Proceedings

Seminar on

HEAVY DUTY PAVEMENTS
for
CONTAINER TERMINALS AND OTHER INDUSTRIES

by
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DANISH SOCIETY OF HYDRAULIC ENGINEERING

SEMINAR ON HEAVY DUTY PAVEMENTS FOR CONTAINER TERMINALS AND OTHER INDUSTRIES

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PREFACE

On the initiative of Professor H. Lundgren, the Danish Society of Hydraulic Engineering has succeeded in arranging a seminar on Heavy Duty Pavements by the internationnally recognized expert Mr. Marios Meletiou from Cyprus Port Authority, who has lately been a consultant to the World Bank and UNDP on 'Container Terminal Design'. Mr. Meletiou is 'Invited Speaker' at the 2nd International Conf. Coastal & Port Eng. in Developing Countries, Beijing, China, September 1987, on the subject 'Container Terminal Pavement Management'.

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OVERVIEW

This document, which is a general handout for the Seminar on "Heavy Duty Pavements for Container Terminals and Other Industries", organized by the Danish Society of Hydraulic Engineering on June 11, 1987, at the Technical University of Denmark, has been written with the aim of introducing those responsible for pavements in ports to the concept of pavement management. Management involves many inter-related functions from conceptual design through to rehabilitation or demolition. Essentially, it is important that Engineers understand the relationship between all of the factors which impinge upon the pavement system so that he can achieve a globally optimised solution. Only that way will he, in turn, ensure that port facility overheads are kept as low as possible. The pavement is a major influence over port infrastructure generated overheads. Accordingly pavement cost optimization is now of paramount importance.

This document is not intended to be a design manual but where specific data may be required, references are provided. In particular, the British Ports Association publication "The Structural Design of Heavy Duty Pavements for Ports and Other Industries" is mentioned frequently and is referred to as the BPA manual.

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CHAPTER (I)

INTRODUCTION

1. GENERAL

Any pavement, whether existing or a new build, can, if managed properly, be made to play an effective role as a container terminal paving system.

History shows that such a system must be treated as a separate entity from conventional paving design and construction. During the period of phenomenal container trade growth in the '70s many ports that stepped boldly into the container handling arena experienced what can only be regarded as catastrophic problems with paving systems. Existing port surface areas when used for container operations suffered sever failures. So too did many newly constructed areas, supposedly built with the imposing demands of container handling uppermost in mind. Furthermore, although much more technology and expertise is at hand to resolve these major and other minor paving related problems they do still persist today in many ports - in the developing and developed world.

As found, however, with other traditionally problematic areas of engineering, the correct design of a new pavement or upgrading of an existing surface for container handling operations is basically dependant on the right management approach. Indeed, a series of steps and functions can be identified that represent what can be called "container terminal pavement management", a base philosophy/doctrine that provides "cures" for many of the old "ailments".

The objective of this seminar is to briefly cover the whole spectrum of the steps and functions associated with "container terminal pavement management". But before doing this, it is essential that the concept of pavement is clearly defined.

A pavement can be defined as one or more layers of selected material constructed over natural soil in order to allow activity to take place which can not take place on natural soil. In particular, if

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natural soils are used by heavy handling equipment, they deform so that rutting and pot holes occur.

Furthermore, in order to permit all weather working, a pavement should be drained either by allowing water to percolate through it (e.g. in the case of gravel beds), or more commonly by encouraging water to enter a drainage system.

A pavement will be expected to meet its loading and drainage objectives over a substantial period which can extend for as long as 25 years.

2. THE GROWTH IN IMPORTANCE OF CONTAINER TERMINAL PAVEMENTS

A modern container terminal requires extensive areas of paving for stacking and moving containers, the provision of which often proves to be one of the most expensive capital cost items that a port has to bear. Sometimes the cost attributable to terminal surfacing works may be as high as 25% of the total investment for a container terminal. Moreover, these areas are expensive to maintain if they are not designed properly, with reconstruction tending to be both time consuming and inconvenient. Certainly, the provision of unsuitable pavements will, sooner or later, have a negative impact on terminal operations. Therefore, the surface of a container terminal should be equally good and reliable as the quay, cranes, electric power, ect.

In addition, the financial implications of error in pavement selection and design can be great. If the pavement is under-designed, it may become unserviceable very quickly and the resulting remedial costs may be greater than original construction costs. If a pavement is over-designed, capital will be tied up unnecessarily in the pavement, so inhibiting other developments.

In developing countries where projects are usually carried out with the assistance of outside loans, any possible savings in construction costs, withouth affecting the integrity of the design build approach, is of prime importance as this will assist in achieving amore productive allocation of limited resources.

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Briefly, the following reasons led to the growth in importance of container terminal pavements:

(i) Areas have become larger owing to the growth of containerisation.

(ii) Loads are heavier and there is a wider range of handling systems available which have different damaging effects on pavements.

(iii) Increased cost consciousness (due to the requirement of stronger and hence more expensive pavements).

(iv) Several major pavement failures in recent years, leading to serious container handling problems have created awareness of pavements.

(v) Greater freedom of material choice: This is due to recent developments in pavement construction methods and materials.

The growth in importance of container terminal pavements has thus, inturn created the necessity to establish the new concept of "pavement management".

Pavement management comprises the following:

a. Selection of a suitable pavement type

b. Economic design

c. Regular monitoring

d. Cost effective maintenance or rehabilitation

e. Upgrading or demolition of pavements

The above five "pavement management" components are briefly covered in the next chapters.

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CHAPTER (II)

SELECTION OF A SUITABLE PAVEMENT TYPE

1. GENERAL

The scope of this Chapter is to emphasise that the selection of container handling equipment and pavement construction materials should be undertaken CONJUNCTIVELY. i.e. You select a complete container handling system, and not each individual item of the system separately.

A complete container handling system (not including documentation) comprises:

(a) Equipment
(b) Lay-out
(c) Infrastructure (pavements)
(d) Services

(a) and (b) above, which are inter-related, largely dictate the operational system and thus the efficiency of the terminal. However, good selection of the right type of equipment coupled with good selection of pavement materials, will definitely add to the efficiency and success of the whole container handling system.

"Selection" basically means to choose from a number of alternatives according to one's preference. This implies the process of comparison of the available alternatives. But in the case of container handling system exactly what are the alternatives?

2. THE PAVEMENT SELECTION APPROACH

2.1 Introduction

The traditional approach has been first to select the container handling equipment, then to design a pavement system to withstand the damage inflicted by the selected equipment.

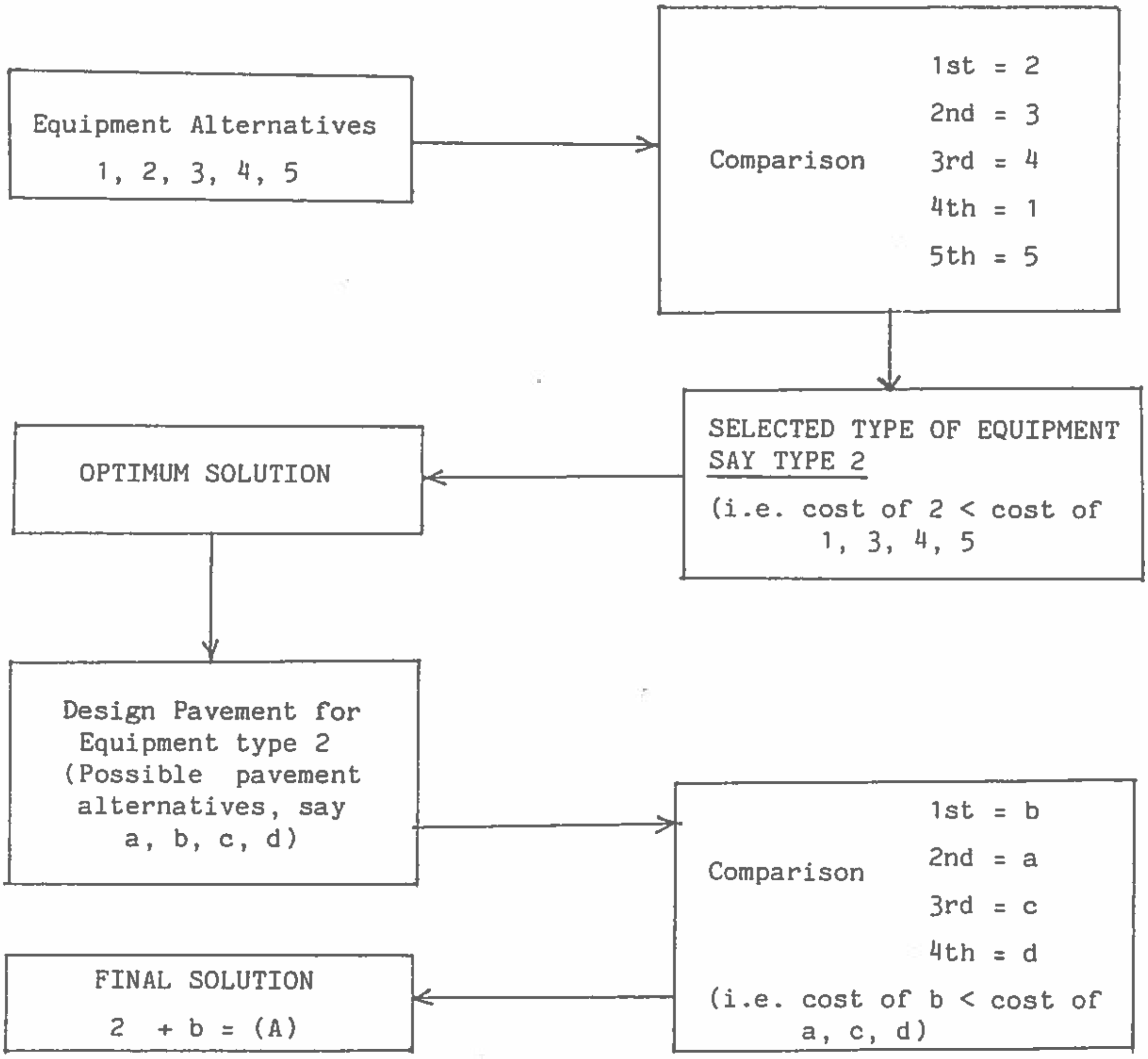
The New approach, which is now recommended, is to consider the selection of container handling equipment and the pavement system in parallel.

So, if we follow the traditional approach the alternatives to be considered are: first all the available types of equipment and second the pavement types which could be used with the particular type of equipment selected. Whereas, if we follow the new recommended approach, then, the alternatives to be considered are combined systems of equipment and pavements.

2.2 The traditional approach

The flow chart below show in a simple form the steps taken for pavement selection when the traditional approach is followed.

TRADITIONAL APPROACH



(A) MAYBE OR MAYBE NOT THE GLOBAL OPTIMUM SOLUTION

In this approach, once you know the type of equipment to be employed then the container handling system is largely defined. It is at this interim stage of the whole process, that the "Optimum Solution" is thought to be reached, and the following steps shown on the flow chart are just complementary to the critical step of equipment selection. The ensuing work is simple and straightforward, as the comparison between the alternative pavements offered for the particular type of equipment already chosen, takes into consideration a specific loading, an identical layout and an equal area.

Therefore when following the traditional approach, once you know the type of equipment to be used, then the next step is to see which types of pavements are compatible with the selected equipment and compare their cost. The cost comparison table below refers to the cost of the most common pavement types but for the same loading, and layout and an equal area.

TABLE I

COST COMPARISON TABLE FOR THE MOST COMMON TYPES OF PAVEMENTS

Construction Cost	Maintenance Cost		
	Low	Intermediate	High
Low	Gravel beds		
Intermediate	Precast concrete blocks	Asphalt	
High	In-situ concrete slabs Conjunctive systems	Precast Concrete rafts Conjunctive system	

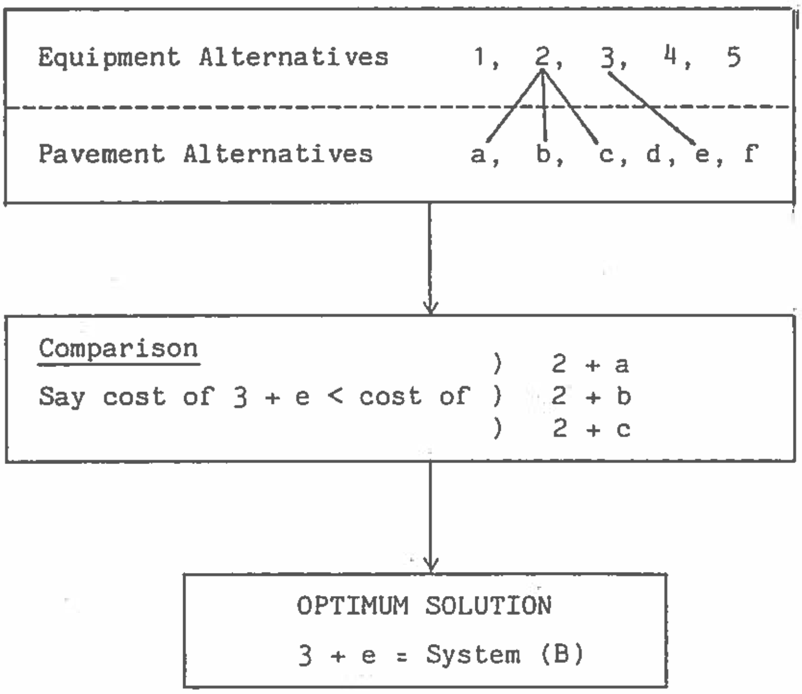
The above table is of a general character without respect to typical local conditions.

2.3 The recommended approach

In contrast to the traditional approach, which when followed sees the selection of equipment prior to pavement choice, the selection of a complete container handling system (i.e. equipment and pavement selection is undertaken conjunctively) under the recommended approach, is not an easy task. For example, the required pavement layouts and areas or loadings are not the same for each type of equipment.

Therefore, despite the fact that the flow chart for the recommended approach appears to be very simple this process is more difficult and requires a more comprehensive knowledge of both the operational and engineering aspects.

RECOMMENDED APPROACH



The parameters to be considered not only increase in number but become more complicated. For this purpose, taking into account the relationship between container handling equipment and pavements, the cost of each pavement type (construction and maintenance cost) as well as the experience gained from the performance of numerous cases world wide, the next table has been prepared as an initial guidance to the container terminal designer. In this way the designer does not have to consider all combications of pavements and equipment but work out only those two or perhaps three that look more promising.

TABLE II

SUITABILITY OF PAVEMENTS FOR DIFFERENT OPERATIONS, TAKING INTO ACCOUNT COST EFFECTIVENESS AND PERFORMANCE

(KEY: 1 = avoid if possible
5 = Reasonable solution
10 = Recommended solution)

Type of Operation	Asphalt	In situ concrete slabs	Concrete rafts	Concrete blocks	Gravel beds
Container stacking	1	3	1	7	10
Trailer parking areas	2	7	6	8	--
Straddle carrier running lanes between containers	1	5	3	7	--
Straddle carrier marshalling areas	4	6	3	7	--
Fork lift truck marshalling areas	2	6	2	8	--
Highway vehicle marshalling areas	8	6	5	6	--
Mobile crane working areas	2	7	2	5	--
Yard stacking cranes	1	3	1	4	10
Maintenance Areas	1	8	4	5	--

An important issue which has been taken into consideration in preparing table II, is the impact that the maintenance works may have on container handling operations. The container terminal designer may have the option of choosing between pavement systems of low construction cost that require frequent and/or expensive maintenance and pavement systems of high initial construction cost but with low maintenance requirements both in cost and frequency. Uninterrupted container handling operations throughout the whole useful life of a container yard, though an ideal situation is, with most, if not all pavements,unattainable.

Experience shows,that the maintenance requirement of a pavement does not depend entirely upon correct or incorrect engineering design but also largely on the nature of the pavement itself. Therefore, operational interruptions due to maintenance works can be minimised through the process of pavement selection.

There are some types of pavement which, no matter how much they are over-designed, require at some stage major maintenance (e.g. asphaltic pavements). On the other hand, recent experience shows that there are other types of pavement whose minimal maintenance requirements are not greatly influenced even if they are under-designed (e.g. gravel beds).

Taking into consideration the prevailing views of many container terminal operators, the position adopted in table II is that more weight should be given to minimum operational interruptions, as these sometimes may prove very costly and may even, to some extent, have a negative impact on the reputation of the port if too frequent.

It is notable, however, that in some cases, due to specific circumstances, the above position may not hold. One example is that the available stacking area, for some reason, may be much larger than is actually required and maintenance can be carried out in phases without effecting container handling. But even so, in such cases, the gradual shifting of operations from one part of the stacking area to another in order to facilitate the maintenance works inevitably implies some deviation from the routine daily operations. This, in turn, can be translated into cost. The reasons behind and the additional cost of providing a larger area than is actually required must also be questioned. The above argument leads to the general question of prevailing local conditions.

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In this respect, it is worth emphasising that the container terminal designer must not take the marks given to each pavement type in Table II literally, but just regard them as an initial starting point. These marks are sensitive to prevailing local conditions which must always be given the appropriate importance. Therefore, one may expect that pavement systems, with only one or two points difference from their marking according to Table II may change their relative position in the comparison list due to prevailing extraordinary local conditions.

As underlined above the preparation of the general criteria in Table II has been based among other things on the relashionship between container terminal equipment and pavements. This is the specific focus of the next part of this chapter.

3. THE RELATIONSHIP BETWEEN CONTAINER TERMINAL HANDLING EQUIPMENT AND PAVEMENTS

3.1 Introduction

The main reason for the poor performance of many container terminal pavements is that these have been constructed on the basis of traditional pavement design methods which completely ignore the close relationship between container handling equipment and the surface over which they operate. From this chapter it may be concluded that special emphasis should be given to the compatibility of surface materials and the container handling equipment that will operate over it. Nowadays this is a prime cost and operational consideration for all modern and efficient container terminals. Regrettably, though, due to either conservatism or failure to keep abreast of new developments in this field, there is still in many cases, a tendency to favour traditional methods of design and construction. Inevitably, such surfacing methods prove to be unsuitable for container handling operations with, in many cases, catastrophic results.

There are many different forms of pavement construction, each suited to a particular set of conditions or simply favoured by a particular port. However, before one makes any attempt to match the container handling equipment with a pavement system, it is advisable to consider first all the options in both respects.

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3.2 Recent Developments in container handling equipment

With the introduction of containers, a new generation of handling equipment has evolved, invariably featuring new characteristics compared to the traditional handling equipment for other types of cargo. Perhaps more than any other factor, the adverse characteristics of massive self-weight and size of the equipment have had a detrimental effect on pavement life and maintenance. This was evident in many cases where existing paved areas, designed for other operations were subsequently used as container yards.

3.3 Equipment imposing loads on terminal surfaces

Apart from the containers themselves the array of different types of equipment which impose loads upon the surfacing of a container terminal is shown below:

(a) Terminal trailers
(b) Multi-trailer systems
(c) Fork lifts
(d) Front loaders
(e) Side loaders
(f) Straddle carriers
(g) Yard stacking cranes (on rails or on tyres)
(h) Mobile cranes
(i) Port packers

Table III shows pavement loads from container stacking which must be considered when designing a container stacking bay.

