233	231	220	205
	Factor A for 150mm HBM sub-base (EPSB2)								
EPT0	150mm slab			150mm slab			150mm slab		
EPT1									
T1	211	198	184	195	183	166	171	166	
T2	242	228	212	224	212	197	196	186	173
T3	262	249	231	242	231	214	212	203	189
T4	277	264	245	256	245	228	225	216	200

Additional note

Except where specifically shown, the above values are factors to be used in Equation B.1 and not slab thicknesses.

Note

For:
Sub-base classes see Table 2
Traffic classes see Table 6
Reinforcement classes see Table 7.

Appendix B. Failure criteria on which TRL RR87 design equations are based

The design thickness equations in TRL RR87[8] are based on a set of defined failure criteria. The failure criteria are different for unreinforced and reinforced slabs

B.1 Unreinforced slabs

The failure criteria for the unreinforced sections of pavement are:

- a crack width equal to or greater than 0.5mm crossing the bay longitudinally or transversely
- a longitudinal and transverse crack intersecting, both starting from an edge and greater than 0.5mm wide, and each longer than 200mm
- corner cracking wider than 1.3mm and more than 200mm radius
- a bay with pumping at a joint or edge
- a replaced or structurally repaired bay.

In addition, some local maintenance to deal with the road surface texture, joint sealants and vertical settlement of bays was required to achieve the design traffic loading.

The design equation includes the number of failed bays at the end of pavement life. In highway design the number of failed bays is often taken as 30% of the bays in the trafficked areas and this value has been adopted in the tabulated values and the factorial approach.

B.2 Reinforced slabs

A bay was considered to have failed when there was at least one full-width wide crack and the rate of wide cracking was increasing.

As the thickness design equations in this report are based on those in TRL RR87,[8] some cracking within bays of pavements designed using them can be anticipated. However, this should not necessarily be considered as the end of the life of the pavement as maintenance procedures are available (see Chapter 9).

Appendix C. Basis of thickness design

C.1 Unreinforced concrete slab

TRL RR87[8] gives the following equation for unreinforced concrete carriageway for the situation where wheel loads can run close to the edge of the slab:

$$\ln(L) = 5.094 \ln(h) + 3.466 \ln(f_{cm,cube}) + 0.4836 \ln(M) + 0.08718 \ln(F) - 40.78$$

which can be rearranged as:

$$h = 2997\left(\frac{L^{0.196}}{f_{cm,cube}^{0.680} M^{0.095} F^{0.017}}\right) \qquad \text{(Equation C.1)}$$

where h = slab thickness (mm)

L = traffic loading over the lifetime of the pavement in millions of standard axles

$f_{cm,cube}$ = concrete <u>mean</u> compressive cube strength.
Note: this is likely to be at least 5MPa greater than the characteristic compressive cube strength and has been taken as (characteristic strength + 7MPa) in the calculation of the tabulated values and the factors in the factorial approach

M = equivalent modulus of a uniform foundation giving the same slab support as the actual foundation (MPa)

F = percentage of failed bays at the end of life; taken as 30 in TRL RR87.[8]

C.2 Conventionally reinforced concrete slab

TRL RR87[8] gives the following equation for conventionally reinforced (fabric) concrete carriageway, again for the case where wheel loads can run close to the edge of the slab:

$$\mathrm{Ln}(L) = 4.786 \,\mathrm{Ln}(h) + 1.418 \,\mathrm{Ln}(A_s) + 3.171 \,\mathrm{Ln}(f_{cm,cube}) + 0.3255 \,\mathrm{Ln}(M) - 45.15$$

which can be rearranged as:

$$h = 12503\left(\frac{L^{0.209}}{f_{cm,cube}^{0.663} A_s^{0.296} M^{0.068}}\right) \qquad \text{(Equation C.2)}$$

where A_s = area of reinforcement inmm^2 per m width and the other symbols have the meanings shown above.

