DESIGN OF PAVED AREAS FOR INDUSTRIAL USAGE

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SUMMARY

The Paper is a review of the information available for the design of paved areas for industrial use. It draws on an extensive documentation search and on current practical experience in order to give guidance to designers, contractors and clients.

The various stages in the design process are considered, together with the alternative construction materials available and the construction materials available and the merits of each, in regard to performance maintenance and suitability.

The scope is limited to United Kingdom experience of exterior paved areas. However, reference is made to certain pavement design concepts originating in the United States of America. Comparative construction costs are given but, due to a dearth of information, relative maintenance costs are not included.

1. INTRODUCTION

This paper is based on Concrete Society Technical Report No. 24 (1) which provides advice for designers of pavements subject to abnormal loads, both dynamic and static, having regard to the information and experience currently available.

It is apparent that there is a lack of knowledge in the particular area of design of pavements for loads in excess of those applied by normal road-going vehicles. Furthermore an appraisal of the various construction materials and methods is needed for the guidance of designers, contractors and clients (owners and users) alike.

There is at present, no generally accepted method of design of paved areas for industrial or dockside traffic similar to that used in highway design. Road Note 29 (2) describes an essentially empirical method relating pavement thickness to projected total cumulative traffic flow and subgrade strength. The comparison of industrial pavements with road construction is difficult, particularly when in the U.K. a 'profit' as such is not pre-requisite for the public road.

2. USER REQUIREMENTS

The client often needs to make the quickest possible use of the facility which he intends constructing, so as to achieve an early return upon his investment. He may have potential customers in mind who may easily be attracted to alternative facilities, or he may have a specific time scale which is linked to a production process or import/export project presently under construction. Design life may therefore not be a major factor but will typically vary from five to fifteen years. However, once the facility is in use then the downtime or loss of availability to allow for maintenance is a vital factor, which may affect the viability of the project.

2.1. Type of operation envisaged

It is unusual for a port or other handling area to perform the same function continually. In many situations, the type of cargo handled may change several times within the design life of the pavement.

The client should indicate whether the operation is Roll on/Roll off (RoRo), Load on/Load off (LoLo) or storage of loose or stacked cargoes. The designer should make clear to the client that if traffic movements can be restricted to certain areas then there could be a lower initial cost for the pavement. This saving is achieved by using a lower grade or thinner pavement in areas subjected to lighter use. However, any subsequent changes in use may have detrimental consequences causing early failure in the lower grade pavements.

An example of the selection process is given in Appendix 1.

2.2. Costs and type of construction

It must be recognised that the project is normally a commercial enterprise, with a major factor being the length of time likely to elapse between the decision to make the investment and the ability to achieve an income. A further issue is whether the rental can be pitched at a level which will attract users.

The client will wish to be advised of a suitable form of pavement construction which will minimise the maintenance costs. The operator or user will require continuous access and freedom of movement, with no delays to the throughput of goods or vehicles, which suggests that the ideal solution is a 'maintenance free' pavement.

2.3. Site Location

For reasons of economy and by virtue of size, sites are frequently located on reclaimed land, fill areas or poor coastal or riverside land. Paving often follows rapidly after reclamation with the inherent risk of considerable settlement occurring. This may be uniform or differential depending on the type and variability of the fill materials used. For example, a paved area at Tilbury, London, was constructed in 1967 on alluvial clay and had settled uniformly approximately 450mm by 1981.

2.4. Surface Characteristics

Surface regularity is of considerable importance particularly with the operation of frontlift trucks which frequently operate with the load in an elevated position, thus any pitching greatly affects stability. It is considered that a maximim depression of 10mm under a 3 metre straight edge should be satisfactory. The maximum deviation in the surface, where containers are to be stacked should be such that there is no risk of container boxes breaking their backs or becoming flooded, bearing in mind that the container castings are only 12mm in height.

