

# UNCTAD MONOGRAPHS ON PORT MANAGEMENT

**5**

**Container Terminal Pavement Management**



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UNCTAD Monographs on Port Management

A series of monographs prepared for UNCTAD in collaboration with  
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Monograph No.5

CONTAINER TERMINAL PAVEMENT MANAGEMENT

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The views expressed in this monograph are those of the authors and not necessarily those of the UNCTAD secretariat.

INTRODUCTION TO THE SERIES

In the ports of industrialized countries, operating systems and personnel development are based on skills acquired through experience, on emulation of other industries and on the innovation which is easily undertaken in advanced industrial environments. These means are generally lacking in developing countries and port improvements occur only after much deliberation and often through a process of trial and error. Some means is required by which ports in developing countries can acquire skills that are taken for granted in countries with a long industrial history, or can learn from the experience of others of new developments and how to meet them.

Formal training is one aspect of this, and UNCTAD has devoted considerable effort to developing and conducting port training courses and seminars for senior management and to preparing training materials to enable middle-management courses to be conducted by local instructors. It was felt that an additional contribution would be the availability of clearly written technical papers devoted to common problems in the management and operation of ports. The sort of text that will capture an audience in the ports of developing countries has to be directed at that very audience, and very few such texts exist today.

Following the endorsement of this proposal by the UNCTAD Committee on Shipping in its resolution 35 (IX), the UNCTAD secretariat decided to seek the collaboration of the International Association of Ports and Harbours, a non-governmental organization having consultative status with UNCTAD, with a view to producing such technical papers. This series of UNCTAD Monographs on Port Management represents the results of this collaboration. It is hoped that the dissemination of the materials contained in these monographs will contribute to the development of the management skills on which the efficiency of ports in developing countries largely depends.

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FOREWORD

When UNCTAD first decided to seek the co-operation of the International Association of Ports and Harbours in producing monographs on port management, the idea was enthusiastically welcomed as a further step forward in the provision of information to managements of ports in developing countries. The preparation of monographs through the IAPH Committee on International Port Development has drawn on the resources of IAPH member ports of industrialized countries and on the willingness of ports in developed countries to record for the benefit of others the experience and lessons learnt in reaching current levels of port technology and management. In addition, valuable assistance has been given by senior management in ports of developing countries in assessing the value of the monographs at the drafting stage.

I am confident that the UNCTAD monograph series will be of value to managements of ports in developing countries in providing indicators towards decision-making for improvements, technological advance and optimum use of existing resources.

The International Association of Ports and Harbours looks forward to continued co-operation with UNCTAD in the preparation of many more papers in the monograph series and expresses the hope that the series will fill a gap in the information currently available to port managements.

C. Bert Kruk  
Chairman  
Committee on International  
Port Development  
IAPH

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OVERVIEW

(i) This monograph has been written with the aim of introducing those responsible for pavements in ports to the concept of pavement management. Management involves many interrelated functions, from conceptual design to rehabilitation or demolition. Essentially, it is important that the manager understands the relationship between all of the factors which impinge upon the pavement system so that he can achieve a globally optimized solution. Only that way will he, in turn, ensure that port facility overheads are kept as low as possible. The pavement has a major influence on port infrastructure-generated overheads. Accordingly pavement cost optimization is now of paramount importance.

(ii) 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.

(iii) The authors, Marios Meletiou, a port engineer, and Dr. John Knapton, a consulting engineer, have experience of port pavements throughout the world.



Chapter I

INTRODUCTION

1. General

1. 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.
2. 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 1970s 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 severe 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, problems do still persist today in many ports - in the developing and developed world.
3. 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 dependent 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".
4. The objective of this monograph 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.
5. 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 cannot take place on natural soil. In particular, if natural soils are used by heavy handling equipment, they deform so that rutting and pot-holes occur.
6. 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.
7. 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

8. 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 per cent 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,



Failure of bituminous pavement in narrow aisles between container stacks resulting from channelized straddle carrier movements. The pavement was designed for the less onerous loading associated with general cargo handling.



It is not uncommon for purposely designed container handling pavements to fail. This unreinforced concrete pavement is four years old.

the provision of unsuitable pavements will, sooner or later, have a negative impact on terminal operations. Accordingly, the surface of a container terminal should be equally good and reliable as the quay, cranes, electric power, etc.

9. 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.

10. In developing countries where projects are usually carried out with the assistance of outside loans, any possible savings in construction costs, without affecting the integrity of the design build approach, is of prime importance as this will assist in achieving a more productive allocation of limited resources.

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

- (a) Areas have become larger owing to the growth of containerization,
- (b) Loads are heavier and there is a wider range of handling systems available which have different damaging effects on pavements,
- (c) Cost consciousness has increased (due to the need for stronger and hence more expensive pavements);
- (d) Several major pavement failures in recent years, leading to serious container handling problems, have created awareness of pavements;
- (e) There is greater freedom of material choice; this is due to recent developments in pavement construction methods and materials.

12. Thus, the growth in importance of container terminal pavements establishes the necessity for the 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.

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

## Chapter II

### SELECTION OF A SUITABLE PAVEMENT TYPE

#### 1. General

14. The main thrust of this chapter is to emphasize that the selection of container handling equipment and pavement construction materials should be undertaken conjunctively, i.e. it is essential to select a complete container handling system, and not each individual item of the system separately.

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

- (a) Equipment;
- (b) Layout;
- (c) Infrastructure (pavements);
- (d) Services.

16. (a) and (b) above, which are interrelated, 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.

17. "Selection" basically means choosing 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 systems, exactly what are the alternatives?

#### 2. The pavement selection approach

##### 2.1 Introduction

18. 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.