Table III

Stacking	Reduction in gross weight	Contact stress (N/mm²)	Load on pavement (kg) for each stacking arrangement		
			Singly	Rows	Blocks
1	0	2.59	7620	15240	30480
2	10%	4.67	13720	27430	54860
3	20%	6.23	18290	36580	73150
4	30%	7.27	21340	42670	85340
5	40%	7.78	22860	45720	91440

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However, the design of a container yard pavement trafficked by the above container handling equipment is not an easy task.

The damage, D, to a pavement, in terms of wheel load, W, and the contact stress (or tyre pressure), P, is given by the following expression:

$$D \propto W^{3.75} \times P^{1.25}$$

This equation implies that the damage to a pavement is proportional to the 3.75 power of the wheel load.

However, unlike the design of highway pavement, in port areas you cannot make the assumption that heavier wheel loads will necessarily require overall stronger and hence more expensive paved areas. This is because the operational characteristics of each type of equipment play a governing role in the design approach of the pavement.

For example, wheel loads of yard stacking cranes may sometimes be as high as 48 tonnes but straddle carriers with the usual 8 wheels which have 12.5t. maximum wheel load or fork lifts with a maximum wheel load of 22t. require, overall, a much more expensive pavement than yard stacking cranes.

The reason is the following:

The operation of yard cranes is in many ways different from that of other types of container stacking equipment. There are two main operational differences which have a direct impact on the design and construction requirements of the pavement over which the equipment will operate:

a) Yard cranes travel only on defined strips (on corridors in the case of rubber tyred yard cranes or on rail tracks in the case of rail mounted yard cranes). This means yard cranes never enter the actual stacking areas, in contrast to the other types of container stacking equipment which have to travel all over the container yard.

b) Yard cranes practically always travel unloaded. (Occasionally, they may travel loaded at low speed for short distances for shifting containers to adjacent rows). This is because the trailer which will

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receive or deliver a container will always travel to meet the yard crane at the correct point by the stacking bay. Thus, the main activity of yard cranes is lifting and lowering and not the horizontal transportation of containers. In contrast, other types of container stacking equipment are continuously involved in both lifting or lowering and the horizontal transportation of containers as they must travel to meet the trailers which wait at a certain point in the container yard to deliver or receive a container.

The above two differences in operations imply a completely different design approach for the container yard pavement. When yard cranes are used there are three different types of pavements to be designed in a container yard. These are:

a) The container stacking bay; this will be designed to carry the static loading resulting from the containers stacked at the maximum possible height,

b) The travel strips of the yard cranes; these will be designed to carry the wheel loads resulting from the operation and travelling of the yard crane,

c) The travel areas of the tug masters and trailers which will be designed to carry the wheel loads imposed by the operation of this equipment.

If, however, any one of the other types of equipment is used, then, the whole container yard has to be designed in a homogeneous way and must be able to carry the heaviest combination of wheel or static loads for all equipment that may be present in the yard i.e. stacked containers, trailers, fork lifts or straddle carriers, etc.

Considering typical container yard layouts whereby rail or rubber mounted yard cranes are used (see figure 1.), then it can be easily calculated that the area to be designed to carry the high wheel loads covers only approximately 2.2% or 7.4% respectively of the whole container yard area. Sixty nine or 62% of the container yard area forms the actual stacking bays which only have to carry the static loading from containers and the remaining 28.8% or 30.6% of the container yard has to be designed to carry the relatively low wheel loads of trailers and tug masters.

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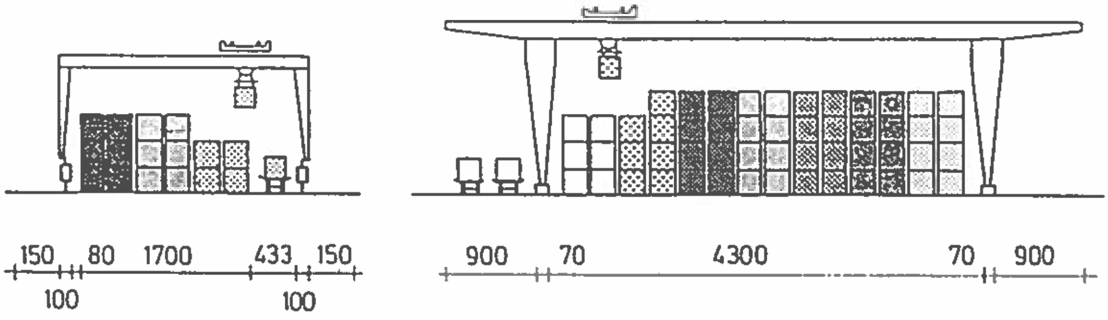

A. Rubber tyred yard crane

B. Rail mounted yard crane

Stacking area : % of container yard area	A 62 %	B 69 %
Yard crane travelling strips : % of container yard area	A 7.4 %	B 2.2 %
Trailer travelling lanes : % of container yard area	A 30.6 %	B 28.8 %

Figure 1: Typical container yard layout when rail or rubber mounted cranes are used.

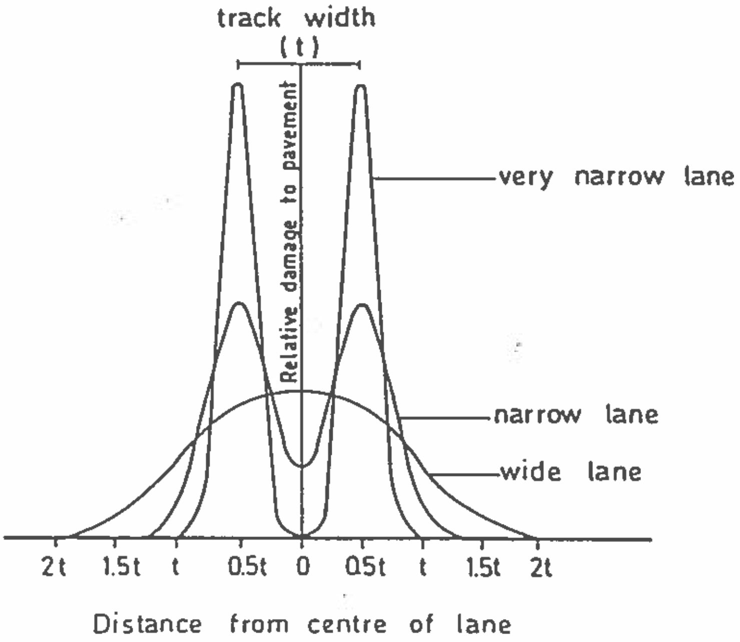

Figure 2: Effect of increased lane width on pavement damage

From the above, it is clear that when yard stacking cranes are used, the largest part of the container yard pavement can be of relatively inexpensive construction.

On the other hand, 12.5 t. wheel load straddle carriers require overall much more expensive pavements. In addition to what has been said above, (horizontal transportation of containers), cost rises in line with the typical layout for the straddle carrier operated container yard. The stacking of containers in single longitudinal rows which are separated from each other by narrow single wheel travelling lanes does not allow for a practical and hence economic isolation of the actual stacking bays which may be designed to carry only the static loading resulting from the container. Furthermore, with straddle carriers stacking containers in long rows their wheels are restricted to very narrow lanes and hence channelling becomes significant. In these cases severe rutting frequently takes place as there is no ironing out effect. Figure 2. shows how the relative damage to a pavement varies with lane width.

In addition to the above, the damaging effect of straddle carriers on pavements due to cornering and braking is very high.

Of all container handling equipment, fork lifts and front loaders have the biggest damaging effect on pavements.

Compared with all other container handling equipment, fork lifts have the highest load classification indices for normal running, braking, cornering, acceleration and uneven surface (the worst damage effect being caused due to cornering). In order to highlight the relatively big damaging effect of fork lifts on pavements, it is significant to note that the 22t. wheel load which is transmitted to the pavement from the front axle of a fork lift handling a 40' container is slightly higher than the maximum wheel loads transmitted to the pavement during take-off by a Boeing 747B.

3.4 Classification of Pavements

Pavements are classified in different ways: some are shown below:

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a) <u>According to flexibility</u>

i. Flexible;
ii. Intermediate;
iii. Rigid;

b) <u>According to binder type</u>

i. Bituminous;
ii. Cement - bound;
iii. Water - bound;

c) <u>According to strata</u>

i. Monolithic;
ii. Two layer or multilayer systems;
iii. Sandwich constructions;

d) <u>Seen from the surface</u>

i. Asphaltic;
ii. Concrete slabs;
iii. Concrete blocks;
iv. Granural

The above classification is far from complete and many more combinations are possible. However, since terminal users usually see the surface itself and not the structure, for the purpose of this seminar this aspect is chosen as it is the most common and understandable to persons who are not specialist in this field.

3.5 Factors governing pavement type selection

The vital question is what is expected of a pavement? There are obviously many considerations. The following factors should be considered during the pavement selection process:

(a) Low construction costs
(b) Low maintenance costs
(c) High reliability
(d) Design life

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(e) Type of trafficking - vehicle speed, wheel loads (dynamic load factors i.e. braking, cornering, acceleration, uneven surface), tyre types, contact pressure and channelisation

(f) Static loading - point loads (shape and type of support)
(g) Impact loading
(h) Port layout and operation
(i) Surface pollution - hydraulic oil, de-icing salts
(j) Strength of subgrade
(k) Anticipated settlement - short term and long term
(l) Climate - rainfall, temperature, frost
(m) Future uses and developments
(n) Availability of local materials
(o) Permissible slopes in different directions regarding equipment use, stacking and rainwater

(p) Available construction time, and
(q) Surface characteristics - smooth, even, clean, always dry, never slippery, absolutely horizontal, without single discontinuity.

The ideal surface could be described as the one which would satisfy all the above factors, and a few more that someone will no doubt be able to add in order to make the ideal even more unattainable. In practice however, every design must be a compromise between a number of contradictory requirements. The art of pavement selection consists of identifying those items in the above list which are of most importance and ensuring that they are given the appropriate priority. It will be impossible to satisfy each item totally and pavement selection requires judgement and experience in balancing possibly conflicting requirements.

3.6 Available choices for a container terminal pavement

A great number of factors may influence the final choice; the terms of reference, substrate data, handling systems, available materials, available labour, contractor's experience, relative price levels, budgets and last but not least; taste, prejudice, and even habits.

It could be very unprofessional to suggest that there is a standard solution for each particular set of conditions but what can be confidently

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stated is that in the last few years an increased range of potential solutions is available.

Without striving for completeness a concise reference to the available types of pavements which are usually adopted for container yards, is given below:

The remarks, however, are of a general character without respect to typical local conditions.

3.6.1 Bituminous or Asphalt Surfacing

Bitumen bound surfacings have been used extensively for both highway and airport pavements and being relatively inexpensive and easy to lay, their application to port pavements seemed logical. However, overall performance has been poor. The rolled asphalt similar to that used in high-ways is too soft to carry the large wheel loads, high contact stresses and low vehicle speeds without severe rutting and indentation. Three characteristics of the asphaltic mix have largerly resulted in this poor performance in port application.

a) The stiffness, or strength, of a bituminous material decreases as the temperature rises.

b) The stiffness of a bituminous mix decreases as the loading time increases; i.e. the slower the vehicle speed and lower the stiffness.

c) Surface oil pollution slowly dissolves the bituminous binder, making it more susceptible to scuff and frost attack.

The first two characteristics cause the rutting and indentations that develop in the summer months. This is a particular problem in warm climates.

The worst problem in container yards is the one caused by trailer dolly wheels. These readily penetrate a soft surfacing to a depth in excess of 75 mm, leaving the surfacing open to frost attact and mechanical disintegration. A similar and equally serious problem occurs in container stacking areas with the corner castings of containers: Owing to the fact

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that the static load is repeated many times at almost the same location, indentations are sometimes very deep, the result being that the centre of the container "bottoms" first. Although an asphaltic pavement is considered to be a flexible construction, excessive differential settlement will lead to the cracking and subsequent breakdown of the bound layer. There is no cheap solution to this problem in large settlement areas and for this reason, asphaltic construction is often rejected in favour of more durable surfacings, such as concrete rafts or concrete blocks. Traditionally, asphalt has been one of the less expensive surfacing materials but the price of bitumen has risen sharply over the past few years, bringing the cost of construction more in line with that of other forms of construction.

3.6.2 In-situ concrete

An in-situ concrete pavement is a rigid form which provides a very durable and hardwearing surface that can withstand high contact stresses. In addition, the surface is smooth thus giving an excellent riding quality with good skid resistance. Concrete slabs do not show permanent deformation under concentrated load and are generally resistent to rough usage. Materials are readily available in almost every country of the world and construction equipment and labour do not in most cases impose any problems. Furthermore, the surface is not weakened by either oil spillage or high temperature. But here again drawbacks must be mentioned. There are a few situations which render the use of this type of pavement construction impracticable. These are:

a) Subgrade settlement cannot be accommodated without excessive cracking. In general concrete slabs can function properly only if laid on established very stable areas where no settlement is anticipated. Unfortunately this is rarely the case in a modern port development where usually new areas are created by reclamation.

b) Some provision for thermal expansion and mode of construction must be made.

c) A high concrete strength, at least 30 N/mm², is necessary to reduce spalling and impact damage.

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d) Repair of broken or deformed concrete slabs is very difficult.

e) Rehabilitation of the surface, digging trenches for cables or access to underground services is also very difficult and expensive.

A recent development in the concrete technology has increased however both the cost effectiveness and performance of in situ concrete pavements thus making this type of pavement more competitive. This development is the use of steel fibres along with cement, fine and course aggregates and water in order to produce a composite material the so called Steel Fibrous Concrete (S.F.C.), a special reinforced concrete material with much better mechanical and physical properties than the conventional concrete.

The successful application of this new technology in a number of industrial, airport and port pavements has made the tremendous advantages of steel fibrous concrete over the conventional concrete more evident.

These advantages can be briefly summarised as follows:

a) Economical advantages:

  i. Simplicity: Steel fibre concrete is extremely suitable for placement by slip-form paver and other normal road construction machinery.

  ii. Savings in maintenance and longer useful life.

  iii. Greater initial strength and early availability for service.

  iv. Reduced work in maintening relative levels when applying overlays due to smaller thickness of steel fibre reinforced concrete.

  v. Greater distance between expansion joints.

b) Technical advantages:

  i. Greater tensile, flexural, compressive and shear strength.

  ii. Higher resistance to spalling.

  iii. Higher fatique resistance

  iv. Greater toughness

  v. Greater impact resistance against static and dynamic loading

  vi. Superior ductility (strain capacity)

  vii. Greater ability to carry loads when cracked

  viii. Better resistance against crack formation and propagation.

The fibre strengthening efficiency and the ability of fibres to resist crack propagation depend primarily on the bond between the fibres and the concrete (fibre shape) and the fibre spacing (aspect ratio i.e. length/diameter,

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and fibre dosage).

The hooked ends of steel fibres now in the market cause a higher efficiency of the reinforcement.

Also in the market various lengths and diameters of steel fibrers for different applications are now available.

3.6.3 Precast concrete rafts

A hard concrete surface is ideal in heavily loaded port areas and the necessary flexibility can be achieved by using a precast concrete surfacing material which can be relaid as settlement takes place. The answer to this is the use of precast concrete rafts which are basically a development of true rigid construction. These rafts are generally 2 metres square, reinforced and usually have a protective steel angle surround to stop the concrete from spalling under local stress concentrations. The units are laid on a layer of compacted sand to give uniform bedding. The sub-base is generally granular and must be free draining to prevent saturation and subsequent development of pumping after periods of heavy rain. Precast concrete rafts offer several advantages:

a) Good quality control in manufacture
b) Full strength achieved in off-site curing
c) Little plant needed for laying
d) Immediate trafficking
e) They can easily be lifted and relaid to accommodate site settlement, and
f) Use of steel Fibrous concrete is possible thus achieving better results as explained for in situ concrete.

However, like any other system, this one has some disadvantages as well:

a) The cost of the rafts is very high and this is aggravated by the large size of the units, weighing around 1.25 tonnes, and haulage is expensive.

b) With the units being larger than the track width of the handling equipment, and the corner castings which support the containers, very large hogging bending moments are induced in the rafts. If the supporting subgrade has settled this can cause cracking across the corners.

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c) Differential settlement between rafts must also be controlled, as excessive steps may be dangerous for moving handling equipment and may also cause problems to surface drainage of rainwater.

Not all experience with rafts has been bad. However, the high cost of construction has unfortunately in many cases, not been offset by a good performance record. In general, overall costs are significantly greater than the alternative precast concrete blocks.

3.6.4 Concrete paving blocks

Concrete blocks have now established themselves as a successful form of surfacing for port area pavements and offer the same advantages as the raft system. They have a highly durable and hard surface, possessing at the same time the flexibility associated with asphalt construction. The individual units are small and provided they have sufficient thickness, tensile cracking does not occur. Since the structure is already "cracked" the surfacing can accommodate extensive deformation without damage. In addition, in cases of settlement the blocks can be lifted and relaid in a few hours. Originally, concrete blocks were laid by hand, but recently a mechanical solution of block laying has been developed. The blocks are laid on a layer of screeded but uncompacted sand. The surface is vibrated to give the final profile and this forces the sand up into the joints, so converting the individual units into a homogeneous surfacing and at the same time giving the surface its strength and continuity. Once the blocks have been locked together with sand i.e. "interlock", the strength of the surface layer is high. Also since the blocks are made of high quality concrete the surface durability is excellent, it can withstand the very harsh loading from trailer dolly wheels and container corner castings without any problems. The initial cost of construction in some countries is usually slightly higher than an asphaltic structure but as existing block pavements require very little maintenance the overall costs may prove to be lower. However, the recent introduction of mechanical laying allows up to 700 m² of concrete blocks to be laid per machine-day. It has been reported that the ensuing saving in concrete block installation has in some cases reduced concrete block paving costs to less than those of an equivalent bituminous pavement.

3.6.5 Form of heavy duty pavements

Experience and research shows that the best way for a pavement to take the heavy loadings applied in container yards, is to possess a very strong base. Therefore it is recommended that the four types of pavements which have been described in the previous paragraphs (i.e. asphalt, in-situ concrete, concrete rafts and concrete paving blocks) should take the form shown in fig. 3.

It is notable that in heavy duty paving, the surfacing contributes relatively little to the overall strength of the pavement, since the base is very thick and provides most of the pavement's strength.

3.6.6 Gravel beds

Most, if not all of the disadvantages, which are associated with pavements, are connected with the necessity to provide a smooth riding surface. Practice has proved that the most economic method to achieve, in an adequate way, such a surface is to use bitumen or cement in conjunction with aggregates. However, the employment of these two very useful materials causes most problems. Cracking, surface damage from oil, difficulty of access to underground services, expensive repairs and maintenance, are only some of the problems due to the presence of these two binders. Once a smooth riding surface is not a prerequisite, then there is no reason why one should use these two expensive aggregate binding materials. The main condition under which a smooth surface is not required is that there are no moving loads. Indeed, there is a case in container handling operations where such a surface is not required namely in the stacking bays between the legs of yard cranes.