In most circumstances a minimum crossfall of 1:40 is suggested, but 1:60 or 1:80 is often adopted for main storage/parking areas. It is considered that a 1:35 slope is the maximum acceptable where crossfall changes occur, to avoid problems with hitching and unhitching of vehicles, and where turning movements are taking place.

The standards for surface texture adopted for residential roads should be adequate for most industrial situations. It is important to achieve a uniform surface having consistent texture and regularity.

In many situations, the surface should be resistant to fuel or oil spillages and to penetration by container castings or trailer jockey wheels bearing in mind that loads of up to 100 tonnes are possible on an area of $0.5m^2$ at adjacent corners of stacked containers.

3. DESIGN PRINCIPLES

Designs for industrial areas are often based on performance in use criteria whereby a particular pavement thickness is selected, and if failure occurs, either the thickness of the layer or the quality of the material is improved to achieve a satisfactory performance. Other methods are based on Road Note 29 (2) or the multi-layer elastic model developed by Ullidtz and Peattie (3) which has also been used in a design method developed by Barber and Knapton (4).

Road Note 29 describes an empirical method of design based on the observed performance of test pavements. In essence the design requires an assessment of the equivalent number of standard axles which will pass over the pavement during the course of its life.

Road Note 29 is not appropriate for very heavy axle loads, particularly those much above the legal limit or where static point loads are expected. However, this method can be used where traffic loadings up to 100 million standard axles (msa) are expected and there is scope for design where axle loadings of up to 18 tonnes are envisaged.

Design is particularly difficult where extremely heavy vehicles are contemplated, such as frontlift trucks capable of handling containers which may have front axle loadings in the order of 90 tonnes compared with the 8.2 tonne standard axle considered in Road Note 29.

An alternative for the design of pavements composed of lean concrete and a precast concrete block wearing surface, has been produced by the Cement and Concrete Association (5). This method is intended for areas where axle loads are greater than those permitted on public roads and may be used where axle loads of up to 90 tonnes are to be encountered.

Analytical design has advanced primarily due to the wider use of computers to a state where semi-analytical and analytical approaches to pavement design are possible.

The multi-layer elastic model with the simplified analytical technique developed by Ullidtz and Peattie (3) has enabled design charts to be produced for various construction alternatives against design life wheel loading or various values of radial tensile strain, verical subgrade strain and elastic modulus. Design criteria have been established and those generally applied to pavements are fatigue cracking and progressive vertical deformation of the pavement structure, including the subgrade.

For heavy loadings, the British Ports Association Design Manual (6) is appropriate. This is based on work by Barber and Knapton (4) who have taken the analytical design further in that having carried out a statistical survey of the loading characteristics of containers and handling vehicles for ports, the wheel loading is expressed in terms of the Port Area Wheel Load (PAWL). A PAWL is defined as a 12 tonne wheel load with a damaging factor of unity equivalent to a 24 tonne axle load. The design method requires knowledge of values of elastic moduli of the various construction materials. If local materials are proposed for use, it is therefore desirable that values should be established from laboratory tests, having regard to standards of compaction likely to be achieved during construction.

Barber and Knapton (4) in a design example cite the use of front lift trucks with lifting capacities of 24 and 37 tonnes, which when fully loaded, impose single wheel loads of 32 to 46 tonnes on the pavement. The example involves a total of 1.3 million vehicle movements representing a traffic load of 21 million

PAWLS. Analysis of the traffic shows that approximately 50% of the wheel loads are in the range 28 to 33 tonnes, while about 5% exceed this, up to a maximum of about 40 tonnes. However, the design assumes that the most damaging load for the whole spectrum is a single wheel load which equates to 36 PAWLS, with the CBR of the subgrade being 20%. Using the charts a range of base course thicknesses are derived at 350, 400 and 500mm respectively for various compressive strength base materials supporting a precast concrete block surfacing.

The British Ports Association Manual (6) has design charts which enable other pavement surfacing and base materials to be utilized. The charts consider loading in the form of a Load Classification Index (LCI) graded A to H, where A is up to 2 PAWL (Lorry), B is 2-4 PAWL, C is 4-6 PAWL (Straddle carrier) and so on up to H which is 128 to 256 PAWL.