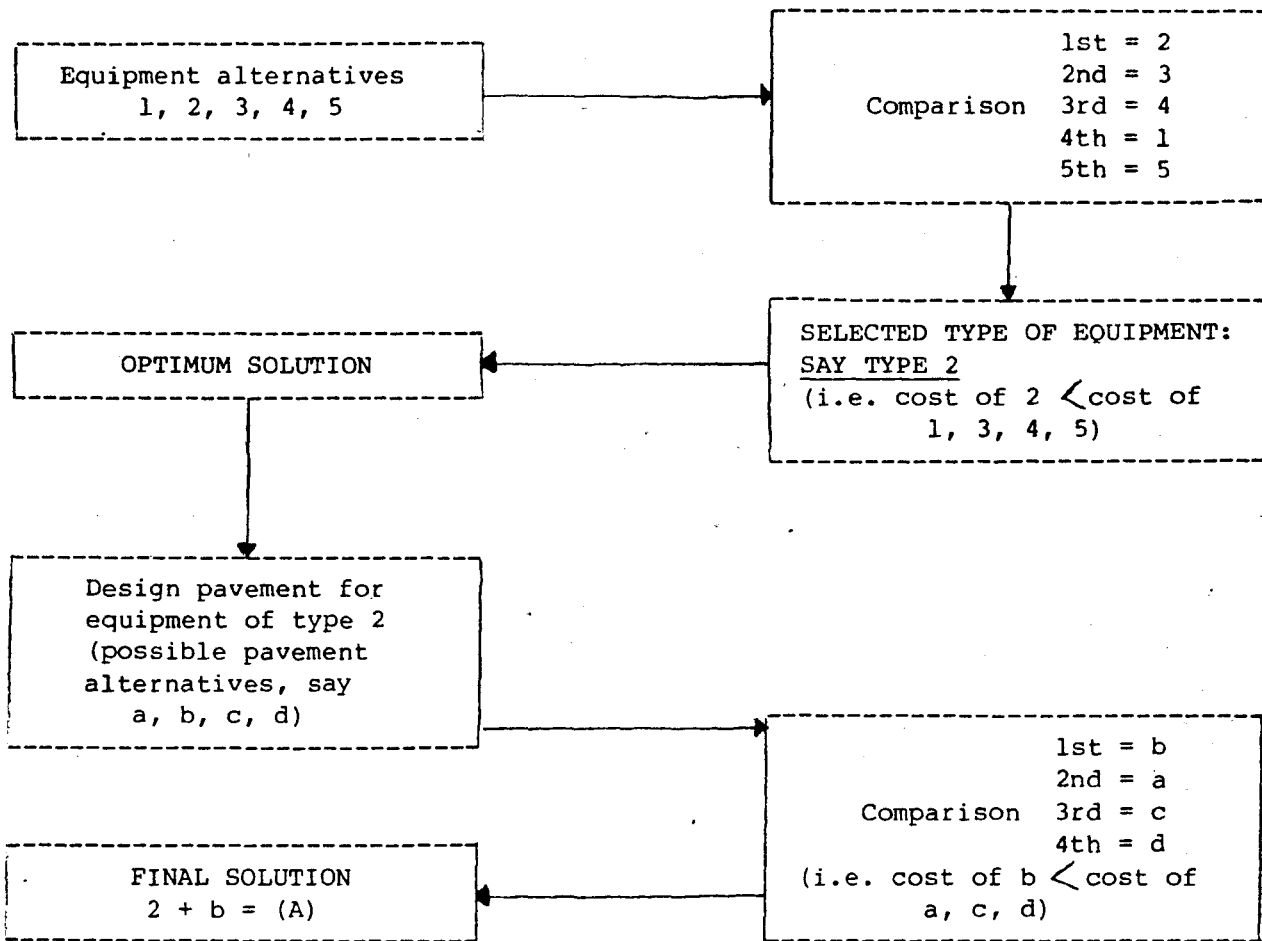
19. The new approach, which is now recommended, is to consider the selection of container handling equipment and the pavement system in parallel.

20. Thus, 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. However, 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

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

Traditional approach



Solution (A) may or may not be the global optimum solution.

22. 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.

23. Accordingly, 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.

24. Table 1 is of a general character without respect to typical local conditions.

Table 1

Cost comparison table for the most common types of pavements

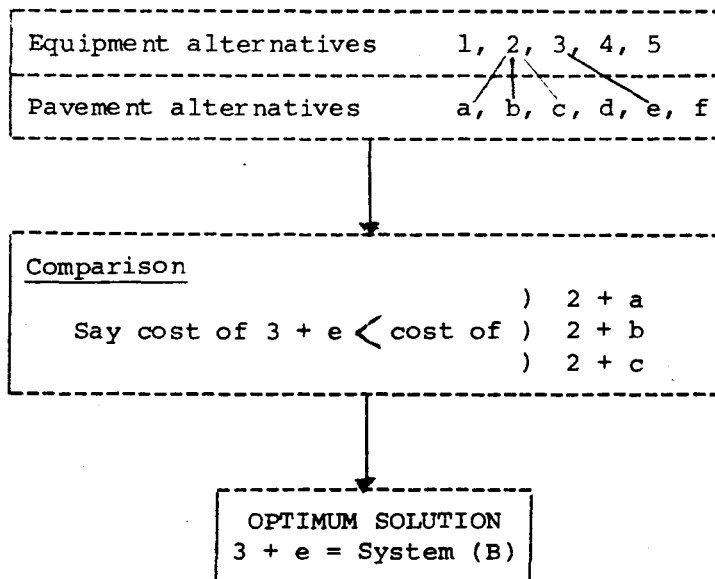
Construction cost	Maintenance cost		High
	Low	Intermediate	
Low	Gravel beds		
Intermediate	Pre-cast concrete blocks	Asphalt	
High	<u>In situ</u> concrete slabs Conjunctive systems	Pre-cast concrete rafts Conjunctive systems	

2.3 The recommended approach

25. 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.