Appendix D. Derivation of equivalent foundation moduli of standard sub-bases

D.1 Background

The thickness design method of TRL RR87[8] outlined in Appendix C uses equivalent foundation modulus as one of the variables. This parameter is described as the modulus of a uniform foundation providing the same support to the slab as the actual foundation. For the purpose of the present report, it was decided that CBR would be an easier starting-point. It was also decided to adopt two standard sub-bases (150mm Highways Agency Type 1, EPSB1 and 150mm HBM, EPSB2) which are thought to be common in external paving applications, as standard.

This Appendix describes how the equivalent foundation moduli of these standard sub-bases on subgrades with a range of CBRs were determined.

D.2 Method

The equivalent foundation moduli for both of the sub-base classes were determined as follows:

1. BISAR analysis was undertaken to calculate deflection of a 151mm diameter plate under a load of 40kN. Analyses were undertaken for each of the range of typical foundations in Table 2 of TRL RR87.
2. Foundation deflections obtained from Step (1) were plotted against the equivalent foundation moduli given in Table 2 of TRL RR87.
3. Moduli were obtained for a range of CBRs using the equation in TRL LR 1132[E.1].
4. BISAR analysis was undertaken to calculate deflection of a 151mm diameter plate under a load of 40kN. Analyses were undertaken for both 150mm Type 1 and 150mm HBM on material with various CBRs in the range 1–30%.
5. Equivalent foundation moduli were determined for each CBR using the relationship developed in Step (2) above.
6. Graphs of Equivalent Foundation Modulus (MPa) versus CBR (%) were plotted and a power relationship was established. The graphs are shown in Figure D.1 and the relationships are:

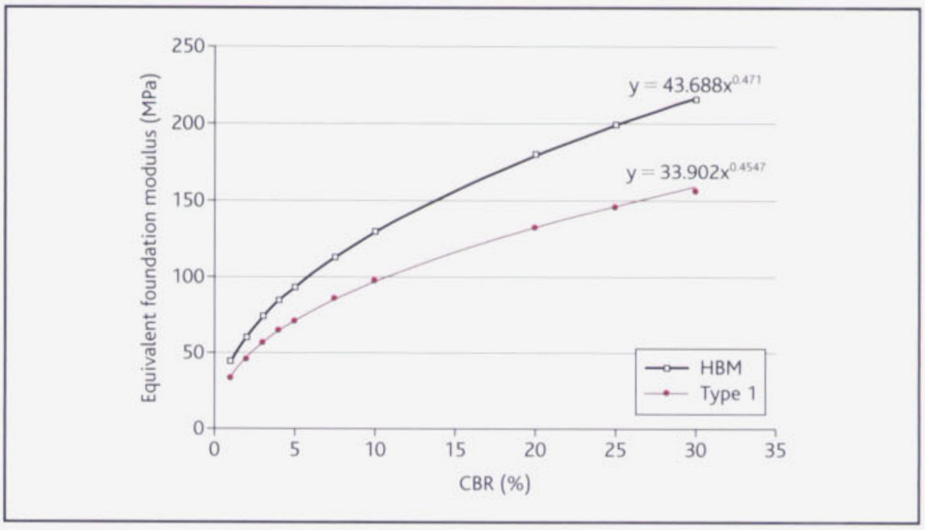
$$\text{Equivalent Foundation Modulus} = 33.902 \times \text{CBR}^{0.4547} \text{ for 150mm Type 1 sub-base}$$

and

$$\text{Equivalent Foundation Modulus} = 43.688 \times \text{CBR}^{0.471} \text{ for 150mm HBM sub-base}$$

Figure D.1

Relationship between CBR and Equivalent Foundation Modulus for sub-bases of 150mm HA Type 1 and 150mm HBM.