Lately, a very simple and inexpensive type of pavement has been very successfully tried for such cases, which is based on gravel.

There is a common prejudice which leads us to equate simple and cheap solutions with bad and inadequate ones but this gravel bed system, though simple and inexpensive, is by no means "cheap" in the context that is normally understand by this word. Gravel beds, being a simple system of paving, are very easy to describe. It is nothing more than a layer of a certain thickness of gravel (crushed or naturally occuring aggregates)

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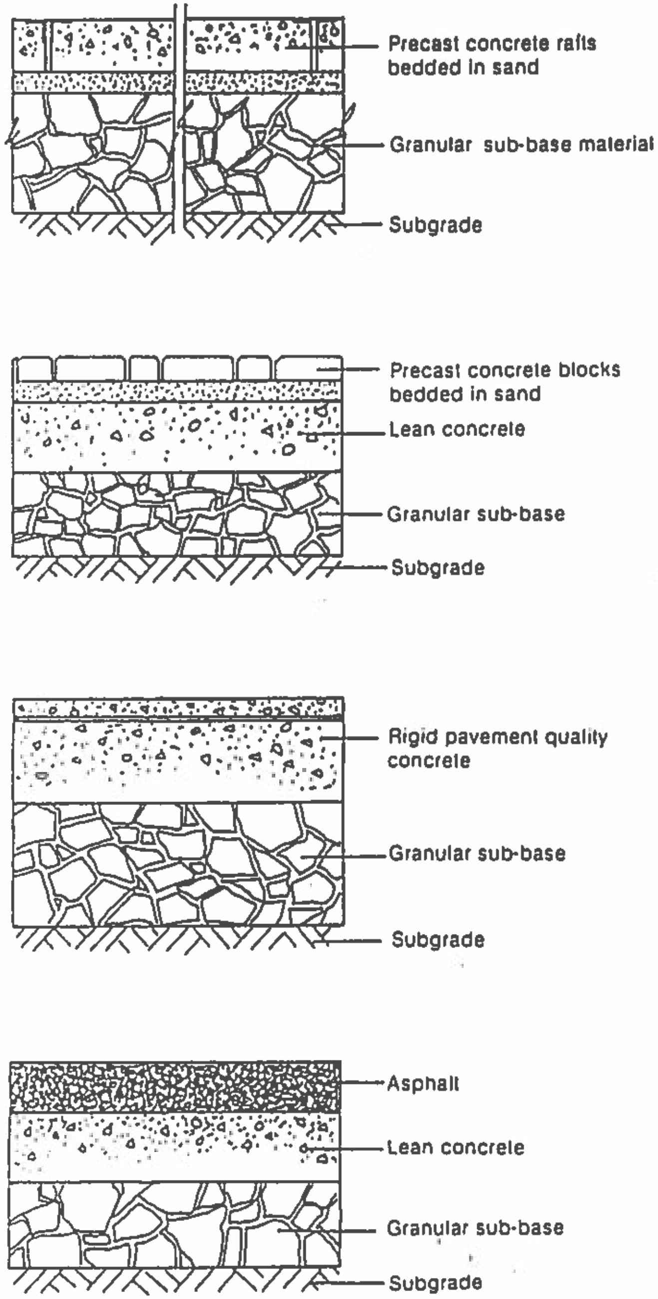

Fig. 3 Four categories of pavement

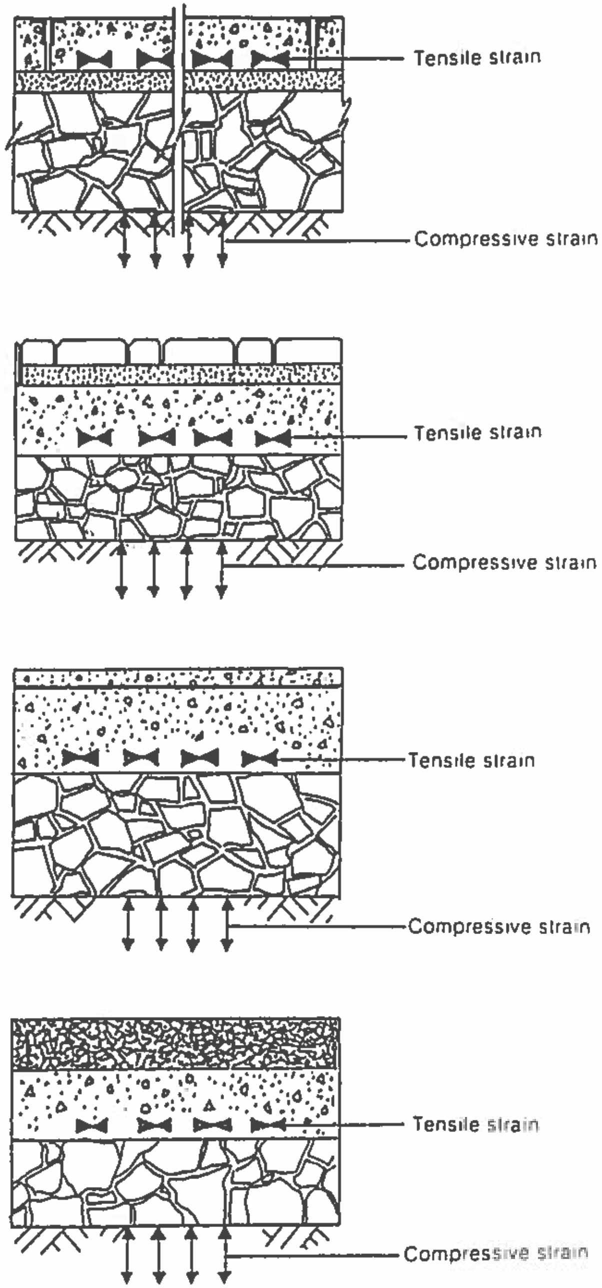

Fig. 4 Strains in four categories of pavement

of a certain gradation, placed, levelled and compacted directly onto the underlying subgrade. The subgrade may be either the natural ground after a proper formation, a filling or reclamation material, or it may be a made up of sub-base material according to special local conditions and design parameters.

The gravel must be hard stone of a size preferably smaller than 50 mm. This is to avoid the possibility of spillage of the gravel onto the neighbouring paved areas as a result of containers retaining gravel in the underside cavity of the corner castings. However, it has been observed that in a few rare cases there has also been some spillage of gravel onto the neighbouring paved areas due to the fact that the very small and hence light aggregates would sometimes stick onto the presence of grease or old paint which has been partly peeled off. Actual field tests proved that aggregates with usual specific gravity which are larger than 20 mm will not stick. Therefore the recommended size of gravel is between 25 mm and 50 mm.

Gravel beds, owing to the very small units that they comprise, form a surface which behaves like a cushion. This situation is similar to floating conditions. This is possible because the corner castings of the container, which project only 12.5 mm, sink into the gravel with the result that containers are supported over their whole bottom face.

Owing to the voids between aggregates, the actual contact area is assumed to be 70% of the plan area of the steel sections which project below and support the floor of the container. This area is about 5 m^2.

NOTE: Maximum gross weight of 20 ft. container: 20.17 tons
Maximum gross weight of 40 ft. container: 30.40 tons

In the case of gravel beds the 20 ft. container gives the worst loading conditions as the 40 ft. unit has double the plan area but its maximum gross weight is less than twice that of the 20 ft. unit. In the case of concrete or asphalt pavements, as containers are supported on their corner castings, the 40 ft. unit gives the worst loading conditions since it weighs more than a 20' unit but still has only four corner castings.

Table IV, gives the maximum loads and stresses for a block stacking arrangement when gravel beds are used. A comparison of Table IV with Table III which refers to asphalt or concrete surfaces, proves that the contact stresses in the case of gravel beds are between 46 to 34 times less, for stacking heights of 1 to 5 respectively.

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Table IV

PAVEMENT LOADS FROM CONTAINER BLOCK STACKING

Stacking hight	Reduction in gross weight	Gravel beds	
		load kg	contact stress
1	0	20,000	0.056 N/mm²
2	10%	38,000	0.107 "
3	20%	54,000	0.15 "
4	30%	68,000	0.190 "
5	40%	80,000	0.224 "

A reasonable question which may follow the above is whether the floors of containers are designed to carry on their underside their own gross weight plus that of another four. This question can only be answered by the container manufacturers. However, what can be said in this monograph is that experience over a number of years in container terminals where gravel beds exist, has yielded no evidence of containers sustaining damage as a result of being stacked on gravel.

Table V, presents a comparison of construction costs in various countries between gravel beds and asphalt, the most traditional type of pavement. All costs, which refer to 1982, have been obtained from either contractors or consultants who are or were involved in projects in these countries. For easy reference these have been converted into U.S. Dollars using the prevailing rates of exchange at the time of preparation of this table. However, the purpose of this comparison is to indicate the order of magnitude of the costs and not exact costs.

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Table V

Country	Cost/m² of 10 cm Asphalt pavement with 20 cm granular base and 15 cm sub-base	Cost/m² of 40 cm gravel bed	Approximate % age saving if gravel beds are adopted
CYPRUS	11 U.S.$	3.5 U.S.$	68%
GREECE	9 U.S.$	3.0 U.S.$	67%
MALAYSIA	11.5 U.S.$	4 U.S.$	65%
INDIA	20 U.S.$	7 U.S.$	65%
U.K.	20 U.S.$	8.2 U.S.$	59%
INDONESIA	17.3 U.S.$	7.7 U.S.$	57%
OMAN	17 U.S.$	8.4 U.S.$	50%
NETHERLANDS	18.3 U.S.$	9.8 U.S.$	46%
SAUDI ARABIA	17 U.S.$	8.2 U.S.$	45%
U.A.E.	16.5 U.S.$	9 U.S.$	45%

Considering a container yard of 100,000 m² where rail mounted yard cranes are used then approximately 69,000 m² form the stacking bays. In such a case the choice of gravel beds instead of asphaltic pavement, would mean with 1982 prices, a saving of about 897,000 U.S.$ in India or 814,000 U.S.$ in U.K. or 517,500 U.S.$ in Cyprus or 414,000 U.S.$ in Greece.

In addition to the tremendous initial cost saving, gravel beds are very cheap to maintain. Indeed, the available experience dictates that they require little or virtually no maintenance. Occasional clearing of debris seems to be all that is required.

Further to the low initial and maintenance costs, gravel beds offer a number of other important advantages:

a) Drainage: Unlike other paving systems, drainage of rainwater can be achieved in a very inexpensive and satisfactory way owing to the natural property of a layer of gravel to absorb water.

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Since vertical drainage is possible over the whole area, there is no need to provide catch pits, manholes, etc.

Three drainage systems have been developed for gravel beds which depend on the relative permeability of the subgrade under the gravel beds down to the sea water table. These are, the completely free draining system, the free draining system with vertical rubble drains and the partially free draining system with horizontal perforated collector drains under the beds.

Gravel beds can also in some cases play temporarily the role of a buffer storage zone to retain any excess water beyond the capacity of the drainage system under the beds, should any storms of unexpectedly high intensity occur.

In addition one can allow water from the adjacent paved areas to drain into the beds, which means that no other drainage provisions are necessary for these areas and hence further cost savings can be achieved.

b) Surface Falls: Since vertical drainage can be achieved with this system, the pavement surface can be completely horizontal. This means that stacked containers will also be horizontal, a situation which makes life easier for yard crane operators and hence better results in throughput can be achieved.

c) Traffic and Safety: Gravel beds do not permit casual cross passage by port and extraneous traffic. This has a positive advantage in channelling the traffic and maintaining predominantly one way circulations. This is of prime importance for both safety (minimising the risk of accidents) and efficiency of port operations, especially with regard to the horizontal transportation of containers.

d) Possibility to increase stacking height or to employ stacking cranes with Shorter Legs: The container stacking bays do not have to be at any specific level in relation to the neighbouring paved

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areas, as these function completely independently. They only have to be at a lower level, mainly for drainage reasons. Underground water table permitting, the gravel bed stacking bays can be constructed at levels much lower than those of the yard crane travel strips, provided that deeper surrounding kerbing beams are provided. This means that one has the flexibility to increase the stacking height under the yard cranes or if this is not required, the legs of the stacking cranes can be made shorter.

e) General

Gravel beds for stacking containers go hand in hand with yard cranes. This combination, however, offers an effective and economical solution to the intensive and well ordered stacking of containers as required in a modern and efficiently run container terminal. Given the criterion that yard stacking cranes are operating in a specialised container terminal, where the stacking areas are exclusively for container operations, then the most economic solution for the stacking surfaces is definitely the gravel bed system. It is believed that with the introduction of the automated container terminal system in conjuction with yard stacking cranes, which requires a defined and fixed terminal layout in order to enable the installation of underground transmission lines, there will be more cases where container stacking bays can be constructed with gravel beds.

Indeed considering the merits of the gravel bed system, it is interesting to see how many container terminals could have taken advantage of this system but have not. There are 119 container terminals throughout the world which use yard cranes for stacking containers. In particular there are 31 in Europe, 3 in Africa, 8 in the Middle East, 32 in the Far East and Asia, 9 in Australia, 30 in North America and 6 in Central and South America allowing, of course, some margin of error for new facilities and others that may have only recently adopted the yard gantry system. There are though, only a few remote cases where gravel beds have been adopted.

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It is not certain whether the designers of all the above mentioned container terminals have considered at all the gravel bed system as a possible surfacing solution or have simply been unaware of it and have decided instead to use much more expensive traditional pavements. Research reveals, however, that in most countries, the system, being a new approach, is still unknown.

3.6.7 Conjunctive systems

Frequently, the performance of some traditional types of pavements in port areas, has been far from satisfactory. Thus an effort has been made to introduce various improvements to these existing methods of construction.

One method which was followed in certain cases was the combination of rigid and flexible pavements i.e. by introducing special concrete standing strips for the corner castings of the containers at 6 m. intervals, the remaining area being surfaced with asphalt. This certainly provided a satisfactory solution to the problem of corner casting indentations but in a rather expensive way. Also experience reveals that in such cases sometimes the disadvantages of the rigid concrete system were added to those of the flexible asphaltic system.

Moreover, in this conjuctive system, ponding of rainwater occurs, because of the unavoidable differential settlement at the interface of concrete and asphalt areas. Therefore one might say that the effort to solve the problem of corner casting indentations resulted in introducing another problem, the ponding of rainwater, albeit not so serious.

In general, this conjuctive system has proved to be very expensive in comparison to other options.

A second method aimed at improving the durability, effective stiffness and the resistance of asphalt surfacing to oil, is the addition of epoxy or other additives to bitumen. It is possible with such special mixes to combine the flexibility of asphalt with the rigidity of concrete to provide a semi-rigid, heavy duty, wearing course which is temperature, oil and penetration resistant. This method provides a satisfactory means of improving asphalt durability, though, the costs of construction are very high and would in many circumstances not be as economic as some of the other surfacings available and may even become prohibitive in this respect.

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CHAPTER (III)

DESIGN OF HEAVY DUTY CONTAINER TERMINAL PAVEMENTS

1. INTRODUCTION

It is interesting to note that loads applied to port pavements by container handling equipment are now similar in magnitude to those applied by the largest aircraft. A Boeing 747B weighs up to 353,000 kg during take off when it applies its most damaging forces to the pavement (the landing impact load is minor, most of the weight is taken by the wings). Nearly all of that weight is taken by 16 wheels under the wing so that the pavement is subject to individual wheel loads of 21,000 kg. A front lift truck with a telescopic top-lift handling a 34,000 kg 40 ft container applies loads of 20,000 kg to 25,000 kg through each of 4 wheels on its front axle i.e. it applies greater loads than the aircraft. Aircraft pavements have been designed according to a systematic process for over 30 years. Only during the last decade has attention been focussed on port paving and the above comparison shows that the design loadings are equal to or greater than aircraft loadings.

The design approach presented here is that upon which the British Ports Association heavy duty pavement manual is based. It is simple to use and has now been used to produce successful and economic pavements for a number of years, both in developed and in developing countries. The approach is to compute strains resulting from a defined loading regime and to determine the permissible strains which pavement construction materials can withstand. A pavement is deemed to be correctly designed when actual and permissible strains are similar. The BPA manual comprises design charts so that numerical work is kept to a minimum and the user can compare several designs employing alternative material rapidly.

2. DESIGN PRINCIPLES

The fundamental design principle is to ensure that the designed pavement remains serviceable while a specified loading regime is applied throughout its design life. At most container handling facilities, the pavements are subject to two loading regimes. In the first containers are stored in blocks and in the second, handling equipment run alongside

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these blocks. Some handling systems (e.g. straddle carriers) require the handling equipment to enter the blocks and this can greatly increase the cost of the pavement since the storage area has to be designed to accommodate both types of loading.

Serviceability failure in a heavy duty pavement occurs either by the development of excessive vertical compressive strain in the subgrade or by the development of excessive horizontal tensile strain in the base. Fig. 4 (page 27) shows the location of these critical strains in each of the four categories of pavement. The allowable subgrade vertical compressive strain adopted is given by:

$$E_v = 21600/N^{0.28}$$

where E_v is allowable subgrade vertical compressive strain (microstrain), and N is number of repetitions of applied load.

For example, if the pavement were subjected to one load repetition, a strain of 21600 microstrain, or 0.0216 strain, would be the maximum allowable, but if there were 10,000 repetitions, the allowable strain would be only 1638 microstrain.

The maximum permitted horizontal tensile strain is given by the following equation:

$$E_h = \frac{F_c \text{ X } 993{,}500}{6 \text{ X } E_b^{1.022} \text{ X } N^{0.0502}}$$

where E_h = allowable base horizontal radial strain (microstrain),

F_c = characteristic compressive strength of base material (N/mm²),

N = number of repetitions of applied load

when F_c is less than 7 N/mm², E_b is given by $E_b = 4000 \text{ X } F_c$

when F_c is greater than 7 N/mm², E_b is given by $E_b = 16{,}800 \text{ X } F_c^{0.25}$

Figure 5 shows the relationship between E_h and N for four values of F_c.

3. ANALYSIS TECHNIQUE

In order to determine whether a proposed pavement meets the two serviceability criteria, it is necessary to determine the actual strains

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in the pavement at the two critical locations when subjected to surface loading. The actual strains are determined by an analysis technique in which each course within the pavement is transformed into an equivalent thickness of the pavement's subgrade material. This transformation is based upon the concept that if an actual pavement course is replaced by a course of different material and different thickness, then provided that the actual course and the transformed course have similar flexural stiffness, an accurate pavement analysis can be performed. For two courses of material to have similar flexural stiffness, the term

$$\frac{h^3 \text{ X } E}{1 - V^2}$$

must be similar for each course, where E = elastic modulus, h = course thickness and V = Poisson's ratio.

Thus, a course of thickness h_1, elastic modulus E_1 and Poisson's ratio V_1 can, in analytical terms, be replaced by a thickness h_2 of a different material of elastic modulus E_2 and Poisson's ration V_2 by:

$$h_2 = h_1 \text{ X } \sqrt[3]{\frac{E_1 \text{ X } (1 - V_2^2)}{E_2 \text{ X } (1 - V_1^2)}}$$

When each course of the pavement has been so transformed, strains are calculated at the boundary of each course and these strains are compared with the limiting strains for the actual material from which the pavement is constructed. Hence the required course thicknesses are determined. Following the transformation procedure, the pavement has been replaced by an equivalent semi-infinite homogeneous isotropic body so that a Boussinesq analysis can be undertaken to determine stresses and hence strains.