26. Accordingly, 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 operational and engineering aspects.

Recommended approach



27. The parameters to be considered not only increase in number but become more complicated. For this reason, taking into account the relationship between container handling equipment and pavements, the cost of each pavement type (construction and maintenance cost) and the experience gained from the performance of numerous cases world wide, table 2 has been prepared as an initial guide to the container terminal designer. In this way the designer does not have to consider all combinations of pavements and equipment but can work out only those two or perhaps three that look more promising.



Recommended solution for trailer parking areas

Table 2

Suitability of pavements for different operations, taking into account cost effectiveness and performance

(KEY: 1 = Avoid if possible

10 = Recommended solution)

5 = Reasonable 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	--

28. An important issue which has been taken into consideration in preparing table 2 is the impact that 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.

29. 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. Accordingly, operational interruptions due to maintenance works can be minimized through the process of pavement selection.



30. There are some types of pavement which, no matter how much they are over-designed, require major maintenance at some stage (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).

31. Taking into consideration the prevailing views of many container terminal operators, the position adopted in table 2 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.

32. It is notable, however, that in some cases, due to specific circumstances, the above position may not hold. One example is where 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 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.

33. In this respect, it is worth emphasizing that the container terminal designer must not take the marks given to each pavement type in table 2 literally but should just regard them as an initial starting point. These marks are sensitive to prevailing local conditions, which must always be given the appropriate importance. Accordingly, one may expect that pavement systems, with only one or two points difference from their marking according to table 2 may change their relative position in the comparison list due to prevailing extraordinary local conditions.

34. As underlined above, the preparation of the general criteria in table 2 has been based among other things on the relationship 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

35. The main reason for the poor performance of many container terminal pavements is that they 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 it operates. 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.

36. 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.

### 3.2 Recent developments in container handling equipment

37. 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 this new generation 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

38. 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.

39. Table 3 shows pavement loads from container stacking which must be considered when designing a container stacking bay.

Table 3

Pavement loads from container stacking

Stacking	Reduction in gross weight (per cent)	Contact stress (N/mm <sup>2</sup> )	Load on pavement (kg) for each stacking arrangement		
			Singly	Rows	Blocks
1	0	2.59	7 620	15 240	30 480
2	10	4.67	13 720	27 430	54 860
3	20	6.23	18 290	36 580	73 150
4	30	7.27	21 340	42 670	85 340
5	40	7.78	22 860	45 720	91 440

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

41. 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:

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

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

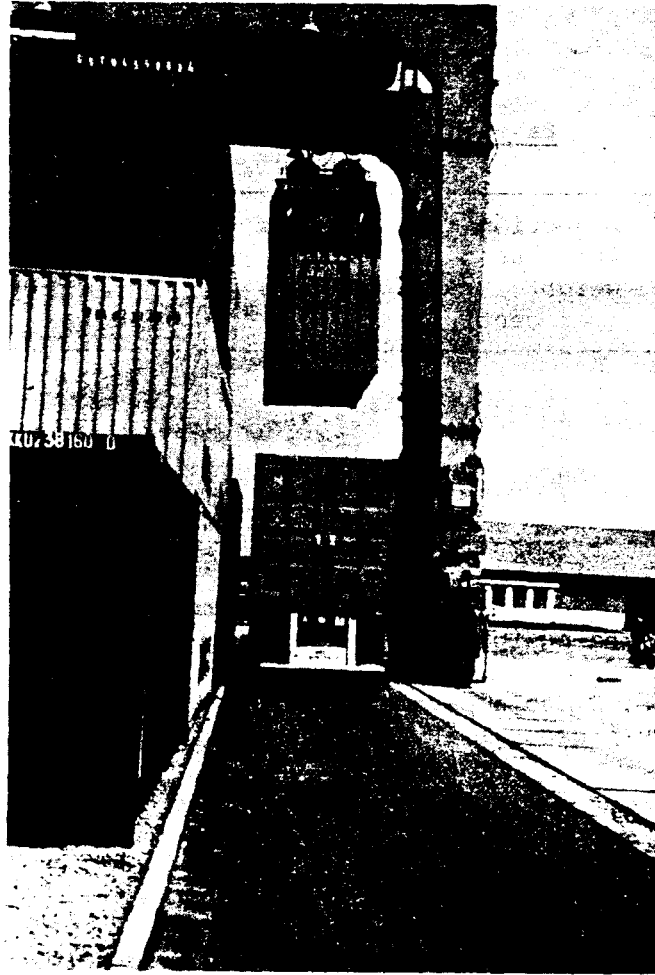
43. However, unlike the design of highway pavements, in port areas you cannot make the assumption that heavier wheel loads will necessarily require overall stronger and hence more expensive paved areas. This is because the operational characteristics of each type of equipment play a governing role in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

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

45. 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 receive or deliver a



The three types of pavement required in a rubber-tyred stacking gantry crane operation. Note, in particular, the use of a low-cost gravel bed in the areas where containers are stacked. Typically, 62 per cent of the area of the facility may comprise gravel beds.



A straddle carrier operation requires that the whole pavement be designed to withstand wheel loads of up to 12.5t, which may be increased by as much as 60 per cent by dynamic effects.

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.

46. 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.

47. 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.