Airfield pavement design methods can also be appropriate to these traffic loadings, with the proviso that the vehicle movements are considerably higher than would normally be considered for airfields.

The current UK Department of the Environment Property Services Agency document Design and evaluation of aircraft pavements 1971 (7) can be used, particularly as the charts consider a single wheel load equivalent of under-carriage loading. This is a graphical analysis of the relevant design parameters identified against a chart chart of suitable construction materials and thickness.

Design methods for rigid airfield generally derive from Westergaard's work (8) although various modifications will need to be applied to make allowance for the equivalent surfacing thickness of precast concrete blocks.

Where a soil cement pavement is being considered the design method developed by the Portland Cement Association (9) could be utilised.

To illustrate the nature of the problems Appendix 2 shows examples of pavement thicknesses produced by various design methods.

4. POSSIBLE SOLUTIONS AVAILABLE

Many clients and designers have established ideas on the most practical form of construction. Set out below, are a number of these solutions of which concrete block paving will be considered in detail:-

1. Lean concrete sub-base and base with a thin wearing course such as surface dressing.

2. In situ concrete pavement (unreinforced)

3. Precast concrete slabs on a cement-bound granular base.

4. Precast concrete blocks on a cement-bound or bituminous-bound granular base.

5. Clay paving bricks on a cement-bound or bituminous-bound granular base.

6. Bituminous pavement comprising wearing course, base course, base and sub-base.

7. Bituminous pavement with specialist overlay wearing course.

4.1. Full depth lean concrete with thin wearing course.

For use where a shorter term solution is desirable and where punching shear loads are less likely. The wearing course can be a double surface dressing or 20mm thickness of machine-laid dense bitumen macadam.

This solution is not viable where there is much oil spillage or where there are high local stresses from, for example, container castings or heavy wheel loads.

4.2. In situ concrete pavement

In situ concrete readily fulfils the requirements that the surfacing should be resistant to deterioration by fuel and lubricating oils and to deformation through concentrated loads applied by trailer jockey wheels and container castings. The total construction thickness of slab plus sub-base is generally less than would be required for an equivalent flexible or composite design.

If there is a risk of differential settlement, the concrete slab should always have additional reinforcement to that required to control thermal movement cracking, as well as dowel bars, incorporated in both longitudinal and ransverse joints.

Post-tensioned in-situ concrete pavements can provide a viable solution.

Reductions in slab thickness in the order of 15 to 20% are possible. The slab is also made more flexible, making it idealy suitable for use on made-up or poor ground conditions. The post-tensioning closes up all construction joints and eliminating cracks, thus reducing the danger of frost damage. Other benefits are a greater resistance to impact and vibration, a dramatic reduction in the number of permanent joints and the ability to recover after an extreme overload.

4.3. Precast concrete slabs

Precast concrete slabs commonly used are up to two metres square and are generally 150mm thick. The slabs are of reinforced concrete with a steel angle nosing to protect the exposed edges and are more tolerant of any settlement. There have been difficulties experienced, in that without adequate interlock load transfer devices, considerable effort is required to maintain the continuity of running surface. The slabs can be relatively easily lifted by means of a mobile crane and re-packed in order to re-establish levels. Such work is expensive to carry out and is disruptive to the operation of a terminal or port area.

There have also been problems whereby the steel angle edge protection strips have been dislodged and tyre damage has occurred particularly to straddle carriers.

4.4 Precast Concrete Blocks

Precast concrete blocks are able to withstand the severe conditions experienced in many industrial pavements. Blocks are resistant to damage from jockey wheels of vehicle trailers, and can accommodate the differential settlement which occurs in many paved areas sited on reclaimed or recently filled land. Lilley and Walker(10) use a simple substitution in Road Note 29, which can be applied to to situations where traffic is comparable to normal road-going vehicles. Where axle loads are far in excess of those envisages for normal highway use, then recourse has to be made to extending the Road Note 29 Charts, or to other design methods, such that proposed by Barber and Knapton (3) and the Cement and Concrete Association (4) where the precast concrete block and sand layer are taken as being equivalent to 110 -120mm of lean concrete.