4. PROPERTIES OF MATERIALS

As the twin design criteria and the analysis are based upon elastic theory, elastic constants (i.e. Elastic modulus and Poisson's ratio) have to be assigned to the four components of the pavement i.e. the subgrade, the sub-base, the base and the surface. In the case of conventional rigid concrete paving, the concrete is considered to be the base and no surfacing is considered during the analysis.

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In the case of the subgrade, it is more common for engineers to refer to its strength in terms of its California Bearing Ratio (CBR), and relationships have been developed between elastic modulus, poisson's ratio and CBR.

5. ASSESSMENT OF APPLIED LOADING

A realistic method of assessing the damaging effect of container handling equipment has been developed which reflects those parameters which are particular to container terminal pavements.

These parameters are:

a) very heavy wheel loads up to 25,000 kg
b) wide area operation
c) severe dynamics
d) wide range of equipment types and sizes

These parameters distinguish port paving from highway paving and eliminate the use of empirical highway pavement design methods. The extrapolation of highway design procedures has led to premature deterioration of many container terminal pavements, owing to the design methods.

5.1 Very heavy wheel loads

As the design method is based upon the assessment of permissible and actual strains heavy loads are dealt with directly and there is no need to replace an actual heavy load with a standard load. An item of plant is assigned a damage rating in the following way. For each wheel on one side of the plant, the damaging effect is calculated from the equation -

$$D = \left(\frac{W}{12000}\right)^{3.75} \times \left(\frac{P}{0.8}\right)^{1.25}$$

where D = pavement damage, W = wheel load (kg) and P = tyre pressure (N/mm²)

This equation employs the fourth power damage rule, which is a statement of the relative sensitivity of pavement damage to applied load, to applied pressure and to the number of repetitions of the load and the pressure. This equation gives pavement damage, D, in units which have been devised during the development of the design method. The unit is the Port Area Wheel Load (PAWL), and a damage effect of one PAWL, can be defined as the damage iniflicted on a pavement by one repetition of a 12000 kg wheel applying a contact pressure of 0.8 N/mm². For each wheel on one side of the plant (some items of plant have different wheel loads on each side, in which case use the heavier side), the PAWLs are assessed and the plant is assigned a Load Classification Index (LCI) according to the relationship shown in Table VI. An LCI of A indicates a relatively undamaging item of plant, and conventional highway vehicles fall into this category. The LCI boundaries have been chosen so that the heaviest materials handling plant in current use fall within categories F, G and H depending upon how they are operated.

Table VI

Relationship between Port Area Wheel Load (PAWL) values and Load Classification Index (LCI)

PAWL value	LCI
Less than 2	A
2 - 4	B
4 - 8	C
8 - 16	D
16 - 32	E
32 - 64	F
64 - 128	G
128 - 256	H

5.2 Wide area operation

The relationship between a vehicle track width and the effective lane width within which it operates governs the number of repetitions to which an isolated point in a pavement is subjected. Therefore, when assessing the number of repetitions for which a pavement should be designed, a reduction of total lane movements is undertaken as follows: When the effective lane width is greater than 5.5 times the trackwidth, only one third of movements are considered to occur over one point. When the effective lane width is between 5.5. and 3 times the trackwidth, a half of the movements are taken in design. When the effective lane width is less than 3 times the trackwidth, the number of design repetitions is equal to the number of movements. These reductions are based upon observations of the lateral distribution of moving plant in lanes of different width (see figure 5 on page 40).

5.3 Severe dynamics

In assessing the PAWL value for each wheel, it is necessary to assume a wheel load, W (kg). This load should take into account the effect of mass transfer induced by dynamics. Dynamic factors have been defined and static wheel loads are multiplied by these factors prior to PAWL calculations. Table VII shows dynamic factors adopted for various types of plant and for various operating conditions. Where two or three operating conditions apply simultaneously, the dynamic factors should be multiplied together prior to static load multiplication.

It should be noted that the effect of dynamics is particularly severe and the factors should be applied simultaneously only where there is specific reason to do so. Dynamic factors can effect pavement thickness by up to 50%. Where vehicle movements can be predetermined, it will be possible to design substantial areas of the pavement without dynamic effects.

Table VII

DYNAMIC FACTORS FOR DIFFERENT CATEGORIES OF PLANT

Type of plant	Type of operation			
	Braking	Cornering	Accelerating	Uneven surface
Front lift trucks	1.3	1.4	1.1	1.2
Straddle carriers	1.5	1.6	1.1	1.2
Side lift trucks	1.2	1.3	1.1	1.2
Tractors and trailers	1.1	1.3	1.1	1.2

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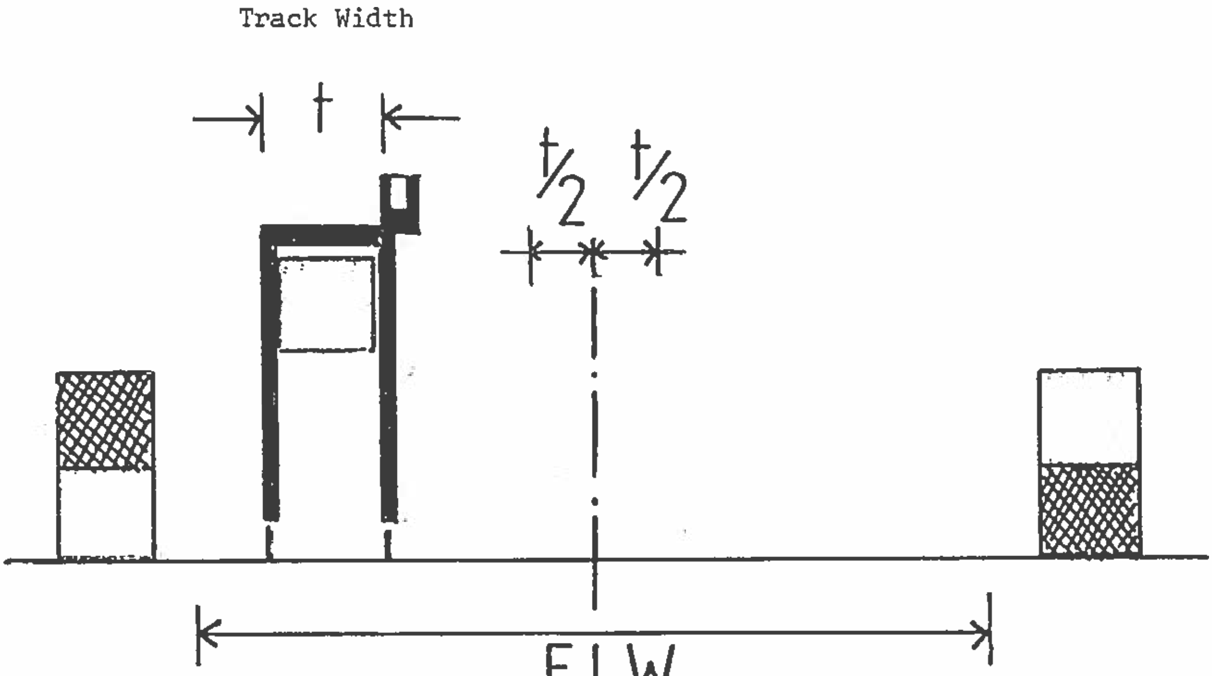
REDUCTION FACTORS FOR WIDE PAVEMENTS



Effective lane width (ELW)

$ELW < 3t$

$f = 1.0$

$ELW \; 3t - 5.5t$

$f = 0.50$

$ELW > 5.5t$

$f = 0.33$

FIGURE 5

5.4 Wide range of equipment types and sizes

The design method, being based upon fatigue-orientated elastic analysis, is not limited to any specific class of plant. Even equipment which have yet to be developed can be classified relatively easily. A factor that is also taken into account is wheel proximity. The addition of strains attributable to closely spaced wheels produces a significant increase in pavement thickness for certain types of plant, e.g. front lift trucks with two or three wheels at each end of their front axle. For wheels bolted side by side, the two or three wheels are considered to be a single wheel of load equal to the sum of the two or three. For wheels in tandem, Table VIII shows proximity factors by which PAWL values for individual wheels are multiplied prior to addition to determine the LCI. The factors in Table VIII are dependent both on longitudinal wheel spacing and, to a lesser sensitivity, on the plant's PAWL value.

Table VIII

Proximity factors for various longitudinal wheel spacings and various PAWL values

Longitudinal wheel spacing (mm)	Proximity factors for various damaging effects							
	2 PAWL	4 PAWL	8 PAWL	16 PAWL	32 PAWL	64 PAWL	128 PAWL	256 PAWL
500	1.94	1.95	1.96	1.96	1.97	1.98	1.98	1.98
1000	1.80	1.84	1.85	1.86	1.87	1.89	1.92	1.93
2000	1.40	1.45	1.51	1.58	1.62	1.64	1.72	1.75
4000	1.00	1.01	1.05	1.09	1.14	1.21	1.28	1.33

6. CALCULATION OF DESIGN LIFE OF A PAVEMENT

The design life of a pavement is the number of movements of the critical load that the pavement shall withstand before becoming unserviceable.

The critical load is the container load passing through the port which will cause the maximum damaging effect i.e. the critical damaging effect. This is a result of both the value of the load and the frequency that this load is repeated i.e. how many containers having this load pass for a given period through the port. Thus the critical damaging effect can be found as follows:

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You multiply the damaging effect caused by the wheel loads considering each possible container load (i.e. from zero for unladen equipment up to 34,000 kg for a 40 feet full container with the maximum permissible gross weight i.e. 35 sets of loads in steps of 1,000 kg) with the corresponding percentage frequency that each of these container loads would pass through the terminal.

The container load which causes the highest proportional damaging effect is the critical load and the actual damaging effect caused due to this critical load is the critical damaging effect. However, before doing this it is essential that the percentages of containers of different weights passing through the port are established and these can be produced by a simple survey and application of simple statistics.

As the design life, L, of the pavement is the equivalent number of movements of the critical load this is calculated as follows:

$$L = \frac{\text{total number of plant movements} \times \text{average damaging effect}}{\text{critical damaging effect}}$$

To calculate the average damaging effect you multiply each of the 35 damaging effects by the corresponding percentage value and the sum of these 35 products divided by 100 is the average damaging effect.

7. THE USE OF DESIGN CHARTS

The BPA manual contains a collection of 120 design charts which allows the user to compare alternative solutions rapidly. This approach has advantages and disadvantages. The primary advantage is the saving in time which encourages the comparison of a greater number of alternatives. It is also possible to examine sensitivity of a given design to changes of design life, soil strength or load magnitude. For example, the charts show that relative large changes in the number of repetitions (say doubling or halfing) affects pavement thickness by only a few millimetres whereas small percentage changes in load magnitude have a more significant influence on pavement thickness. A further advantage is the virtual elimination in the possibility of gross error. It is difficult to see how a user could be in error by more than a few millimetres.

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By contrast, calculation leads to very high apparent accuracy but always with the fear that an order of magnitude error may have been made. In effect, design charts provide a design space through which the user travels, becoming aware whenever he approaches a boundary which would warn him that he is operating in an unorthodox situation.

Design charts have some disadvantages. They are expensive to produce and in the case of the BPA manual, this may have dissuaded some casual designers from purchasing it (and they are probably the ones who would benefit most).

Also, solutions can be presented for only a few discrete combinations of design variables. In pavement design, this is less of a problem than it might be in some other areas since many of the design inputs are little more than educated guesses. Principally, soil strength is required as a California Bearing Ratio (CBR). This is a messure of the shear strength of the material. In many port situations CBR varies throughout the life of a pavement and it is difficult to predict how it will vary. Also, the pavement design chart depend upon a knowledge of the way handling equipment is handled and upon the way its tyres behave. Identical equipment in two locations may be operated differently. There may be port imposed speed limits or tighter braking or turning zones. Also, tyres specifications are frequently changed and it is not uncommon for one vehicle to have two or more entirely different tyres. Tyres vary between a theoretical totally stiff tyre in which a transient load increase manifests itself in a change in pressure and no change in contact area and a theoretically totally flexible tyre in which the reverse occurs.

Taking into account all of the factors, design charts are considered to be the most appropriate medium for presenting a design method for heavy duty paving. Over 500 copies of the BPA manual are now in use in over 40 countries and feedback indicates that the method produces sound solutions which allow a local designer to take full advantage of his local materials.

An example of a BPA chart is shown in figure 6 and diagramatically in figure 7. (see pages 44 and 45 respectively).

The most straightforward way to use such a chart is to start at point A which means a number of repetitions of the design load is needed.

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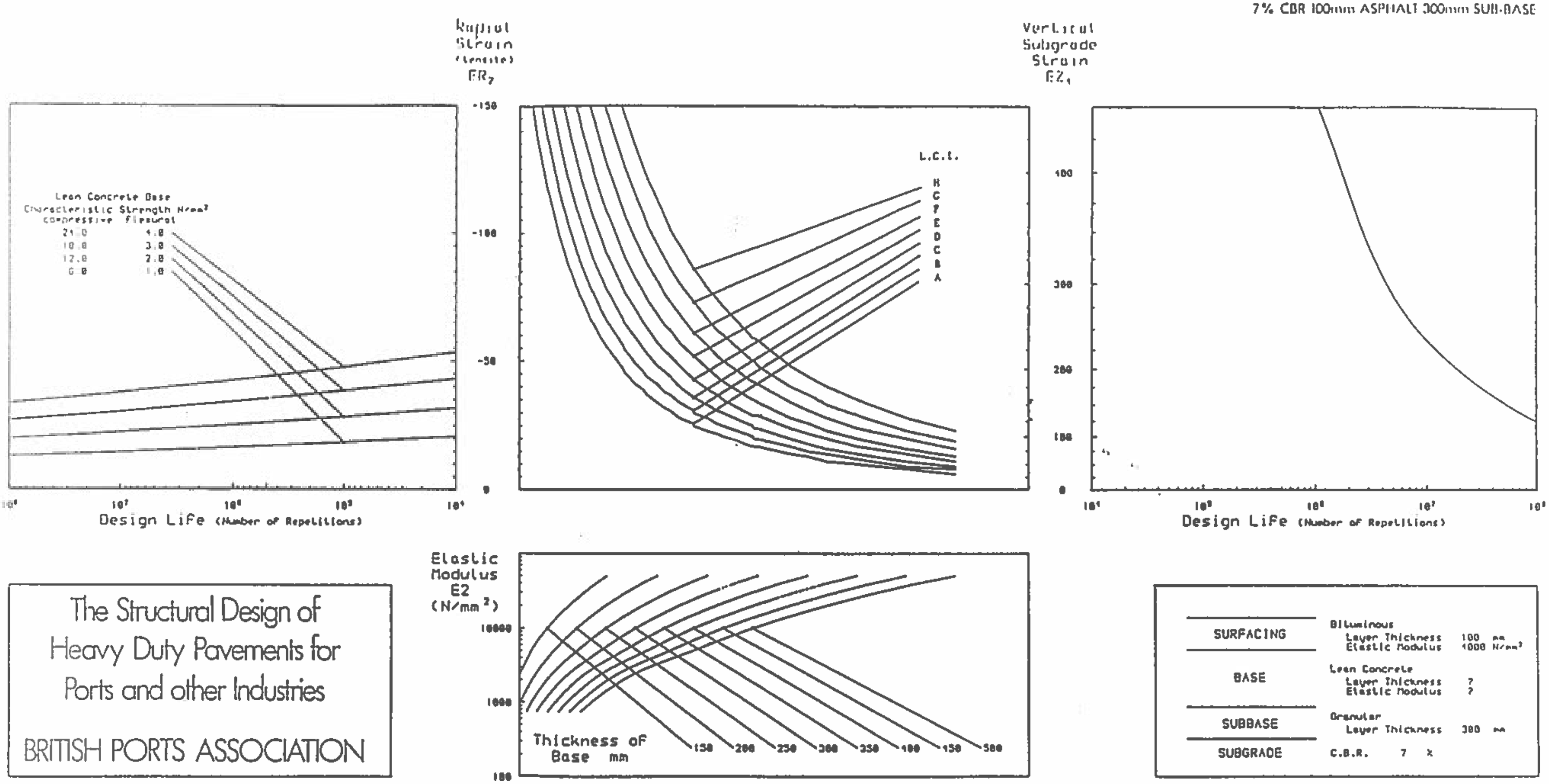

FIGURE 6. AN EXAMPLE OF A B.P.A CHART

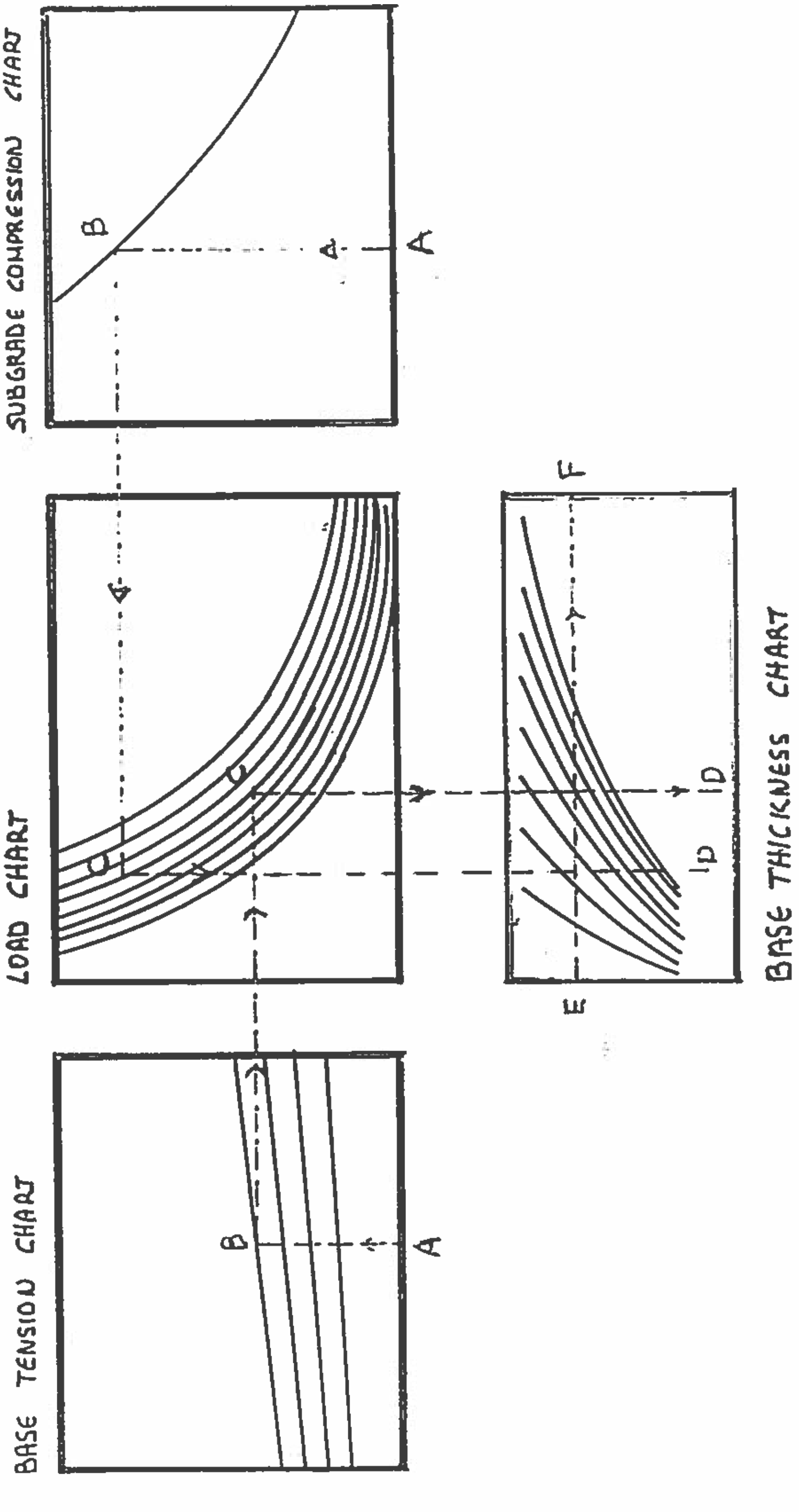

FIGURE 7. B.P.A. CHART IN DIAGRAMATIC FORM SHOWING THE SEQUENCE OF STEPS/READINGS FOR CHOOSING THE BASE THICKNESS.