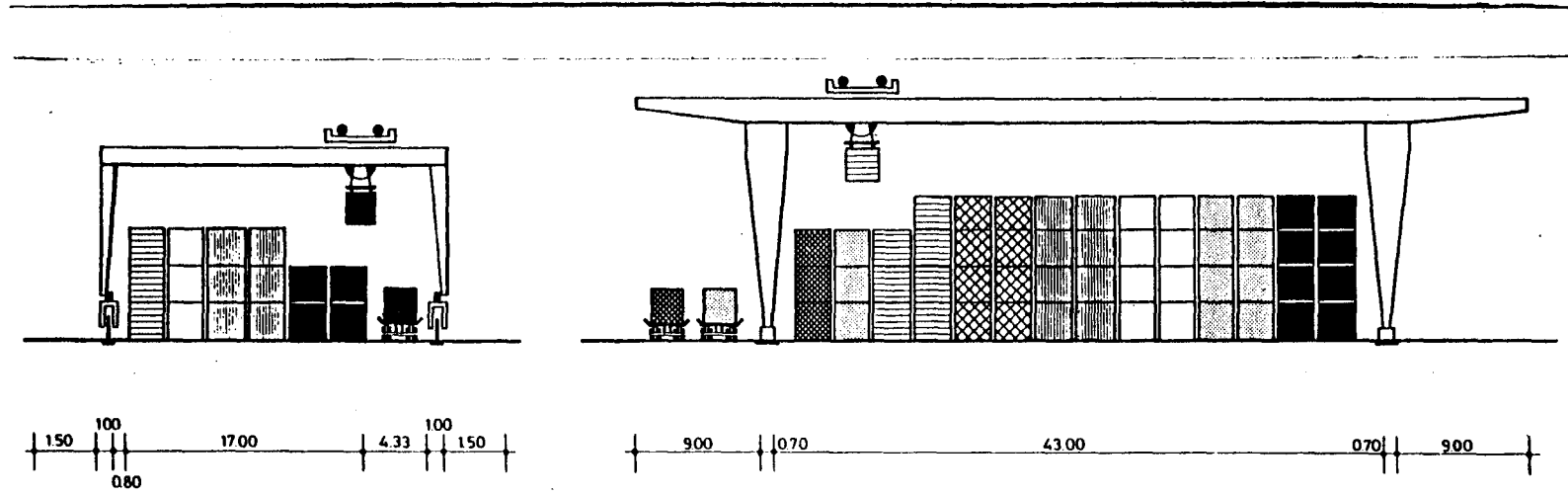
48. Considering typical container yard layouts whereby rail or rubber mounted yard cranes are used (see figure 1), then it can easily be calculated that the area to be designed to carry the high wheel loads covers only approximately 2.2 per cent or 7.4 per cent respectively of the whole container yard area. Sixty-nine or 62 per cent 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 per cent or 30.6 per cent of the container yard has to be designed to carry the relatively low wheel loads of trailers and tug masters.

49. 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.

50. 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 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.