The form of construction generally adopted in accordance with the Code of Practice for laying precast concrete block pavements (11) is to lay and compact a sub-base granular material or bound materials. The latter is preferred so as ensure stability, not only in the laying process, but also in service whilst under load.

For heavy duty pavements (over 1.5 million standard axles) an impervious base is needed beneath the laying course of sand. This may be lean concrete, dense macadam or rolled asphalt. Joints between the blocks will become sealed, but with an impervious base beneath the sand, there is less risk of damage due to water penetration during the early life of the pavement.

The next stage involves a laying course of clean sharp zone 2/3 sand, having a finished thickness of 50mm. It is essential that this sand layer is uniformly screeded and surcharged by about 30%. Concrete blocks are then laid by hand in herringbone pattern. The blocks are compacted by a vibrating plate compactor which forces sand up into the joints, thus ensuring inter-lock between blocks. Opinion varies as to whether the sand should be compacted and re-screeded prior to block laying so as to ensure uniform finished level and block to block sand interlock. There is also a school of thought which considers that the compacted thickness need only be 30mm.

Blocks of 80mm thickness are generally used for heavy loading situations. In the UK 80mm blocks have performed satisfactorily so far, but for very heavy load applications 100mm thickness blocks are available. Thicker blocks, up to 120mm have been used in some port areas in Europe (12).

Repairs to a concrete block pavement are simple, quick and involve lifting out blocks and placing additional sand to achieve a return to level. If settlement is excessive, the base will have to be built up. Such repairs ean be completed within a few hours without specialist equipment.

The speed of construction of block paving is comparable with other forms of pavement construction and in situations where large areas are involved very high construction rates have been achieved, by several men working on one long face. In the future, it may well be possible to mechanize the laying of concrete blocks, as well as the sand laying course.

4.5. Clay paving bricks

Rectangular and shaped clay paving bricks are now available in the U.K. These are designed and laid in a similar way to concrete paving blocks. A factor to bear in mind, is their higher initial cost.

4.6. Bituminous construction

Bituminous materials have been used primarily due to their ability to tolerate uneven settlement. Repairs are relatively easy and quick to carry out. However, there are considerable disadvantages to the use of these materials, due to the extent of damage which can occur to the surfacing from oils and concentrated loads.

Oils and petroleum spirit have an immediate effect on the binder, and the use of bituminous surfacing in areas where spillage is likely should be avoided.

Rutting is likely to occur under straddle carrier or fork lift truck wheels in aisles and at loading points.

4.7. Bituminous construction with specialist overlay.

The problems with bituminus surfacing can be overcome to an extent by the use of an open textured macadam with a cementitious resin grout. These are expensive but provide a more durable surface than conventional bituminous surfacing. Currently, there are a number of such systems available. These require the laying of an open textured bituminous macadam having between 20 and 25% voids, onto a non porous surfacing. The grout is screeded onto and vibrated into the surface. The grout thus penetrates the macadam, filling the voids and leaving a hard, oil resistant surface.

5. CURRENT USE OF BLOCK PAVING IN UK

Over the past three years approximately 3.7 million square metres of block paving have been laid at approximately 3500 locations, varying from hard landscaping to port cargo handling areas. The trend over the three year period, shows quite a significant increase in use of blocks during 1982 and early 1983.

It is interesting to record that for approximately two thirds of the sites blocks of 80mm thickness were used, the remainder being 65mm

thickness.

Generally, the method of design used was based upon the Cement and Concrete Association method (5) or Road Note 29 (2).

Enquiries have shown that virtually all of the blocks laid were placed by hand with very little use of semi mechanical means. However, rate of production are in the order of 70-100m² per day for a 3 man gang, and there have been occasions on large site where a 3 man gang has achieved outputs of 280m² per day.