If there is no firm data available, it is suggested that a value of 2,000,000 repetitions should be sufficient for most pavement and this would correspond with a life of 25 years in a typical busy handling facility. From A, a line is taken vertically to one of the four almost straight lean concrete curves (say to point B). A horizontal line is then taken from B to the appropriate load Classification Index (LCI) curve at C (see section 5 of this chapter for LCI determination). Now project a line vertically down from C through a family of curves within the lower box. Also, draw a horizontal line from E corresponding with the elastic modulus of the pavement base material. This line meets the previous vertical line within the family of curves at point D. Each of the curves within the family is a base thickness contour. Point D represents the base thickness required.

8. SURFACE FALLS

With the exception of gravel beds, with which vertical drainage can be achieved, a certain surface gradient must be provided for all other types of pavements for carrying the rain water into the sewers. Steep falls will guarantee an effective surface run-off of the rainwater but on the other hand may cause operational disturbances. This is particularly important with regard to the use of tug masters and especially the multi-trailer system, since steeper falls require greater tractor power. The flexibility of the layout is sometimes hampered by such falls in different directions. Also severe falls in container stacking yards will result in a situation where the containers are not properly supported on their four corner castings and in some cases they may cantilever for a certain length. On the other hand, flat surfaces will cause ponding of water which again cause operational disturbance.

Effectively, surface slopes represent a compromise between what is possible from a civil engineering point of view and what an equipment designer will accept.

Practice has proved that pavements with gradients of about 1% (but not less than this) have worked perfectly in container terminals from all points of view.

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9. PROVISION OF UNDERGROUND SERVICES

One of the prerequisites for the proper operation of a container terminal is the satisfactory provision of various services e.g. water, telephone and electricity. These services must be distributed to various locations throughout the terminal and inevitably have to cross the terminal from one end to the other and in all directions. It is very important that the presence of these services will not cause any problems to the terminal operations and on the other hand it is equally important that services will not suffer any damage owing to these operations. The only way to prevent this from happening is to install the required services in such a way that their interference with the surfaces over which the terminal operations are carried is minimised. Practice has proved that the best way to achieve this is to lay all cables or pipes in service ducts. This system guarantees easy accessibility to the services for maintenance, repairs or extensions without having to disturb the pavement and cause inconvenience and further cost when reinstating the surface. Service ducts in the form of covered concrete channels are very convenient, but have proved to be very expensive. Also these covers are sometimes required to be so heavy that to lift them is not an easy job. Another type of ducting, which proved to be much cheaper and convenient, is the use of plastic pipes surrounded with lean concrete. Cables or water pipes can be passed through the plastic pipes of larger diameter but this can only be done if manholes are provided at appropriate distances and at points where the direction of the ducting changes. With this system, however, it is always recommended to install up to 40% additional spare plastic ducting pipes for future extensions. If the plastic pipes are placed at the appropriate depth under the pavements and protected with the necessary concrete surround, then it is expected that the ducting system will be successful and free of problems. Special care must be taken for the protection of water pipes as any large leakage of water under the surface may change the properties of the subgrade and cause failure of the pavement. This is very dangerous as the failure will, in most cases, occur suddently when subjected to the load of a moving piece of equipment.

In container terminals it is recommended that duct and manhole covers, drainage catch pits, etc., must be designed to carry 30 ton wheel loads, unless for special reasons a higher load must be considered.

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CHAPTER (IV)

REGULAR MONITORING OF PAVEMENTS

With many types of pavement, once deterioration commences, total unserviceability is imminent and rapid degradation takes place over a short interval, particularly during severe weather. If remedial work is undertaken in good time then the useful life of the pavement can be extented at minimum cost.

One may logically expect that a well designed and constructed pavement should remain serviceable for the period which the designer intended. However many times even a well designed pavement may be prematurely damaged by being overloaded or by being subjected to abnormal internal stresses during particularly severe weather. Therefore, a pavement may remain serviceable for its whole design life or for only part of it.

Consequently, a prudent authority should undertake at regular intervals a condition survey of its paved areas in order to register any deterioration at an early stage. The frequency of monitoring will vary with the workload of the facility, the location of the facility and the local conditions such as climatic variations and other factors.

The condition survey of pavements can be defined in two categories:

1. Condition of the material
2. Degree of localised rutting or settlement

Usually, the material condition survey simply acounts to a record of the amount of cracking and spalling of the surface which is nothing more than a visual inspection. It may be difficult to assess the condition of lower pavement courses with regard to cracking and therefore conservative assumptions should be made. If however there is strong suspicion of abnormal deterioration of the lower pavement courses then cores or trial holes should be taken to verify the actual condition. The material condition survey has been standardised so that standard condition factors for cracking and spalling can be used. The various degrees of

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cracking are shown in figure 6. and the corresponding condition factors are as follows:

Condition of material	Condition factors, CF1
As New	1.0
Slightly cracked	0.8
Substantially cracked	0.5
Fully cracked, crazed or spalled	0.2

The survey to establish the degree of localised rutting or settlement has also been standardised.

It is recommended that immediately following construction of a new area, a level survey be undertaken using instruments accurate to 1 mm. Levelling positions should be as follows:

(i) rigid concrete and precast concrete rafts: at each corner of each bay or raft.

(ii) bituminous or concrete block paving: one level for each 100 m² of paving, at locations which will be possible to re-establish at later date.

In the case of bituminous or concrete block paving, a secondary level survey should be taken immediately following construction. Levels should be taken in one or more 10 m. X 10 m. representative areas, using a 1 m. grid. Rutting and settlement is measured in levels under a 3 metre straight edge. If a pavement has deformed, cores should be taken to determine which courses of the pavement are affected.

The corresponding condition factors to be applied to the various degrees of localised rutting or settlement are as follows:

Degree of localised rutting of settlement	Condition factors, CF2
0 - 10 mm	1.0
11 - 20 mm	0.9
21 - 40 mm	0.6
40 + mm	0.3

The above condition factors for both cases do not serve any particular purpose at the monitoring stage. However they play a major role in the design of the remedial works, as they are used to determine the residual strength of an existing pavement which the designer will take advantage of so that a lower cost strengthening arrangement can be undertaken.

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CHAPTER (V)

MAINTENANCE, REHABILITATION AND UPGRADING OF PAVEMENTS

While initial cost plays a large part in the choice made for a pavement type in a given situation, it must be recognised that recuring maintenance costs are of equal importance. There have been many examples where maintenance costs over the entire expected useful life of the pavement have by far exceeded the initial cost.

As with many types of structures, the key to minimum pavement maintenance is proper selection, design and construction. Despite all of the measures which are taken to ensure that the original construction of a pavement will be properly accomplished, it must be expected that some maintenance will be required. It must be emphasized that where maintenance costs become substantial, consideration must be given to a major rehabilitation or ugrading or even total replacement of the pavement.

A usual definition of maintenance is "the day-by-day function to keep a facility in good operating condition". However, the responsibilities of a "Container Terminal Pavement Manager" must be extended beyond the narrow interpretation of the above definition. His efforts must not be confined to keeping the facility in good operating condition by taking care of defects. He should achieve many other tasks such as avoiding major repairs which will affect terminal operations and guarantee or even extend the expected useful life of the pavement.

The key to this is the regular monitoring of pavements which was covered in brief in the previous chapter. In fact "regular monitoring" is the starting point of a correct "pavement management programme" which must be implemented from the day after the completion of the construction of the pavement. This programme can be descriped as follows:

(i) Regular monitoring
(ii) Preventative maintenance
(iii) Repair of damage and breakdowns
(iv) Rehabilitation or Upgrading
(v) Demolition and reconstruction

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The above five phases cover all the stages that a pavement will undergo during its life-cycle. Therefore the proper and successful execution of the above five functions will largely define the extent of the useful life of the pavement.

Regular monitoring will lead to preventative maintenance. This will ensure that any tendency for deterioration is noted and the "pavement manager" will then be able to undertake minor remedial measures and so avoid major repairs at a later stage. Preventative maintenance is therefore the prevention of breakdowns by taking corrective action before costly disruption in operation can occur. Preventative maintenance has long been recognised as being extremely important not only in the reduction of total maintenance costs and the improvement of facility reliability but also in safeguarding or even extending the expected useful life of a terminal pavement.

On the other hand if regular monitoring is not properly or at all undertaken then the preventative maintenance phase may become too short or even non existant and repair work will have to be undertaken earlier than should have been the case. Furthermore if damage and breakdowns are not properly repaired the need for rehabilitation or upgrading may arise at a much earlier time than originally anticipated. Moreover, if the need for rehabilitation or upgrading is not recognised on time and the strengthening of an existing pavement is delayed then the demolition and reconstruction of the pavement may be the only option.

From the above it is clear that each of five phases of the "pavement management programme" has an influence on all of the remaining phases and all of these phases have a direct influence on the useful life of terminal pavements and by inference on that of the terminal itself. Therefore the terminal operators should take the maintenance of their surfacing as seriously as they take the maintenance of their handling equipment.

The reasons for the deterioration of a container terminal pavement can be covered under the following headings:

(i) Age

(ii) Overloading and abuse

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(iii) Weathering
(iv) Settlement
(v) Accident
(vi) Pavement installed with undue care
(vii) Wrong pavement choice

The most common reasons for rehabilitation or upgrading of container terminal pavements are the following:

(i) Pavement has become unserviceable
(ii) Change in operation - heavier equipment
(iii) Change in operation - revised levels or layout
(iv) Improvement of surface properties e.g. skidding and water penetration.

Pavement rehabilitation requires that the condition of the existing pavement is assessed so that advantage can be taken of its residual strength. It is usually cost effective to use the existing pavement as a major structural component of the new pavement.

Sometimes a pavement can be revitalised by removing the upper course replacing it with similar, or alternative material of similar thickness. Whilst this approach is unlikely to provide significant additional strength, it can form a very low cost solution in cases where the existing surface course is distressed and the other courses are satisfactory.

However the most cost effective way of pavement strengthening is commonly the overlay technique. Once the residula strength of an existing pavement has been assessed, the overlay design technique must be capable of selecting the thickness and the properties of the overlay materials. The demand worldwide for reduction of the immense repair costs of aged bituminous pavements has recently resulted in the deployment of the new technology of geotextiles in developing a very successful overlay technique for asphaltic pavements. Asphalt overlay for the prevention of reflective cracking in bituminous surfaces has now become a major application area for geotextiles.

Secondary crack formation or vertical crack propagation in the surface of an asphaltic pavement is not uncommon. These cracks usually result from flexural fatique, natural aging of the surface because of the many diverse environmental influences and due to a few other mechnisms. These cracks result in the loss of the sealing function of the surface course, thus,

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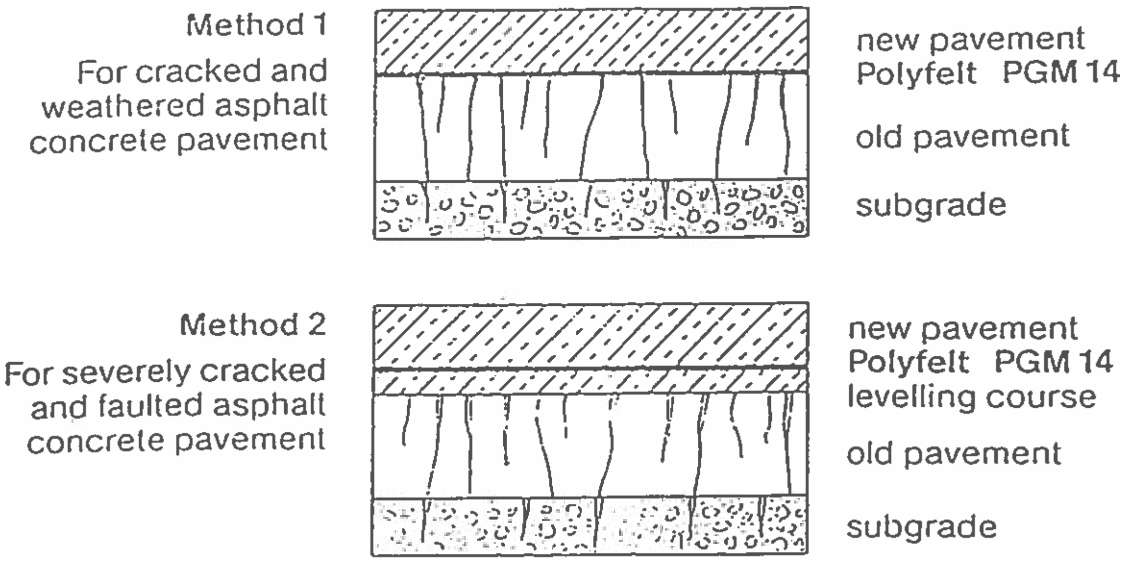
allowing the penetration of moisture and rainwater through the cracked surface into the base course, causing a reduction in the shear strength of the base course material. The resulting damage is the formation of ruts, concentrated longitudinal cracks in the traffic lanes, potholes and frost damage.

If the cracked pavement surface is renovated by resurfacing, reflection cracking, i.e., crack propagation from the old to the new pavement surface can lead to the formation of tertiary cracks in the new surface cover. These cracks are also caused by the combined influence of temperature and traffic stresses and also lead to the loss of the sealing effect of the bituminous surfacing, and thus to a further reduction of the shear strength of the base course material.

This has been the case in the ports of Larnaca and Limassol in Cyprus, for which the author of this paper is responsible concerning maintenance and construction, where for many years, the common resurfacing of aged asphaltic pavements proved to be only a temporary measure, as the crack paterns of the old surfaces were reappearing of the new surfaces within a period of a few months, usually following a climatic seasonal change. However, since the introduction of a geotextile membrane in the overlay systems applied for the renovation of aged asphaltic pavements in both the above mentioned ports, the problem of reflection cracking has been solved. In particular, in the cases mentioned above a polypropylene, nonwoven, needlepunched, weldable, asphalt impregnated geotextile of the type polyfelt PGM14 was used with excellent results. This type of geotextile when used to prevent reflective cracking in asphalt overlay, fulfills two main functions: the sealing or water proofing function and the reinforcing function.

The sealing function of the asphalt impregnated geotextile polyfelt PGM14, as well as the increased resistance to flexural fatique of the new asphalt overlays at the ports of Larnaca and Limassol, are considered to be the determining influence factors for extending the life of the existing asphaltic pavement in these ports. An observation period of more than 12 years in field testing in other cases leads to an empirical value for the increase in pavement life factor ranging 2 and 3.



Above: The two methods of application of asphalt overlay adopted at the Ports of Limassol and Larnaca in Cyprus.

The chief disadvantage of overlaying is that the pavement surface level is raised so that drainage, kerbs and other details will need attention.

The overlay design technique suggested is the one described in the British Ports Association Manual "The Structural design of heavy duty pavements for ports and other industries" which is based on the "component analysis method and the pavement transformation procedure".

The strengthening operation may be to extend the life of the pavement or it may be to allow an existing pavement to carry more damaging handling plant. This second reason for strengthening a pavement is of particular relevance to container terminals since it is common for new developments in handling plant to require stronger pavements. Table I gives suggested alternative overlay techniques for four types of existing terminal pavement.

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Concrete Rafts	Concrete Blocks	Rigid Concrete	Asphalt
1 Lift rafts, rescreed sand & replace rafts	Lift blocks, rescreed sand and replace blocks	Lay thin bonded topping over slabs	Lay additional asphalt
2 Lift rafts, strengthen base and replace rafts	Lift blocks, strengthen base and replace blocks	Lay concrete overslabs over old slabs	Lay concrete blocks
3 Lift rafts, remove sand and lay asphalt	Lift blocks remove sand strengthen base & lay asphalt	Lay asphalt over old slabs	Lay unbonded overslab
4 Lift rafts, remove sand and lay concrete	Lift blocks, remove sand and lay concrete	Lay concrete blocks over old slabs	Strengthen and lay new surfacing
5 Lift rafts, remove sand and lay concrete blocks	Lift blocks, rescreed sand and lay rafts		

Table IX Suggested alternative overlay techniques for four types of existing pavement

CHAPTER (VI)

CONCLUSIONS

The traditional approach has been to select container handling equipment according to operational requirements, then to design a pavement system to withstand the damage inflicted by the selected equipment.

From this seminar it may be concluded that it is worthwhile paying a proportional amount of attention to the pavement with emphasis on the relationship between terminal equipment and surfacing systems. The selection of container handling equipment and pavement systems should be considered in paralell.

The pavement is an essential and integral part of the terminal as a container handling system.

It is clear that there is no standard solution for the pavement of the average terminal, and even for a particular terminal the choice will be a compromise. Most important is that one is aware of the available choices and the relevant factors.

It is fortunate that now terminal designers can take advantage of the benefits offered by new techniques and methods which have been recently developed for the design and construction of terminal pavements.

With recent development of port pavement design methods and the introduction of many new materials and techniques, the pavement engineer now has many more options and accurate ways to evaluate these options. In effect, he is now less of a technician and is more of a manager. His contribution to the financial well being of his port is now of the first order and it is imperative that his pavements life cycle costs are as low as possible. In an age of increasing competition his port will be financially disadvantaged if the overhead cost associated with pavement design, maintenance, upgrading and rehabilitation is greater than that of the port along the cost. It is hoped that this seminar will stimulate all those responsible for port pavements to take the widest possible view of their work.

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CHAPTER VII

WORKED EXAMPLE

DESIGN OF A CONTAINER TERMINAL PAVEMENT

Design Example

Loading

FLT unladen weight = 50,500 kg

Load to be carried = 21,000 kg (containers)

Track width = 3,300 m

Tyre pressure = 0.70 N/mm^2

X1 = 2,480 m)
)
X2 = 7,980 m) Refer to page 61
)
XT = 5,080 m)
)

Sub-grade: C.B.R. 7%

Required design life of pavement = 20 years (1,000,000 estimated number of cumulative repetitions of load).