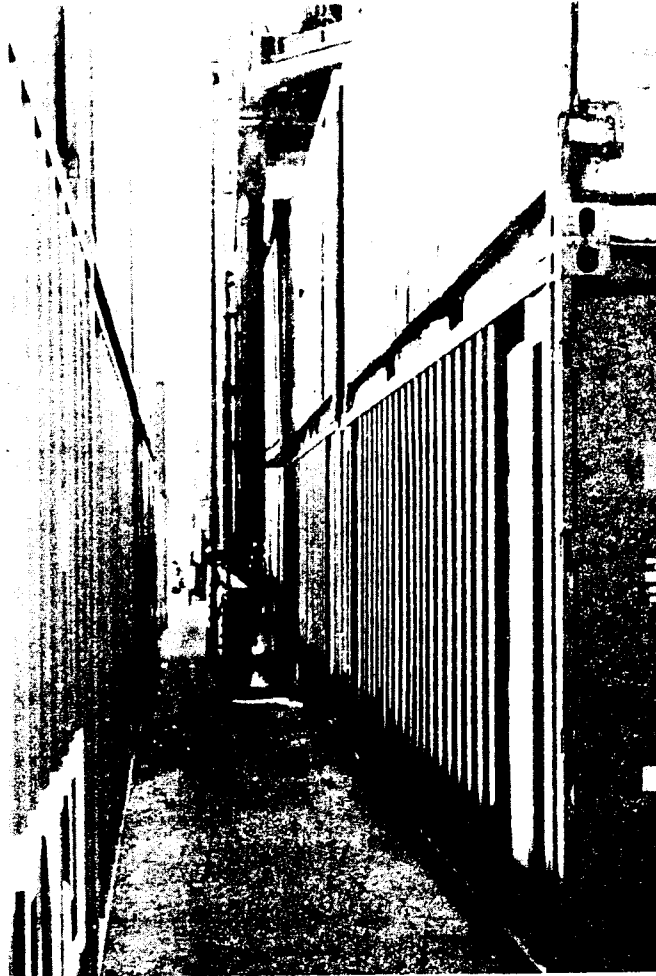
Figure 1

Typical configurations of rubber tyred and rail mounted gantry cranes



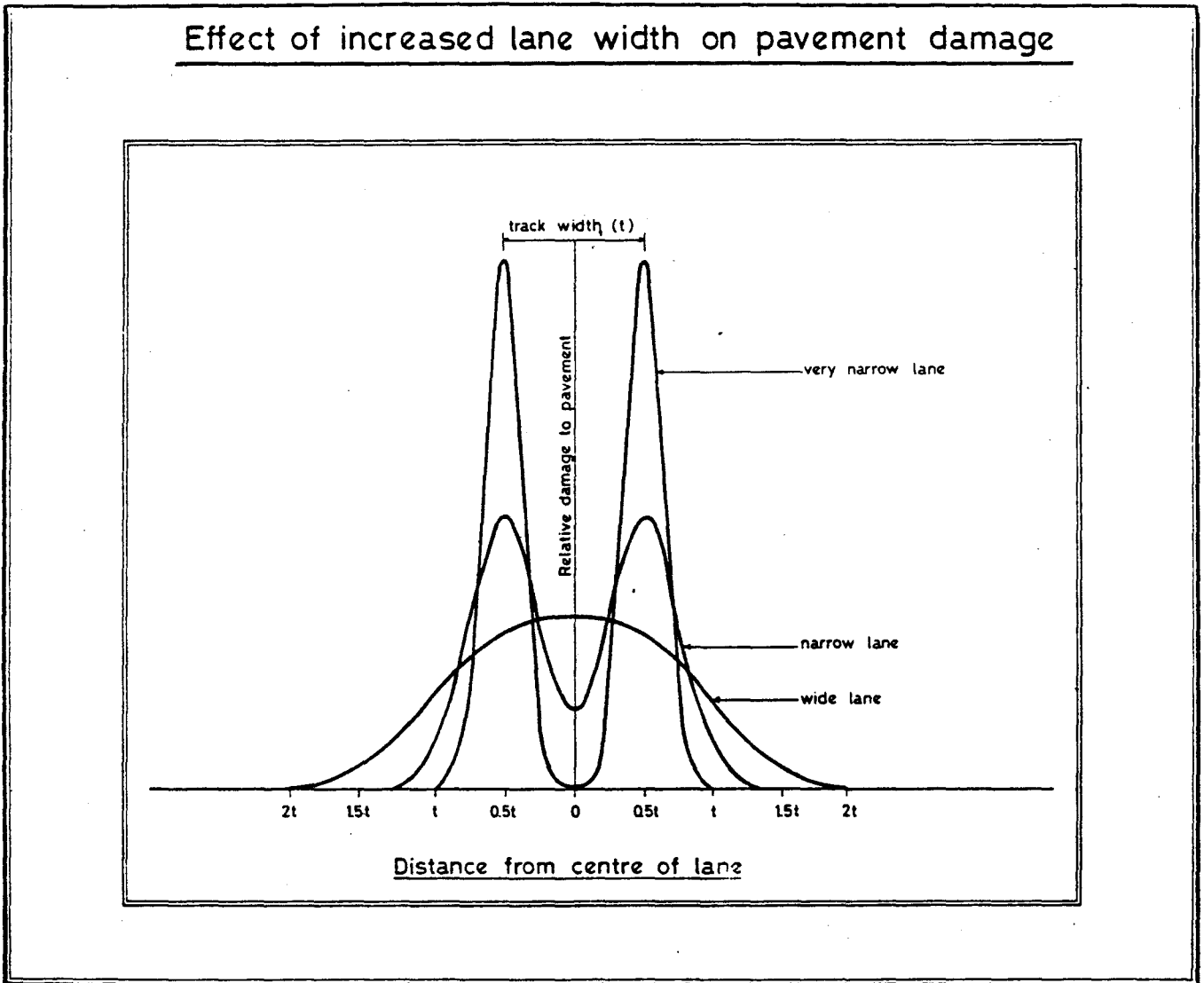
A. Rubber tyred yard crane.

B. Rail mounted yard crane.



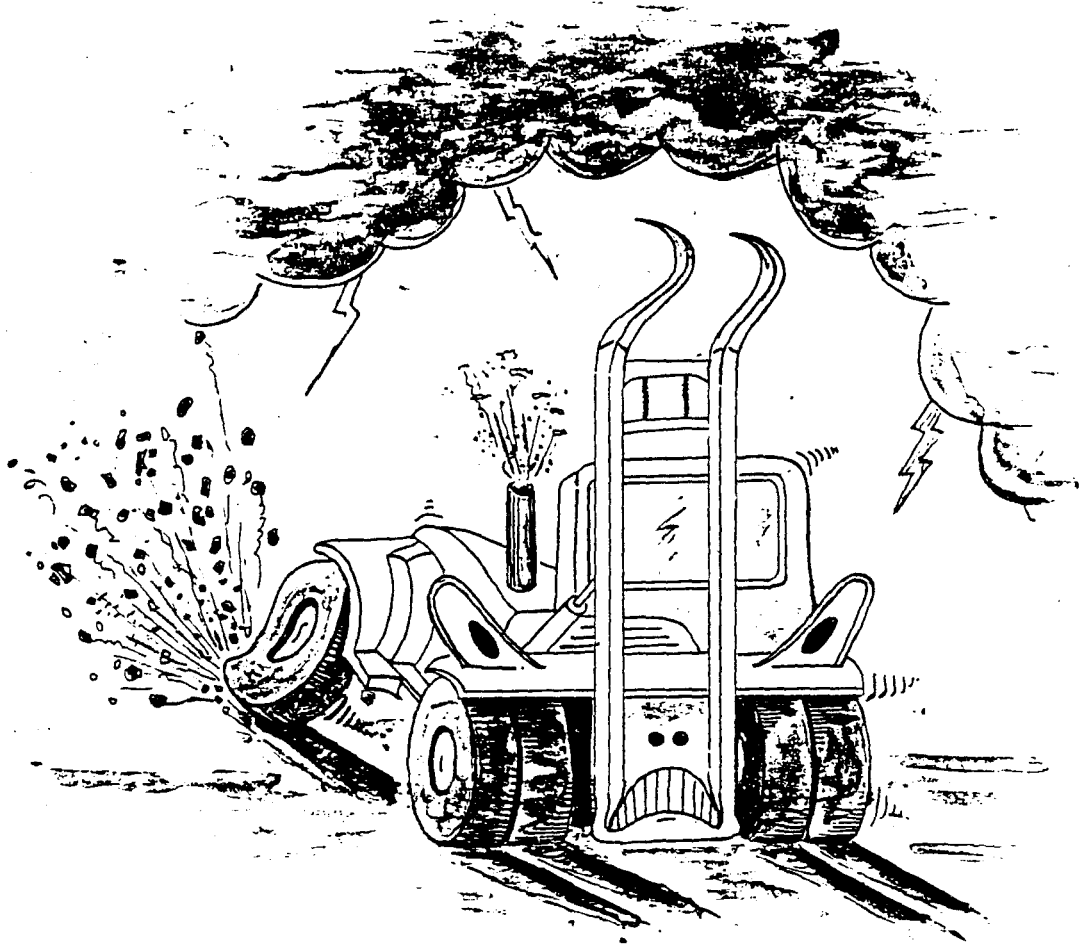
Typically, the narrow aisles between containers are 1,500mm wide, which results in severe channelization of straddle carrier wheel loads. Rut depth of over 100mm is common, and this may lead to premature pavement deterioration and operational difficulties.