6. COMPARATIVE CONSTRUCTION COSTS

Comparisons of initial construction costs of the various alternative types of pavement on a generalized basis do not show a clear advantage in favour of any one particular type of pavement. This is principally due to a wide varation in the relative cost of the differing materials in different parts of the country, but variations in labour and plant costs will also occur depending on site circumstances. There are many instances where this factor over-rides the cost differences due to design thickness varations brought about by loading and sub-grade strength criteria.

Material costs normally represent some 50 to 60% of the cost of a pavement but variations of 20 to 25% can occur in the price of a particular material delivered to site in different regions of the country. Mobilization costs in relation to the size of contract and the ease with which continuity of construction of the various pavement elements can be organised, are two of the main factors governing labour and plant costs.

However, within the range of price variations which can occur, a general trend is evident. For relatively lightly trafficked pavements on sub-grades of reasonable bearing capacity, a fully flexible or composite bituminous construction on cement treated base will probably prove cheapest. If a bituminous surfacing is unacceptable for operational reasons then a concrete block pavement will be perhaps 5 to 10% more costly. Where bituminous materials are not readily available, concrete block paving may well be the cheapest construction in terms of first cost.

In situations where very heavy loadings are expected, it is likely that in situ concrete or precast concrete blocks will be more appropriate on the basis of both first cost, and maintenance cost.

On weaker subgrades, however, flexible forms of construction require substantially thicker layers of sub-base, while for heavier traffic loads from either individual wheels or axles or from repetitions of loading, thicker bases are required. Under these circumstances it has to be said that a jointed reinforced concrete pavement may become competitive.

A comparison of estimated construction costs is given in Appendix 3, in relative terms for a particular example. Likely costs are not included, even though maintenance problems can be one of the prime considerations in choosing a pavement type. The 'total cost' approach, that is, construction costs plus maintenance costs over the design life, can be a more meaningful way of evaluation, especially since the cost of closure during repairs can be out of all proportion to the initial pavement cost. There is unfortunately a lack of objective information on both the actual cost and consequential costs of paved area maintenance.

7. CONCLUSIONS

There is no particular form of construction which could be said to be universally applicable for all situations, and it is obvious that the choice is dependent upon a number of variables. The optimum solution will be obtained from a thorough study of all the factors during the design process including maintenance costs and the disruption to operations. Without exception the paving is required to suit the cargo-handling equipment and not the reverse situation.

A considerable proportion of pavements can be designed using Road Note 29(2) with the remainder being dealt with by reference to either empirical methods such as the Portland Cement Association (9) or analytical methods such as Ullidtz and Peattie (3). The British Ports Association Design Manual'The Structural Design of Heavy Duty Pavement for Ports and other Industries (6) is a further step forward, particularly from the traffic loading view point. The next stage is to perhaps make more use of analytical methods of design, recognising that these methods are only as good as the input data provided.

It is considered that pavement design is still an art rather than a science. This paper will enable designers and clients alike to at least consider all the various influence factors and assist in narrowing the field towards the option which is most suitable to the particular case under consideration.

It would appear on balance, that a solution incorporating concrete blocks in some form is likely to produce overall, an economic pavement.

8. ACKNOWLEDGMENT

I wish to record my thanks to Mr.A.A.Lilley and Mr.J.W.Grey for their work as fellow members of the Concrete Society Working Party which prepared the Technical Report No.24 (1) and also the permission of the Concrete Society to utilise information contained in the Report.

APPENDIX 1

Example of the selection process

A container trailer park is required which will operate with road-going vehicles de-

mounting and mounting loaded trailers in bays. Some of the containers will be stacked whilst some of the area will be taken up with vehicle parking. The site under consideration is a 'land-fill' site, with the filling generally unsupervised. The client envisages that a design life of 25 years would be appropriate and has indicated that vehicle movements will amount to 100 per day.