Wheel Load Calculations (Refer to page 62)

For front wheels:

$$W1 = fD \; X \; fp \; X \left(\frac{A1 \; X \; Wc + B1}{M} \right)$$

For rear wheels:

$$W2 = fD \; X \left(\frac{A2 \; X \; Wc + B2}{2} \right)$$

The terms in these equations are:

i) fD = dynamic factor (assume most critical dynamic effect is cornering only)

∴ fD = 1.40 (refer to Chapter III, page 39, Table VII)

ii) $A1 = \frac{-X2}{X1 - X2} = 1.45$

iii) $A2 = \frac{-X1}{X2 - X1} = -0.45$

iv) $B1 = \frac{WT\,(XT - X2)}{X1 - X2} = 26627$ kg

v) $B2 = \frac{WT\ (XT - X1)}{X2 - X1} = 23873$ kg

vi) fp = Wheel proximity factor (the plant has 2 wheels side by side)

$\therefore$ fp = 2.0 (refer to Chapter III, page 41, Table VIII)

The equivalent front and rear wheel loads can now be expressed in terms of container weights Wc:

$$W1 = 2.0 \times 1.4 \times \frac{(1.45 \times Wc + 26627)}{4}$$

$$W2 = 1.4 \times \frac{(0.45 \times Wc + 23873)}{2}$$

Assume a container weight of 21,000 kg

W1 = 39,954 kg

W2 = 10,096 kg

Damaging effect = D

Tyre pressure = 0.70 N/mm^2 = P

$\therefore$ PAWL equation is: $D = \left(\frac{W}{12000}\right)^{3.75} \times \left(\frac{P}{0.8}\right)^{1.25}$

$$\therefore D = \left(\frac{W}{12000}\right)^{3.75} \times \left(\frac{0.7}{0.8}\right)^{1.25}$$

The above equation is applied to one equivalent front wheel and to one equivalent rear wheel to obtain the number of PAWL per pass

$$D = \left(\frac{39,954}{12,000}\right)^{3.75} \times \left(\frac{0.7}{0.8}\right)^{1.25} + \left(\frac{10,096}{12,000}\right)^{3.75} \times \left(\frac{0.7}{0.8}\right)^{1.25} =$$

$= 77.08 + 0.44 =$ 77.52 PAWLS

i.e. L.C.I = G (refer to Chapter III, page 38, Table VI.)

Lane width factor

Lane width = 5m

Plant track = 3.3m
width

∴ Lane width factor = 1.0 (refer to Chapter III, page 40, figure 5)

Pavement selection

C.B.R. = 7%

N = 1,000,000

L.C.I = G

Consider the following alternative pavement materials

i) Asphalt
thickness = 100 mm
E = 4000 N/mm^2 (refer to page 63)

ii) Concrete blocks + bedding sand
thickness = 130 mm
E = 7500 N/mm^2 (refer to page 63)

iii) Rigid concrete
fc = 30 N/mm^2
E = 30,000 N/mm^2 (refer to page 63)

The alternative design solutions are tabulated below:
(solutions can be obtained by using the appropriate charts. See pages 64 to 72).

Surface	Base (mm)	Sub-base (mm)
Asphalt	410 390 370	150 300 600
Concrete blocks	400 380 360	150 300 600
Rigid Concrete	390 370 350	150 300 600

Strength of base concrete = 18 N/mm^2 (for properties see page 63).

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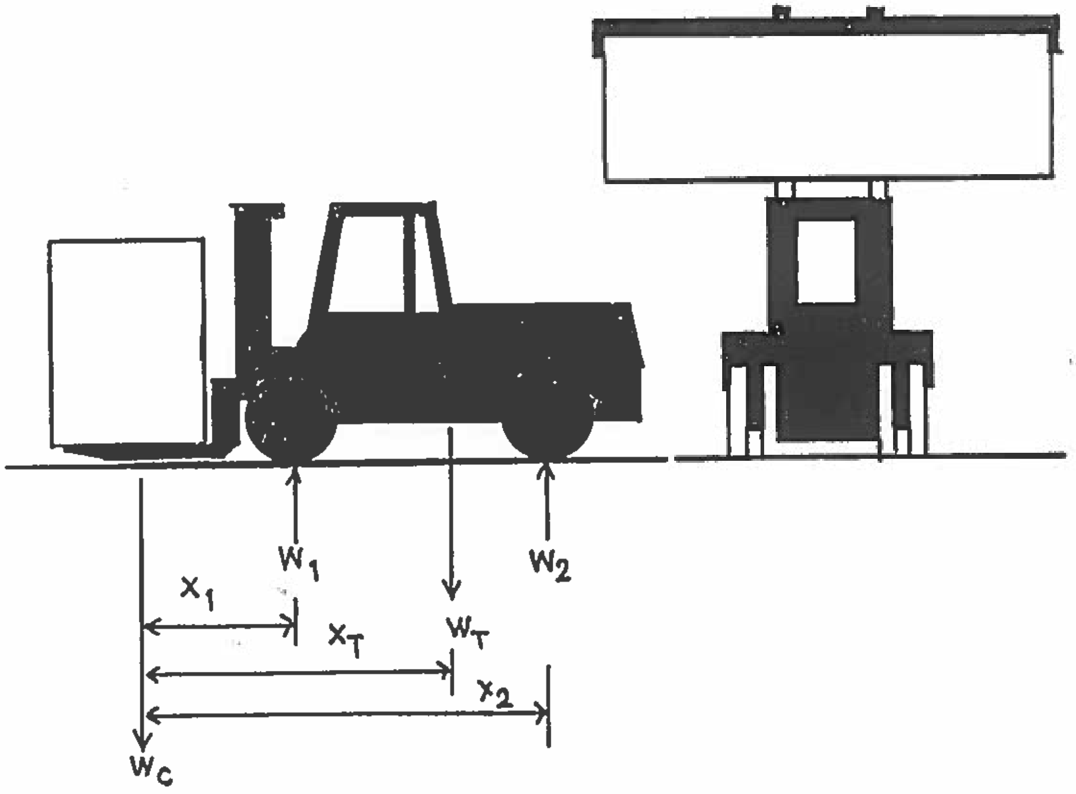

FRONT LIFT TRUCK

WHEEL LOAD CALCULATIONS FOR

Front Lift Truck

$$W_1 = f_D \times \left(\frac{A_1 \times W_C + B_1}{M} \right)$$

$$W_2 = f_D \times \left(\frac{A_2 \times W_C + B_2}{2} \right)$$

where W_1 = load on front wheel (Kg)

W_2 = Load on rear wheel (Kg)

W_C = Weight of container (Kg)

M = number of wheels on front axle (usually 2, 4 or 6)

f_D = dynamic factor (see section 2.5)

A_1, A_2, B_1 and B_2 are :

$$A_1 = \frac{-X_2}{X_1 - X_2}$$

$$A_2 = \frac{-X_1}{X_2 - X_1}$$

$$B_1 = \frac{W_T(X_T - X_2)}{X_1 - X_2}$$

$$B_2 = \frac{W_T(X_T - X_1)}{X_2 - X_1}$$

X_1, X_2 and W_T are shown in Figure 3

W_T = self weight or truck (Kg)

ELASTIC CONSTANTS FOR COMMONLY USED PAVEMENT MATERIALS

E = Elastic modulus

V = Poisson's ratio

1) ASPHALT SURFACE

$E = 4,000\ N/mm^2$

$V = 0.4$

2) CONCRETE BLOCKS (80 mm thick bedded in 50 mm of sand. i.e. course thickness 130 mm)

$E = 7,500\ N/mm^2$

$V = 0.2$

3) RIGID CONCRETE (reinforced, with compressive strength of 30 N/mm^2

$E = 30,000\ N/mm$

$V = 0.2$

ELASTIC COSTANTS FOR PAVEMENT SUBGRADE AND SUB-BASE

1) SUBGRADE

$Es = 10 \times CBR\ (N/mm^2)$

$V = 0.82 - 0.10 \times \log_e Es$

2) SUB-BASE

$E = 0.2H^{0.45} \times Es\ (N/mm^2)$

$V = 0.82 - 0.10 \times \log_e E$

H = thickness of sub-base in mm

PROPERTIES OF LEAN CONCRETE

Compressive strength N/mm^2	Flexural strength N/mm^2	Elastic modulus N/mm^2
6	1	27,000
12	2	35,000
18	3	42,000
24	4	48,000

POISSON'S RATION $V = 0.2$

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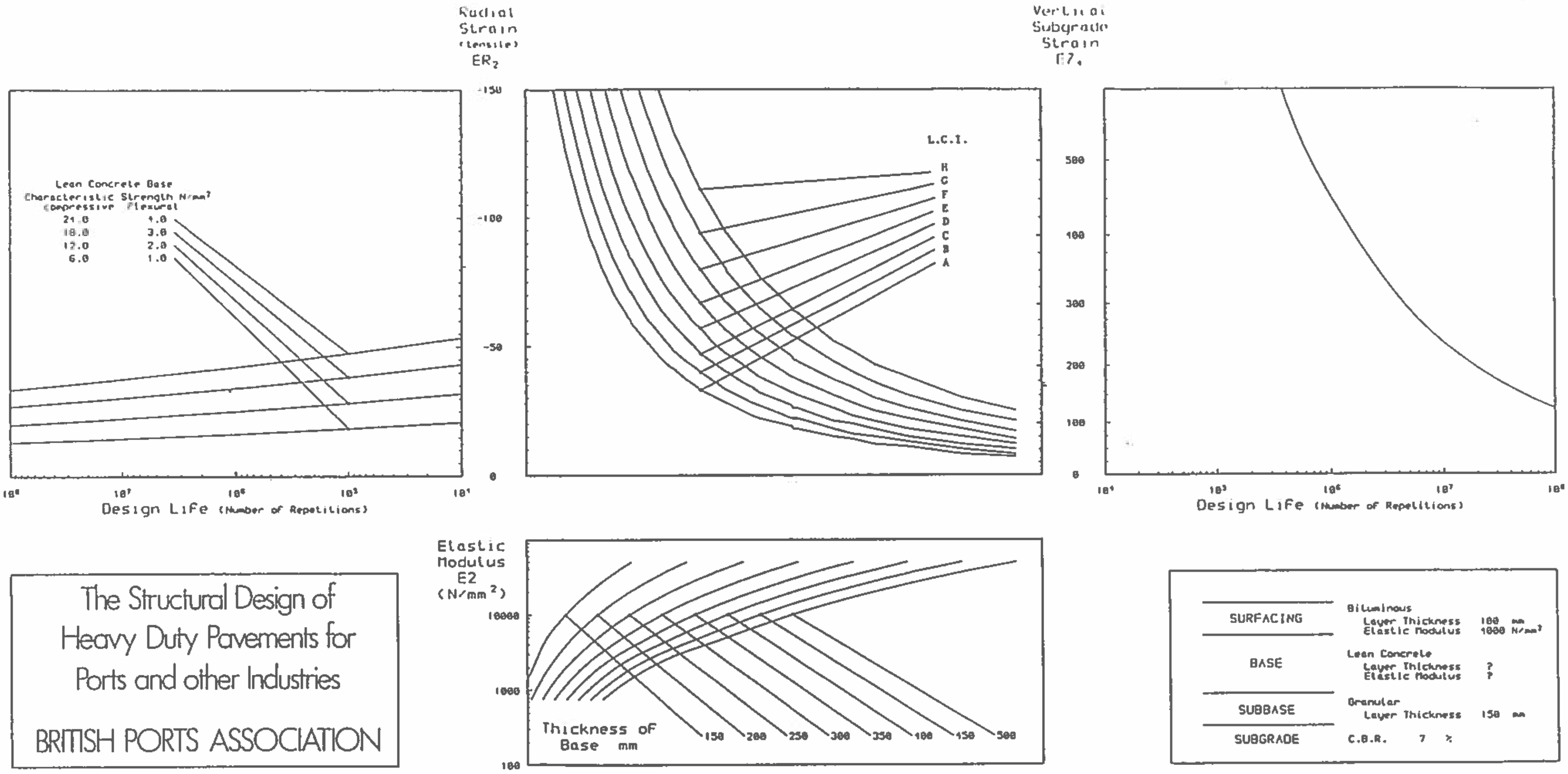
7% CBR 100mm ASPHALT 150mm SUB-BASE



SURFACING	Bituminous Layer Thickness Elastic Modulus	 100 mm 1000 N/mm²
BASE	Lean Concrete Layer Thickness Elastic Modulus	 ? ?
SUBBASE	Granular Layer Thickness	 150 mm
SUBGRADE	C.B.R.	7 %

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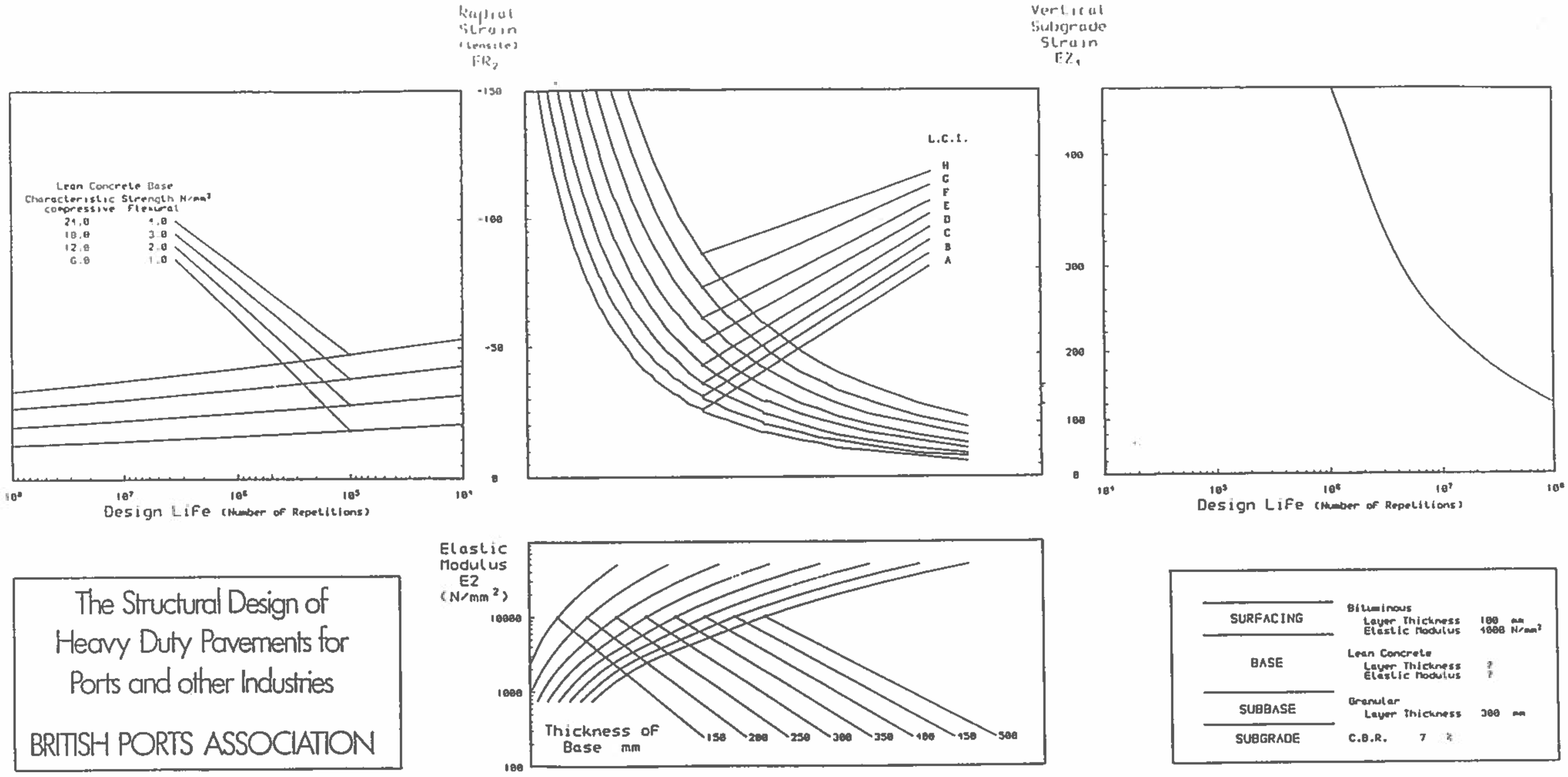
7% CBR 100mm ASPHALT 300mm SUB-BASE



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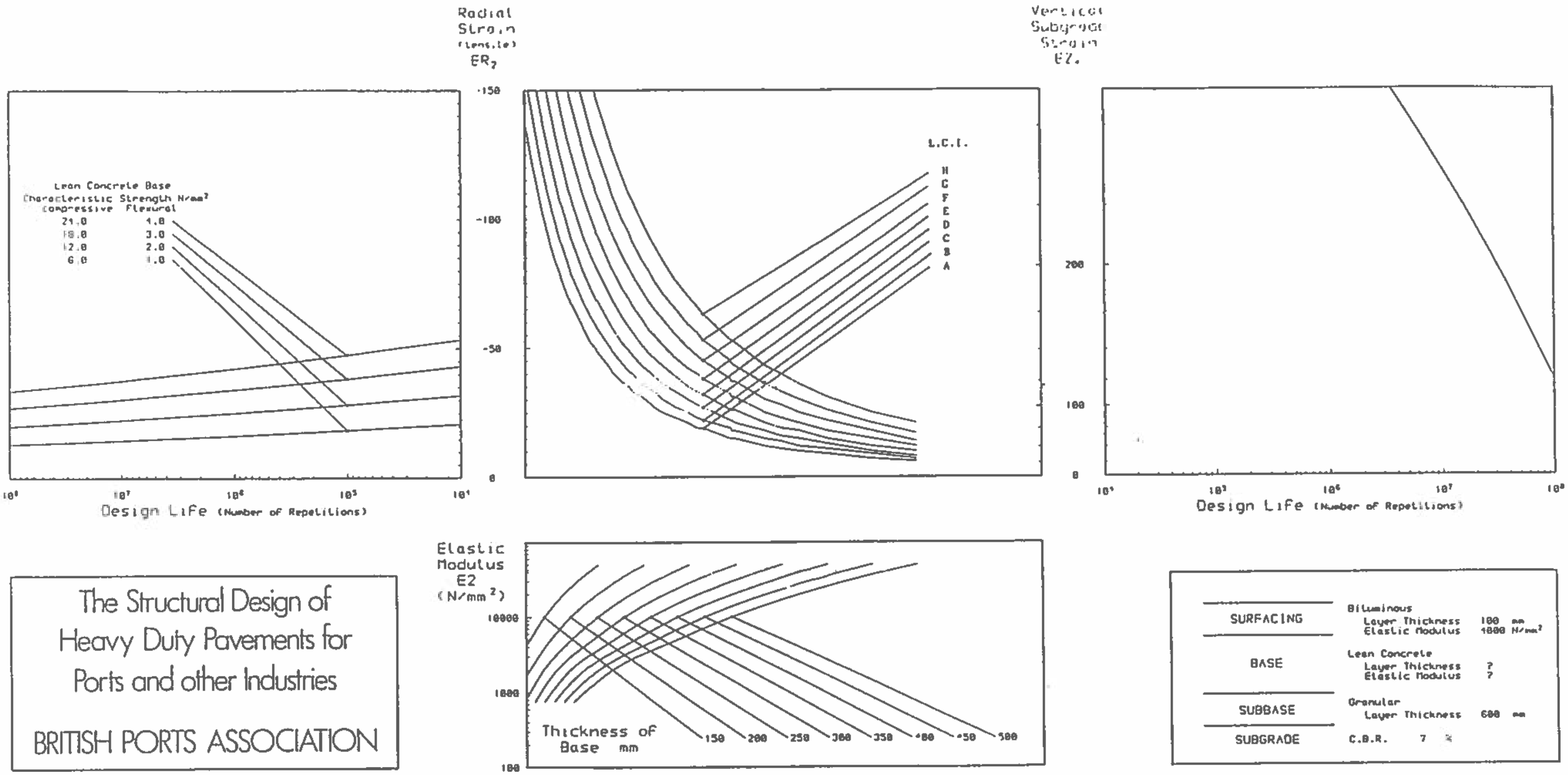
7% CBR 100mm ASPHALT 600mm SUB-BASE