Reference

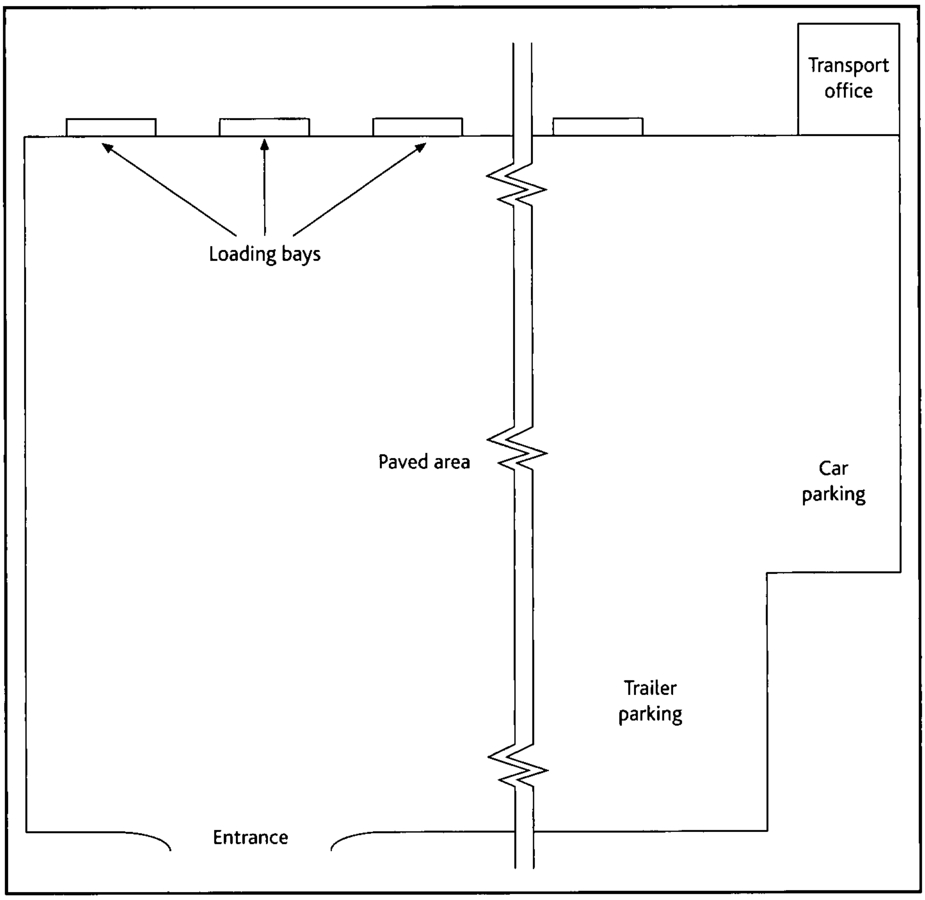
D.1 POWELL, W.D., POTTER, J.F., MAYHEW, H.C. and NUNN M.E. *The structural design of bituminous roads*, Report L1132. The Transport Laboratory, Crowthorne, 1984.

Appendix E. Worked examples – thickness design

E.1 Background information

The local distribution centre shown in Figure E.1 operates six days per week and is supplied by a 50/50 mix of five-axle and three-axle articulated lorries. There are 30 deliveries per day. Distribution is by a fleet of 20 three-axle rigid trucks, each of which visits the facility on average twice per day. It is anticipated that traffic will grow at a rate of 3% per year. The CBR of the soil underlying the paved area is 4.5%. The design period is 40 years.

Figure E1
Layout of paved area in design example.



E.2 Traffic loading

Assuming for simplicity that each part of the paved area is trafficked by all of the vehicles twice during each visit (i.e. on entry and on exit) and that unloaded vehicles are treated in the same way as loaded vehicles, the traffic loading can be calculated as shown in Table E.1.

From Table 6, design traffic class is T3 (15msa). From the layout, vehicle wheels will not frequently traffic the slab edge.

Table E.1
Estimation of design traffic loading.