Taking each aspect in turn:

a. Design life of 25 years and the sensitivity of the subgrade rules out an unsurfaced parking area

b. The subgrade sensitivity requires a waterproof pavement.

c. As the backfill material and compaction are unknown, differential settlement is likely. (The client has indicated a preference for reinforced concrete on past performance).

d. De-mounting and mounting operations demands a pavement surface that will be resistant to the high point loads from jockey wheels.

e. Parking areas should have a surface which is resistant to diesel and oil spillage.

f. The client has also experienced problems with precast concrete slabs due to slabs rocking when laid on poor ground.

g. An assessment of the construction costs shows the following order:

Conventional bituminous pavement (lowest)
Reinforced concrete
Bituminous with specialist overlay
Precast concrete blocks (highest)

h. Predictions of maintenance costs places the forms of construction in the following order:

Precast concrete blockwork (lowest)
Conventional Bituminous Construction
Reinforced concrete
Bituminous with specialised overlay (highest)

Precast concrete block paving is therefore chosen for this site, on the following grounds tolerance to settlement, resistance to indentation, resistance to fuel and oil spillage.

The higher initial cost is outweighed in the forecast of 'cost in use'.

This example is for one particular set of circumstances. Applying the same analysis to a stable site would produce a preference for reinforced concrete. In the case of a Roll-on/Roll Off operation, without any parked vehicles, on a similar site, bituminous construction might well be a more appropriate solution.

APPENDIX 2
Examples of pavement thickness produced by Various Design Methods

Example 1 Normal road-going vehicles

A Roll-on/Roll off operation has an estimated traffic loading of 20msa during the design life. The subgrade has a CBR of 5%.

Design Method	RN29(2) Insitu Conc.	RN29(2) Bit.comp.	RN29(2) Blocks/ Sand	C&CA(10) Blocks/ Sand
Surfg.	245	145	80(B) 50(S)	80(B) 50(S)
Base	-	210	130	110
Sub-Base	150	270	270	270
	395mm	625mm	530mm	510mm

Example 2 Very heavy axle vehicles

The pavement is to carry a 31,500 kg wheel load (70,000lb) front lift truck, the granular sub-grade has a CBR of 20% and the flexural strength of the concrete is 4 N/mm² at 28 days.

	BPA(6)	PSA(7)	B&K(4)
Surfacing	420	300	80(B) 50(S)
Base	-	-	500
Sub-Base	-	150	-
	420mm	450mm	630mm

APPENDIX 3

Comparison of Estimated Construction Costs
Pavement category 5 million standard axles.
Sub-grade CBR 5%. 1982 prices.

		Mean	Typical Range
1.	Full depth lean concrete with thin wearing course.		
1a.	25mm DBM wearing course 320mm lean concrete base 240mm sub-base	87	77 - 79
1b.	Double surface dressing wearing course 320mm lean concrete base 240mm sub-base	78	68 - 88
2.	In situ concrete		
2a.	210mm reinforced concrete 130mm sub-base (non-frost susceptible sub-grade)	104	97 - 110
2b.	210mm reinforced concrete 240mm sub-base (additional 110mm thickness for frost susceptible subgrade)	112	112 - 122
2c.	170mm prestressed concrete 130mm sub-base	128	110 - 146
3.	Precast concrete slabs 150mm precast concrete slabs 50mm sand bedding course 250mm granular sub-base	119	110 128
4.	Concrete block paving 80mm concrete blocks 50mm sand bed 100mm lean concrete base 240mm sub-base	100	93 - 107
5.	Bituminous (fully flexible) construction		
5a.	40mm HRA wearing course 165mm HRA base course/base 240mm sub-base	125	103 - 146
5b.	40mm HRA wearing course 185mm DBM base course/base 240mm sub-base	104	89 - 120
6.	Bituminous (Composite) Construction 40mm HRA wearing course 60mm DBM base course 190mm lean concrete base 240mm sub-base	103	91 - 115
7.	Bituminous construction with specialist overlay 40mm open textured DBM including grout. 40mm HRA wearing course 185mm DBM base 240mm sub-base	113	103 - 123

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