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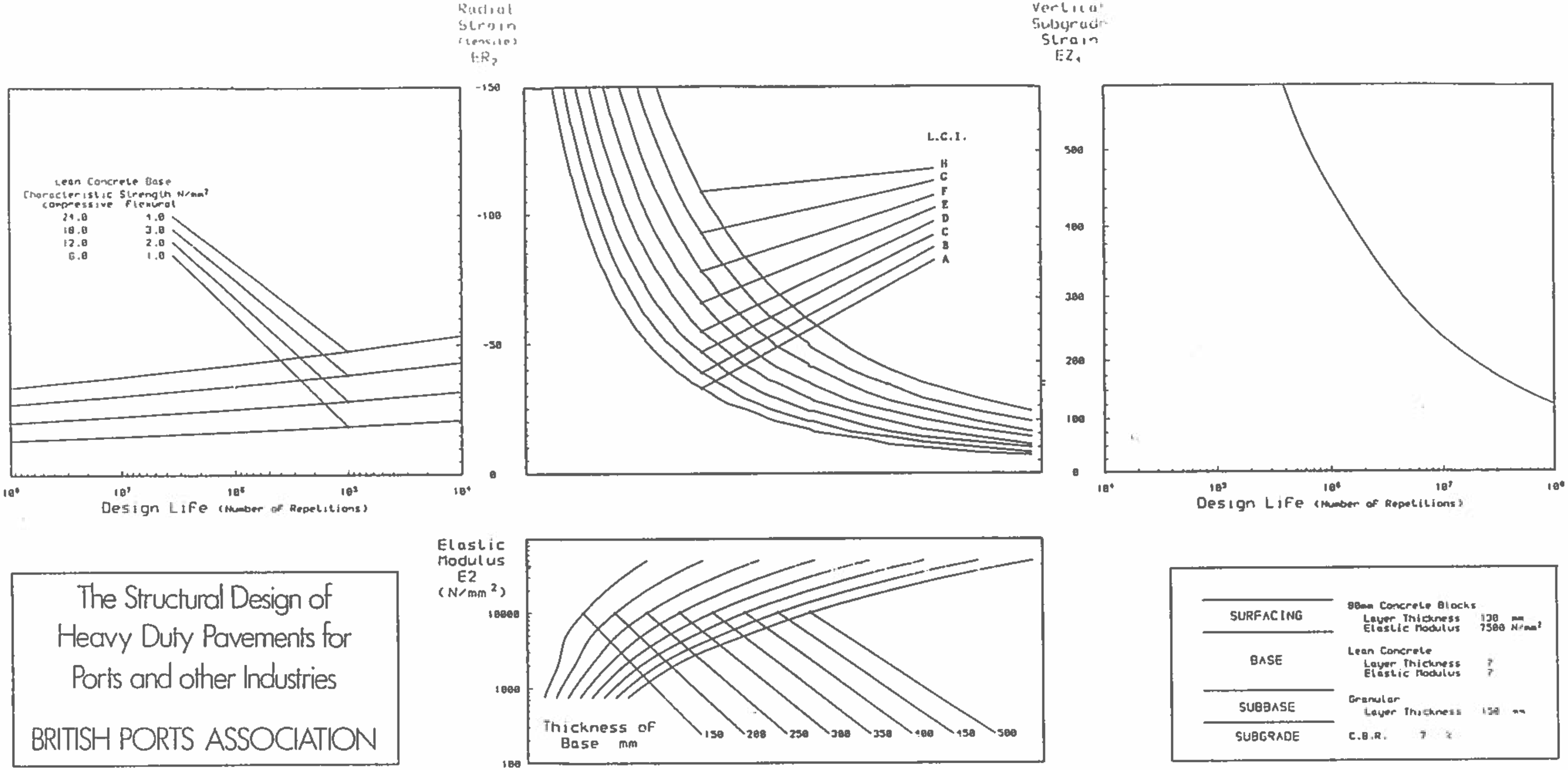
80mm BLOCKS 7% CBR 150mm SUB-BASE



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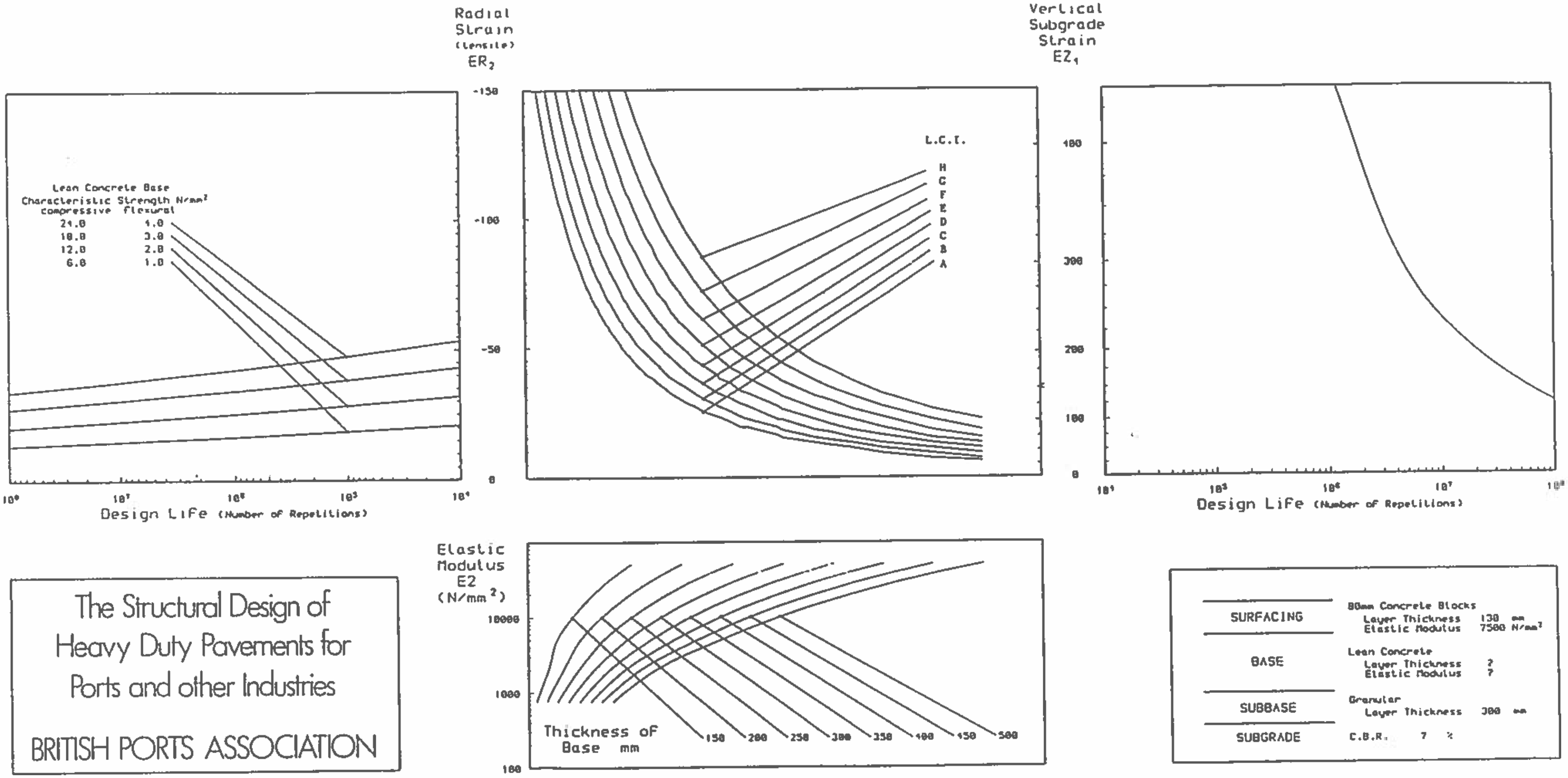
SURFACING	80mm Concrete Blocks Layer Thickness 130 mm Elastic Modulus 7500 N/mm²
BASE	Lean Concrete Layer Thickness ? Elastic Modulus ?
SUBBASE	Granular Layer Thickness 150 mm
SUBGRADE	C.B.R. 7 %

80mm BLOCKS 7% CBR 300mm SUB-BASE



The Structural Design of
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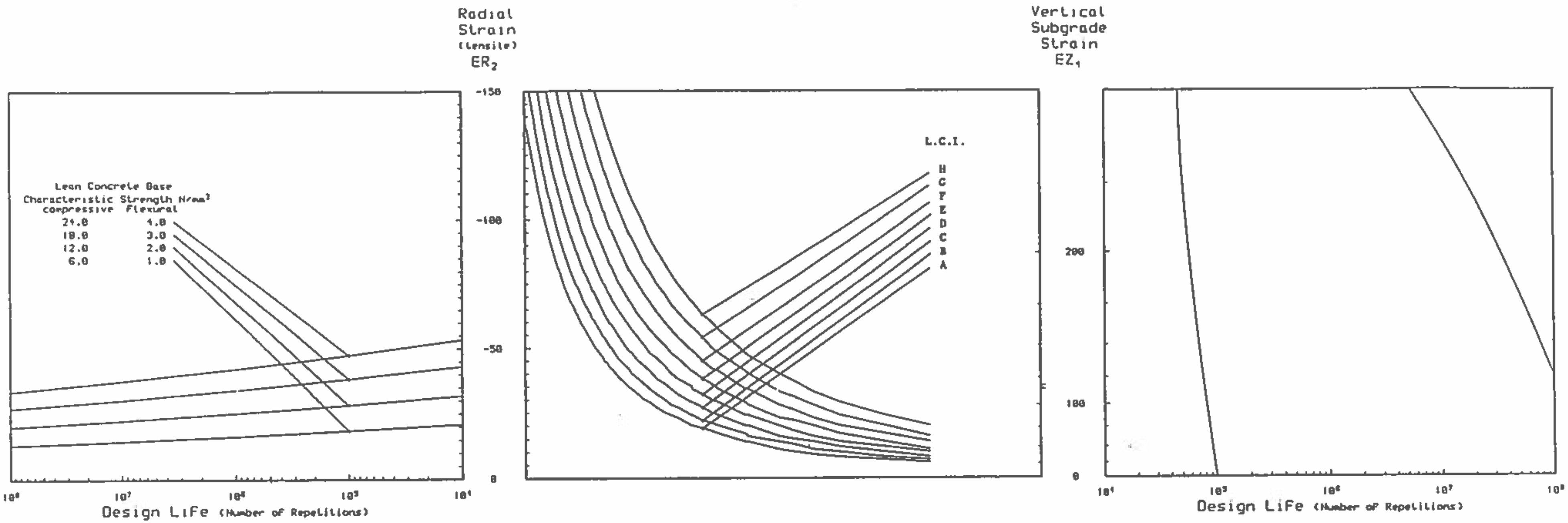
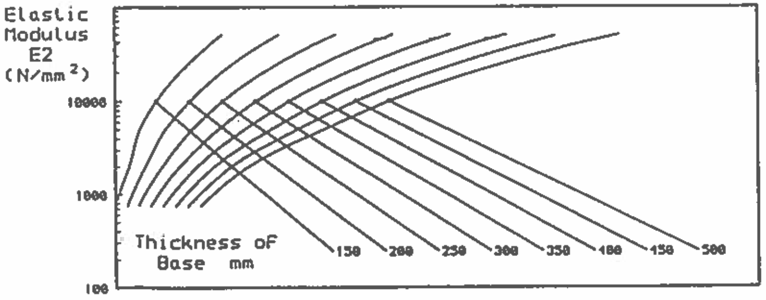
Ports and other Industries

BRITISH PORTS ASSOCIATION

SURFACING	80mm Concrete Blocks Layer Thickness 130 mm Elastic Modulus 7500 N/mm²
BASE	Lean Concrete Layer Thickness ? Elastic Modulus ?
SUBBASE	Granular Layer Thickness 300 mm
SUBGRADE	C.B.R. 7 %

80mm BLOCKS 7% CBR 600mm SUB-BASE



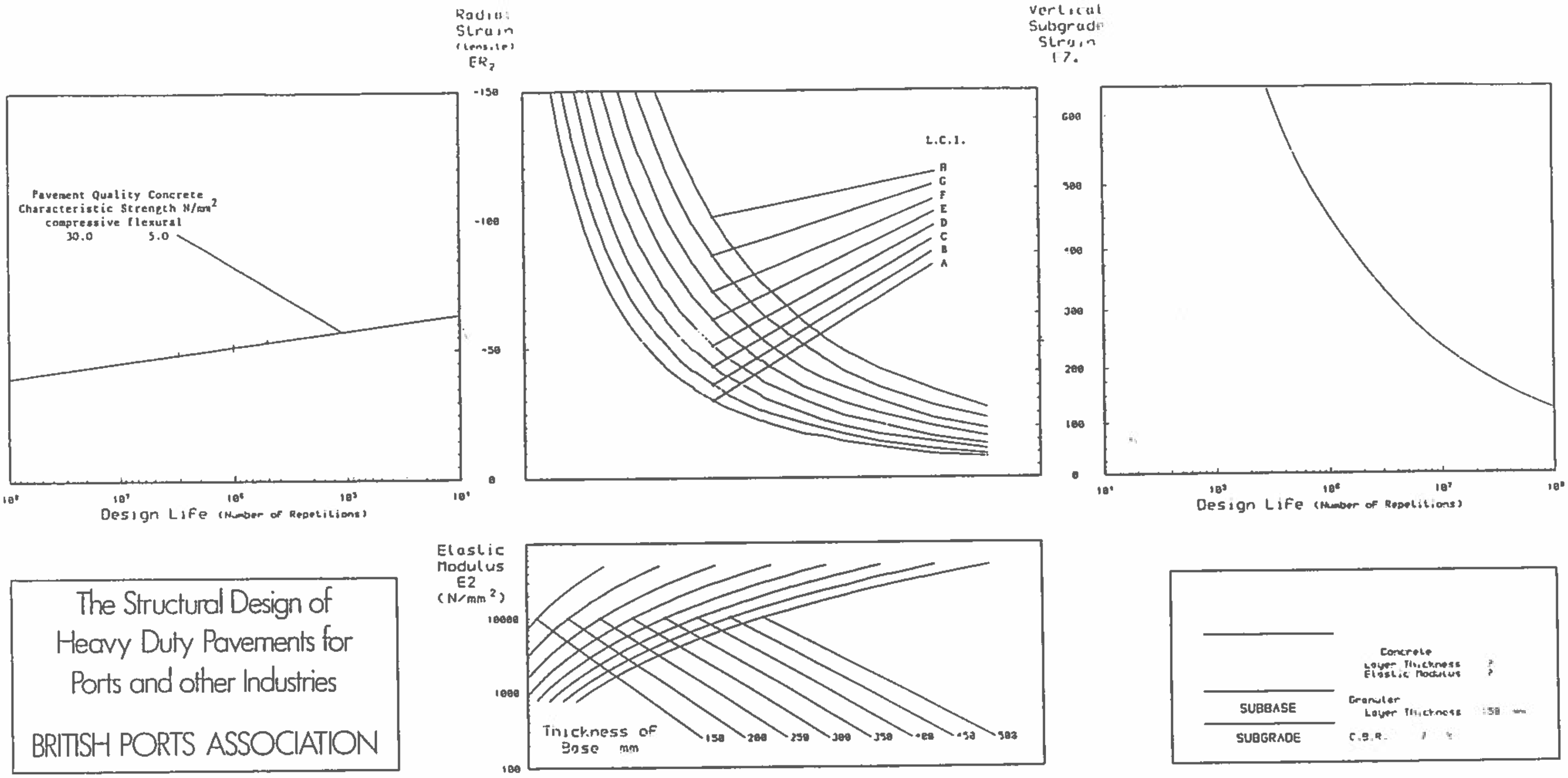


The Structural Design of
Heavy Duty Pavements for
Ports and other Industries

BRITISH PORTS ASSOCIATION

SURFACING	80mm Concrete Blocks Layer Thickness 130 mm Elastic Modulus 7500 N/mm²
BASE	Lean Concrete Layer Thickness ? Elastic Modulus ?
SUBBASE	Granular Layer Thickness 600 mm
SUBGRADE	C.B.R. 7 %