Figure 2



When equipment operates in narrow lanes, the damage inflicted on the pavement increases. When straddle carriers operate within container stacking areas, the track width and the lane width are effectively equal.





Front lift trucks may have front axle loads of up to 100 tons and in consequence are particularly damaging to pavements.

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

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

53. Compared with all other container handling equipment, fork lifts have the highest load classification indices for normal running, braking, cornering, acceleration and uneven surfaces (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 22 t. 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

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

(a) According to flexibility

- (i) Flexible;
- (ii) Intermediate;
- (iii) Rigid;

(b) According to binder type

- (i) Bituminous;
- (ii) Cement-bound;
- (iii) Water-bound;

(c) According to strata

- (i) Monolithic;
- (ii) Two layer or multilayer systems;
- (iii) Sandwich constructions;

(d) Seen from the surface

- (i) Asphaltic;
- (ii) Concrete slabs;
- (iii) Concrete blocks;
- (iv) Granular.

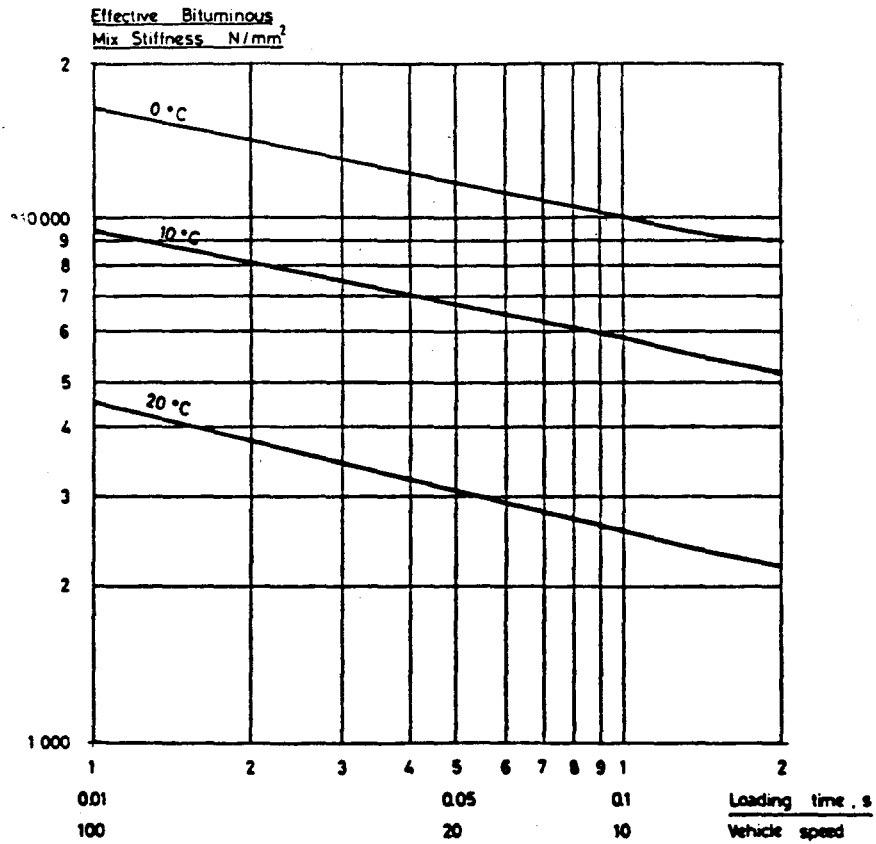
55. The above classification is far from complete, and many more combinations are possible. However, since terminal users usually see the surface itself and not the structure, for the purpose of this monograph this aspect is chosen, as it is the most common and understandable to persons who are not specialists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

### 3.5 Factors governing pavement type selection

56. 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;
- (e) Type of trafficking - vehicle speed, wheel loads (dynamic load factors, i.e. braking, cornering, acceleration, uneven surface), tyre types, contact pressure and channelization;
- (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;
- (q) Surface characteristics - smooth, even, clean, always dry, never slippery, absolutely horizontal, without single discontinuity.