Category		Daily number, *F*	Days in working week, *D*	Growth factor, Table 5, *G*	Wear factor, *W*	Weighted annual traffic for category ($52^* \times F \times D \times G \times W \times 10^{-6}$)
OGV1 and PSV	Buses and coaches				3.9	
	2-axle rigid				0.6	
	3-axle rigid	80	6	1.89	3.4	0.1604
	4-axle rigid				4.6	
OGV2	3- and 4-axle articulated	30	6	1.89	2.5	0.0442
	5-axle articulated	30	6	1.89	4.4	0.0778
	6-axle articulated				5.6	
					Total weighted annual traffic (*AT*)	0.2824
					Design period (*Y*)	40
					Design traffic (*Y*) × (*G*) × (*AT*) msa	11.3

E.3 Sub-base

Sub-base of 150mm HA Type 1 will be used under the concrete slab. This is EPSB1 in Table 2.

E.4 Fabric reinforcement

To reduce slab thickness and to maximise joint spacing an A393 fabric will be used. This is reinforcement class EPR1 in Table 7.

E.5 Concrete

Concrete strength class C28/35 with air entrainment will be used for the slab.

E.6 TRL method

Using Equation C2

$$Thickness = 12503\left(\frac{L^{0.209}}{f_{cm,cube}^{0.663} \times A_s^{0.296} \times M^{0.068}}\right)$$

L traffic loading = 15msa
$f_{cm,cube} = (35 + 7)$ N/mm^2 (see Section C.1 in Appendix C)
$A_s = 393$mm^2/m
$M = 33.902 \times 4.5^{0.4547}$ MPa (see Appendix D)

This gives:

$$Thickness = 12503 \times \left(\frac{15^{0.209}}{42^{0.663} \times 393^{0.296} \times 67.18^{0.068}}\right)$$

$$= 237\text{mm}$$

This is for the design situation where the wheel loads frequently approach the pavement edge. The reduction in thickness for the design situation where wheel loads do not frequently traffic the pavement edge is given by:

$$\text{Decrease in thickness} = 0.0658 \times 237 + 12.5\text{mm} = 28\text{mm}$$

The thickness is therefore (237 – 28) = 209mm and the design thickness rounded up to the nearest 5mm is 210mm.

E.7 Factorial equation

The factorial equation (Equation A.1) is:

$$\text{Slab thickness} = A \times CBR^{-0.0378}\ (\text{mm})$$

where the factor A is given in Tables A.1 and A.2.

In this case, since the wheel loads do not frequently traffic the pavement edges, Table B.1 is used. The value of A for concrete strength class C28/35, traffic class T3, HA Type 1 sub-base and fabric reinforcement class EPR1 is 223 and

$$\text{Slab thickness} = 223 \times 4.5^{-0.0379}\text{mm} = 211\text{mm}$$

This value is rounded up to 215mm.

E.8 Tabulated values

The appropriate table for infrequent traffic loading on the pavement edge is Table 8. Using the bottom half of the table for A393 mesh, the entry for concrete strength class C28/35, 15 million standard axles and 4% CBR is 210mm.

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Winvic Construction have forged an enviable reputation for their modern and innovative approach to construction. As specialists in the construction of warehousing and distribution centres, covering millions of square metres every year, our reputation has secured work from the sectors biggest Clients. Working closely with a mature supply chain Winvic offer a full Design and Build service where delivery on time is paramount.

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CI/Sfb

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625.84

External In-situ Concrete Paving

Very large areas of paving are constructed around distribution centres and retail and manufacturing facilities each year. Most of this paving is constructed using in-situ concrete. Concrete provides many benefits in this application. It is rigid and hard-wearing and provides a surface which drains well at low gradients and which can be textured to provide skid resistance.

This report is intended for designers, contractors, owners and operators. It provides guidance on design, materials, construction and maintenance of external insitu concrete paved areas.

CCIP-023
Published August 2007
ISBN 1-904482-37-6

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