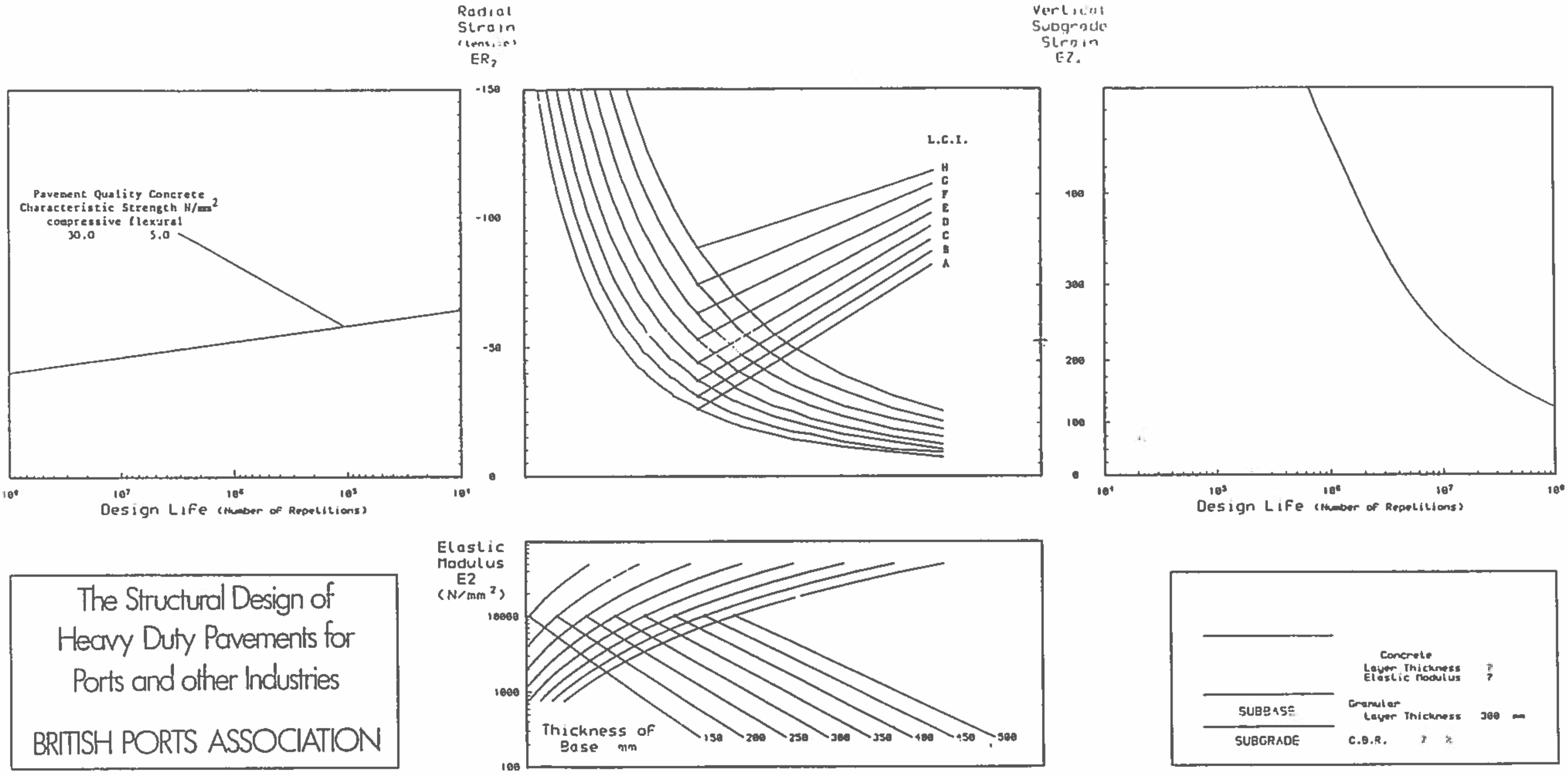
7% CBR 150mm SUB-BASE RIGID



The Structural Design of
Heavy Duty Pavements for
Ports and other Industries

BRITISH PORTS ASSOCIATION

7% CBR 300mm SUB-BASE RIGID



The Structural Design of
Heavy Duty Pavements for
Ports and other Industries

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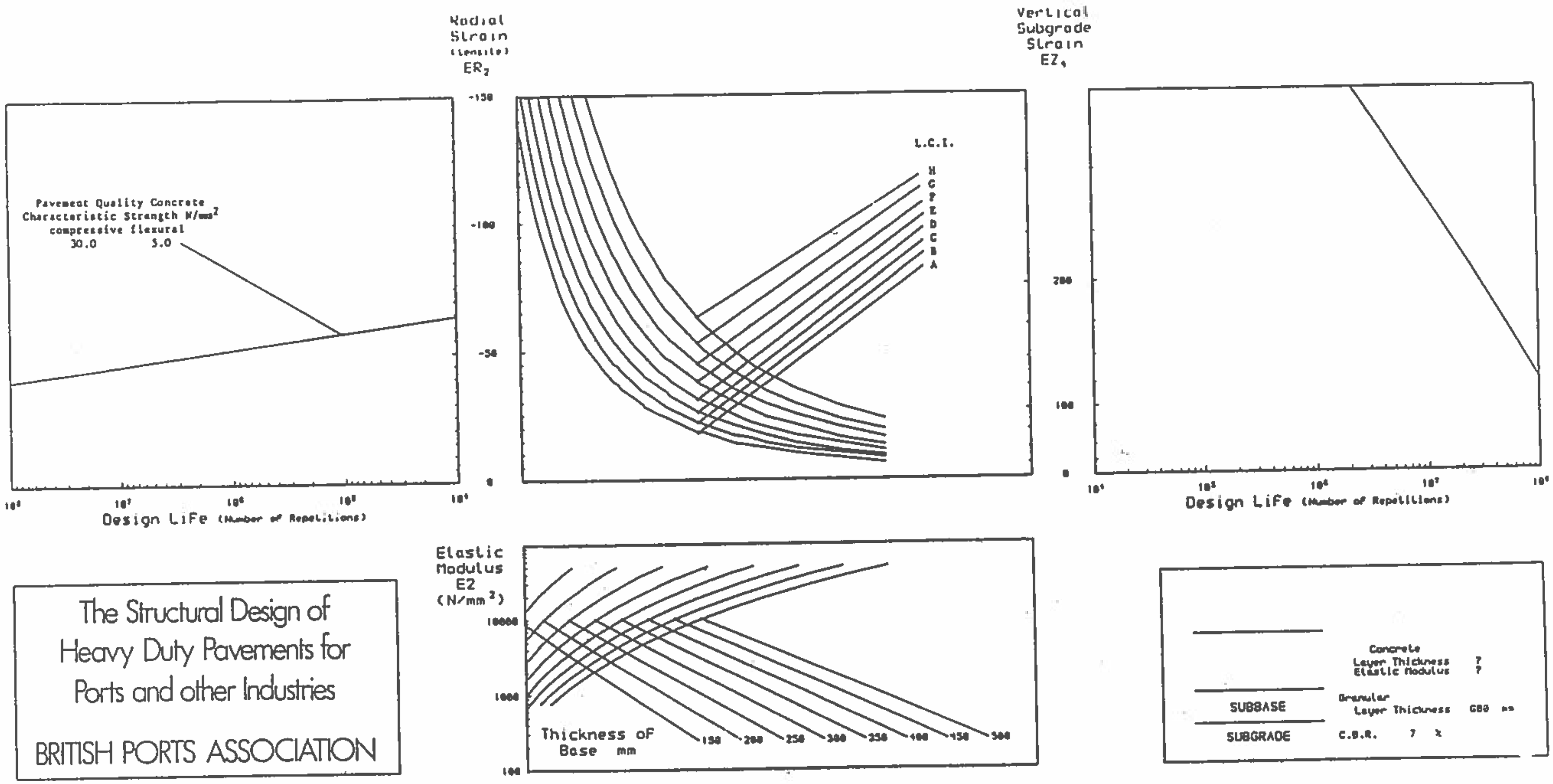
7% CBR 600mm SUB-BASE RIGID



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CHAPTER (VIII)

WORKED EXAMPLE:

UPGRADING OF AN EXISTING TERMINAL PAVEMENT USING THE OVERLAY TECHNIQUE

1. General

In many industrial situations, a particularly relevant problem is that of strengthening an existing pavement. An existing pavement may be showing signs of distress, or the operator may purchase new and more damaging plant which the existing pavement will not support. In these situations, the engineer will require a pavement design method which takes account of the residual strength of the existing pavement and which allows him to design an overlay comprising one or more courses of new material. The strengthened pavement should act as a coherent structure if full advantage of the residual strength of the existing pavement is to be gained.

The first stage in the design of an overlay is to assess the strength of the existing pavement. To do this, information should be obtained from construction records supplemented by taking cores throughout the area. The thickness and condition of each existing course is transformed into an equivalent thickness of 12 N/mm^2 lean concrete. The actual thickness of each course is multiplied by a constant taken from the table in the next page. The factors in this table are a measure of the ratio of the strength of the material concerned to the strength of lean concrete.

Account must also be taken of the less than perfect condition of each course of the existing pavement. This is accomplished by multiplying the equivalent thicknesses by two condition factors, CF1 and CF2. Factor CF1 applies an equivalent thickness reduction for cracked areas. The values of CF1 and CF2 are shown in Chapter IV page 49.

When the factors (material conversion factor for component analysis method, CF1 and CF2) have been applied to each course of the pavement, the result is a thickness of 12 N/mm lean concrete to which the existing pavement is equivalent. Secondly, the BPA design charts can be used to determine how much 12 N/mm^2 lean concrete is required for strengthened pavement. The difference between that required and that currently existing is the amount to be provided. This does not constrain the designer to use 12 N/mm^2 lean concrete as the strengthening material, since when he has evaluated the thickness of 12 N/mm^2 lean concrete required, he can return to the table which gives the material conversion factors and determine the thickness of any of the other bound materials which he may prefer, to use.

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Material conversion factors for component analysis method

Type of material	Material conversion factor
12 N/mm^2 lean concrete	1·0
18 N/mm^2 lean concrete	1·3
30 N/mm^2 pavement quality concrete	1·7
Cement-bound granular material	0·7
Soil cement	0·5
130 mm concrete block paving including 50 mm sand	1·1
Concrete raft units (2 m × 2 m)	1·5
Open textured bituminous material stiffened with latex slurry	1·5
Dense bituminous macadam	1·0
Rolled asphalt	0·8
Wet-mix macadam	0·4
Dry-bound macadam	0·4
Type 1 sub-base material over subgrades with CBR > 5%	0·3
Type 1 sub-base material over subgrades with CBR $\leqslant$ 5%	0·2
Type 2 sub-base material over subgrades with CBR > 5%	0·2
Type 2 sub-base material over subgrades with CBR $\leqslant$ 5%	0·1
Subgrade	0·0

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2. Example

An existing pavement comprises the materials shown in Fig. 1(a). It was originally designed to withstand straddle carriers of LCI value B (see chapter III, page 38 table VI). The pavement is in good condition except for 15 mm deep ruts, which occur only in the asphalt surface course. It is proposed to replace the straddle carrier with a front lift truck (FLT) of LCI value G (see Chapter III, page 38, Table VI). The most severely trafficked part of the pavement will carry 200 passes per day of the laden FLT and the strengthened pavement is required to last a further 12 years, each with 300 working days.

Number of FLT repetitions = 200 X 300 X 12 = 720000 cumulative passes

Using the relevant BPA chart for 5% CBR subgrade with a 300 mm thick sub-base and asphalt surface, (see next page), the pavement shown in Fig. 1(b) is shown to be required i.e. if a new pavement were being designed for the FLT, it would be as shown in Fig. 1(b).

The residual effective thickness of the existing rutted pavement is 397 mm of 12 N/mm^2 lean concrete and the table below shows how the above mentioned three factors are used to determine this thickness.

Effective thickness of existing pavement in overlay design example

Course	Actual thickness(mm)	Material conversion factor	Condition Factor		Equivalent thickness of 12 N/mm^2 lean concrete (mm)
			CF1	CF2	
Asphalt	100	0.8	1.0	0.9	72
18 N/mm^2 lean concrete	250	1.3	1.0	1.0	325
					397

Therefore, the thickness of 12 N/mm^2 lean concrete required in the overlay is 500 mm - 397 mm = 103 mm, say 100 mm.

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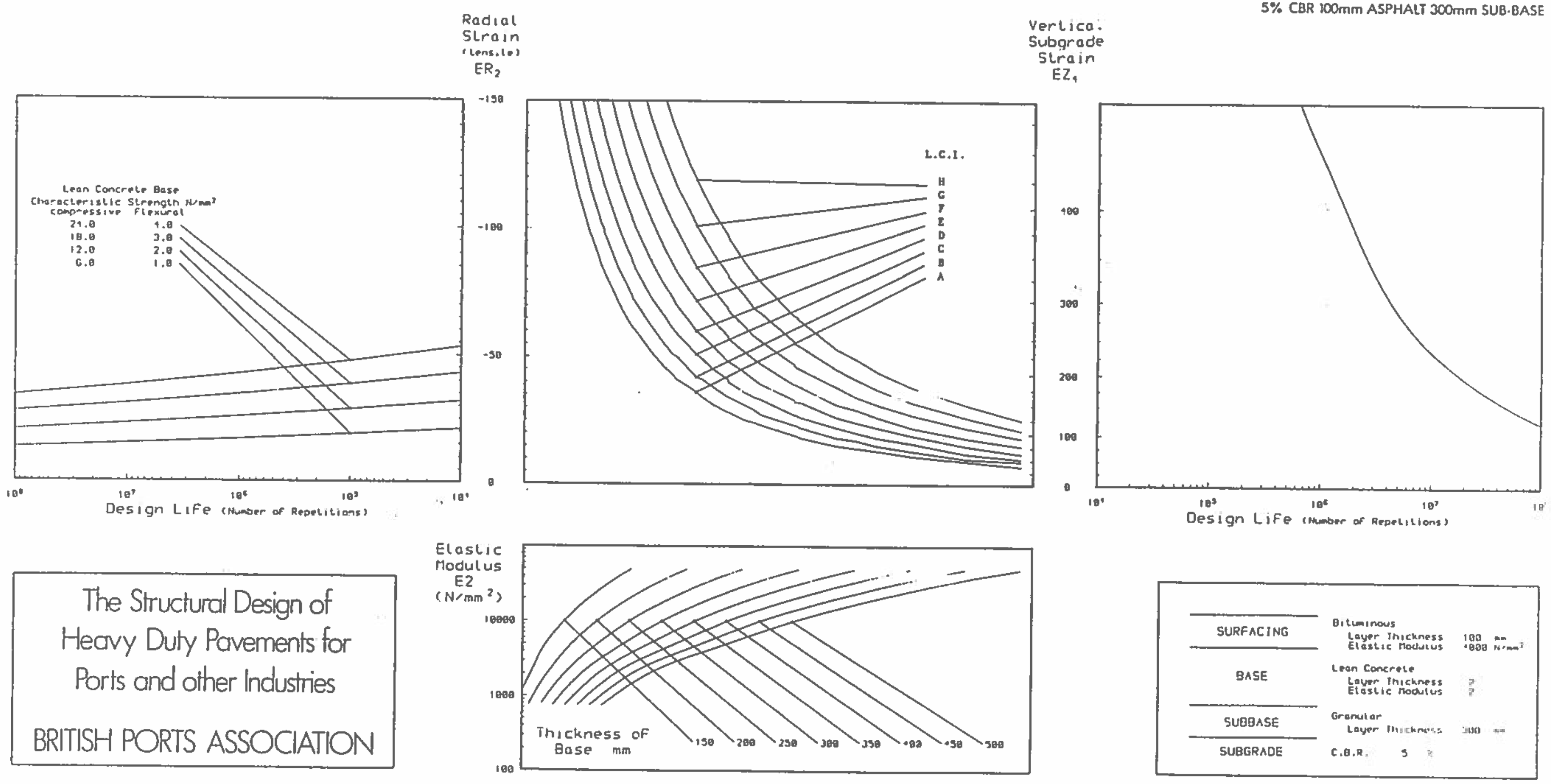
5% CBR 100mm ASPHALT 300mm SUB-BASE



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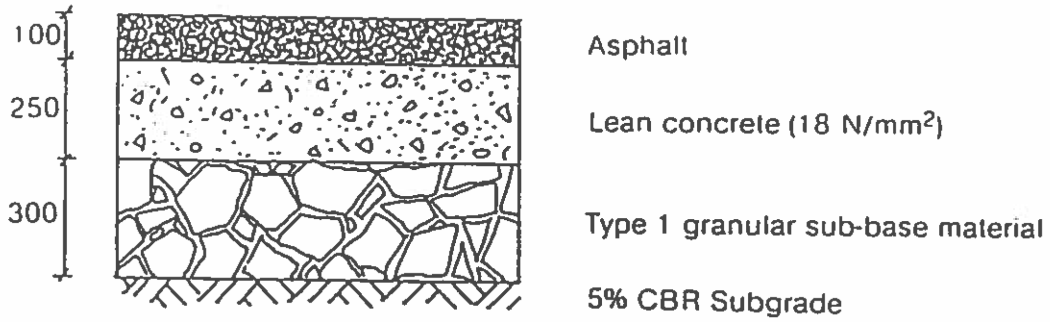
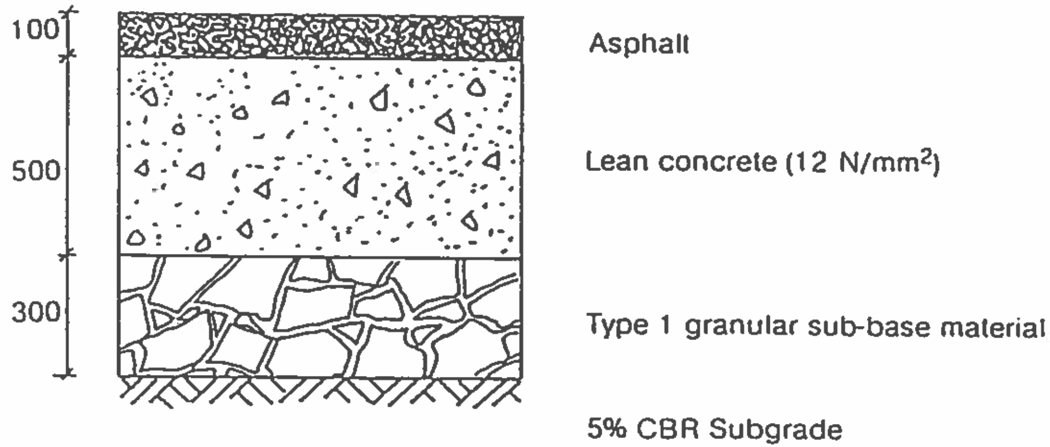
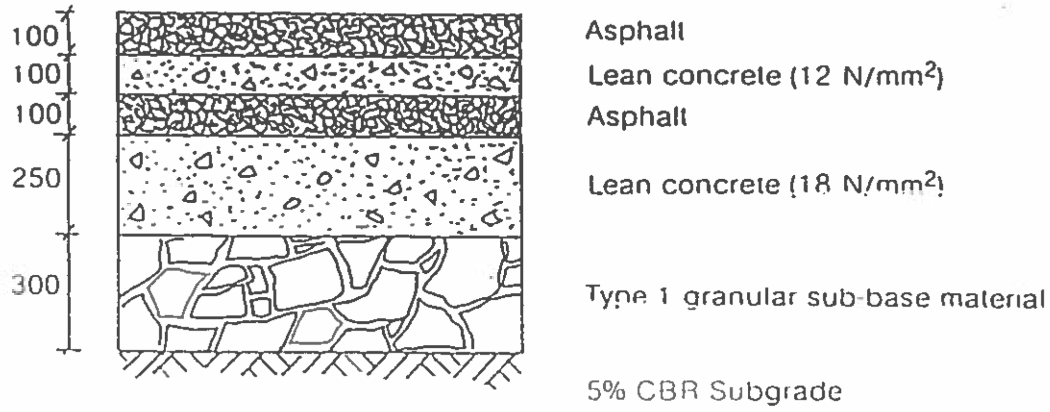
The strengthened pavement is shown in Fig. 1(c), in which 12 N/mm^2 is actually used as the overlay structural material. If required, an alternative material could be used in which the material conversion factors shown on page 74 are used to determine the thickness of the alternative material required. For example, if wet-mix macadam were used as the strengthening material, the thickness required would be 103/0.4, i.e. 257 mm (0.4 is the material conversion factor for wet-mix macadam).



(a) EXISTING PAVEMENT



(b) REQUIRED PAVEMENT



(c) STRENGTHENED PAVEMENT

Fig. 1 Pavement section for overlay design example