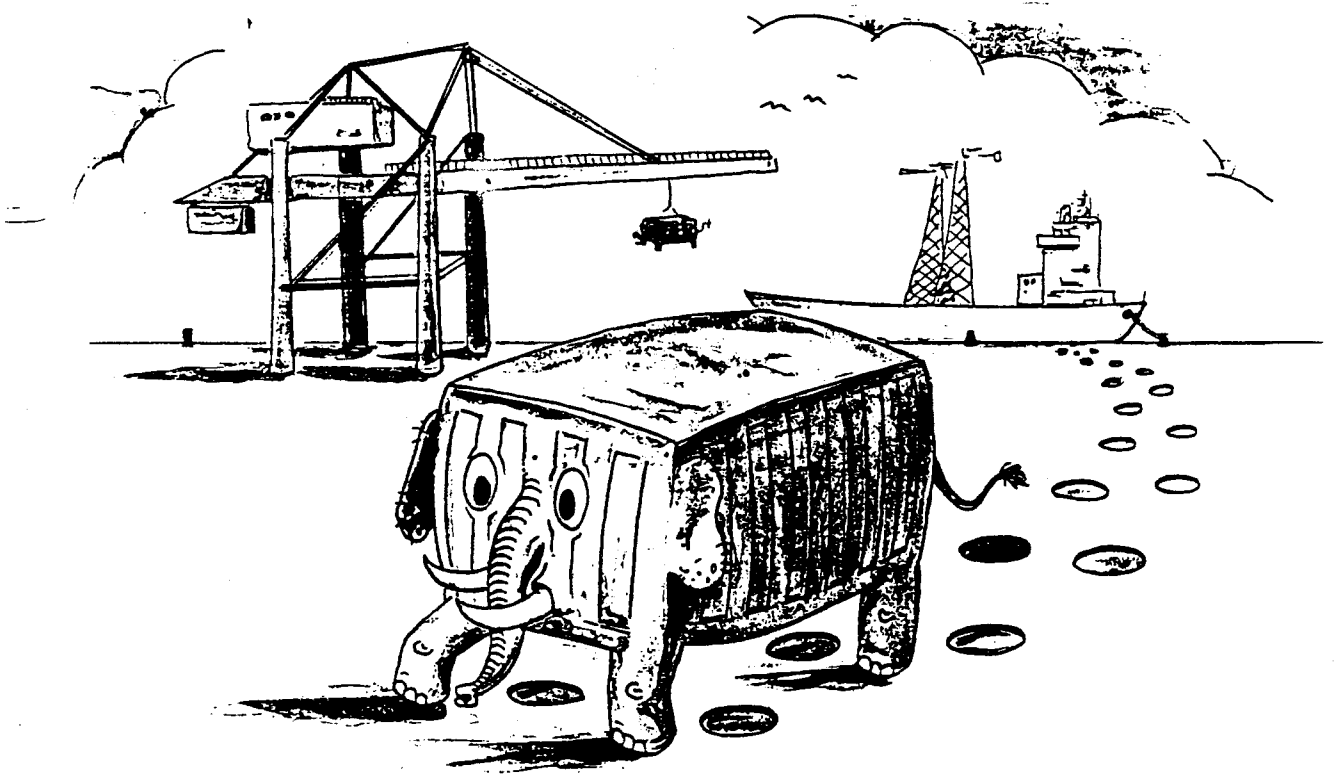
57. The ideal surface could be described as the one which would satisfy all the above factors, and a few more that someone will, no doubt, be able to add in order to make the ideal even more unattainable. In practice however, every design must be a compromise between a number of contradictory requirements.



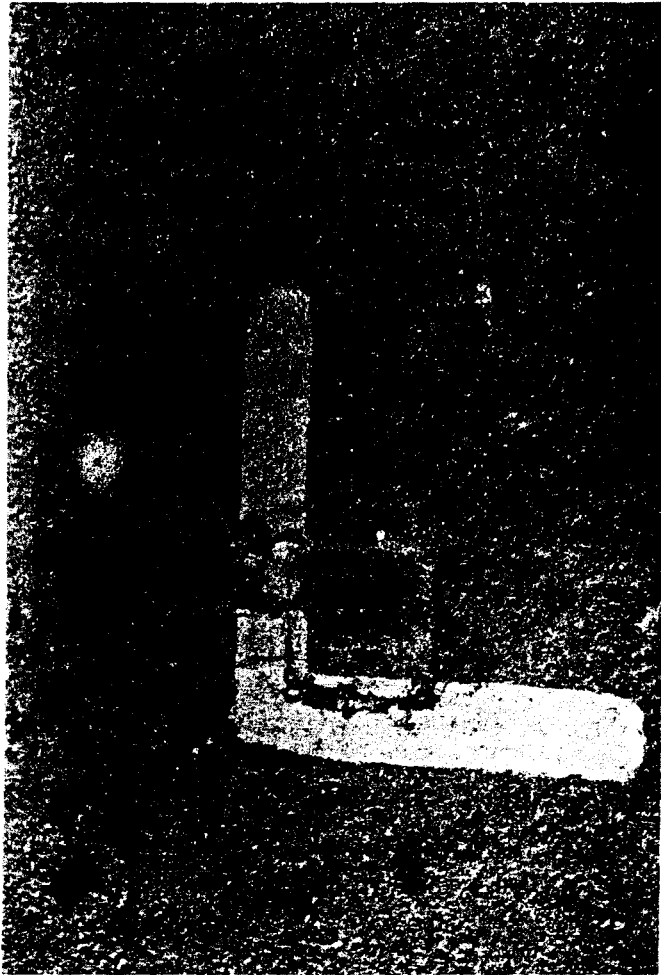
Effect of vehicle speed and pavement temperature  
on bituminous mix stiffness



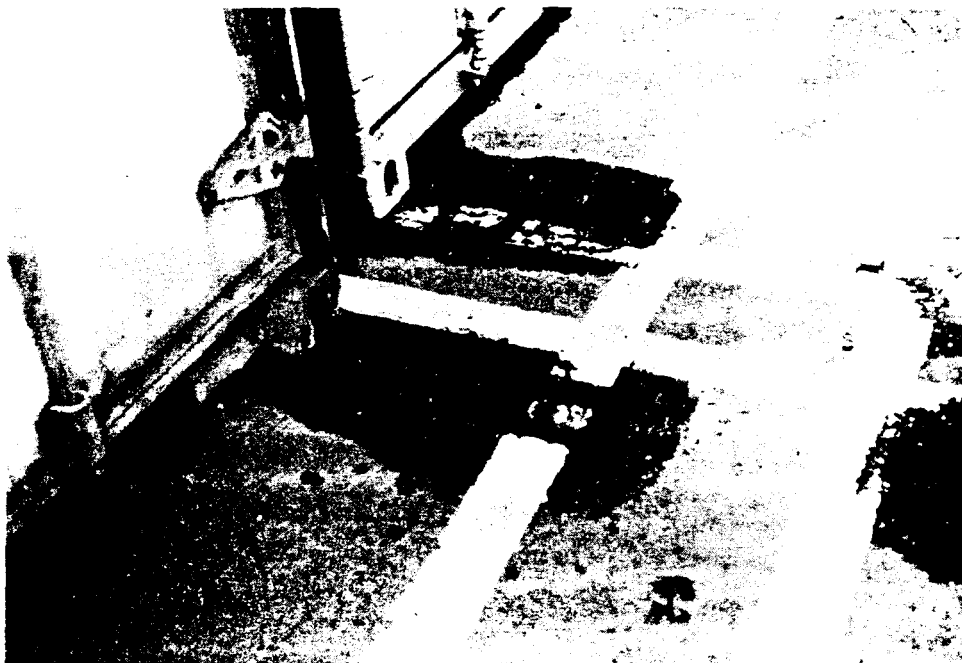
Asphalt degradation resulting from oil spillage  
from handling equipment.



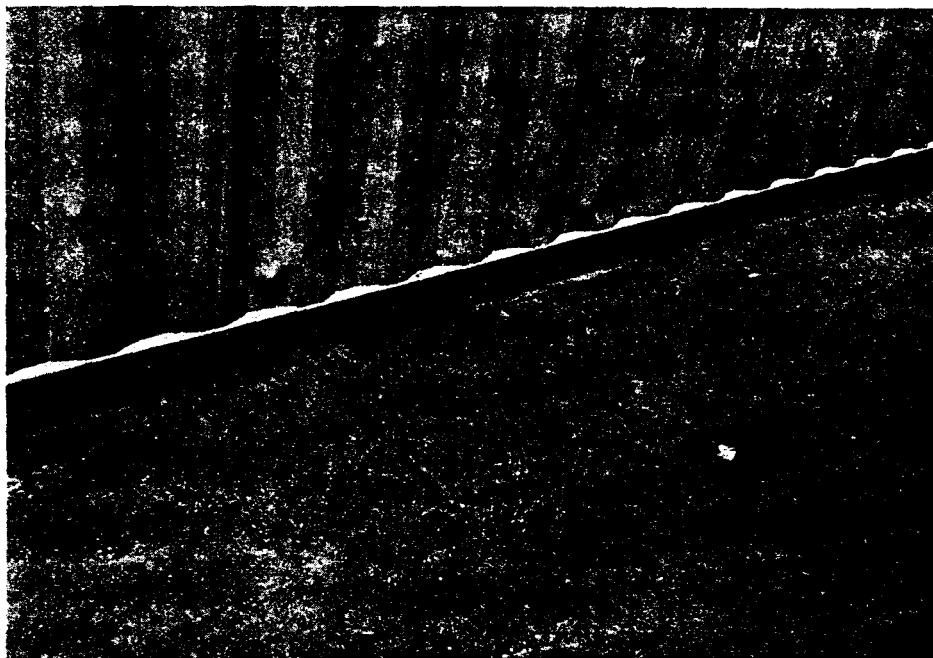
Containers may weigh 30 tons or more and all of that load is transmitted to the pavement through four small corner castings which project 12.5mm beneath the bottom of the container.



Typical indentation from corner casting.



Water standing in corner casting indentations can accelerate pavement degradation.



Corner casting indentation leads to contact between the underside of the container and the pavement. Both the container and the pavement may be damaged.



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

58. 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.

59. It could be very unprofessional to suggest that there is a standard solution for each particular set of conditions, but what can be confidently stated is that in the last few years an increased range of potential solutions is available.

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

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

#### 3.6.1 Bituminous or asphalt surfacing

62. 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 highways is too soft to carry the large wheel loads, high contact stresses and low vehicle speeds without severe rutting and indentations. Three characteristics of the asphaltic mix have largely 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 the lower the stiffness;

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

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

64. 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 attack and mechanical disintegration. A similar and equally serious problem occurs in container stacking areas with the corner castings of containers: owing to the fact 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 into line with that of other forms of construction.

### 3.6.2. In situ concrete

65. An in situ concrete pavement is a rigid form which provides a very durable and hard-wearing 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 resistant 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. The factors involved are as follows:

(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 new areas are usually created by reclamation;

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

(c) A high concrete strength, at least  $30 \text{ N/mm}^2$ , is necessary to reduce spalling and impact damage;

(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.

### 3.6.3. Precast concrete rafts

66. 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.

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

(a) The cost of the rafts is very high; this is aggravated by the large size of the units, which weigh around 1.25 tonnes, and haulage is expensive;

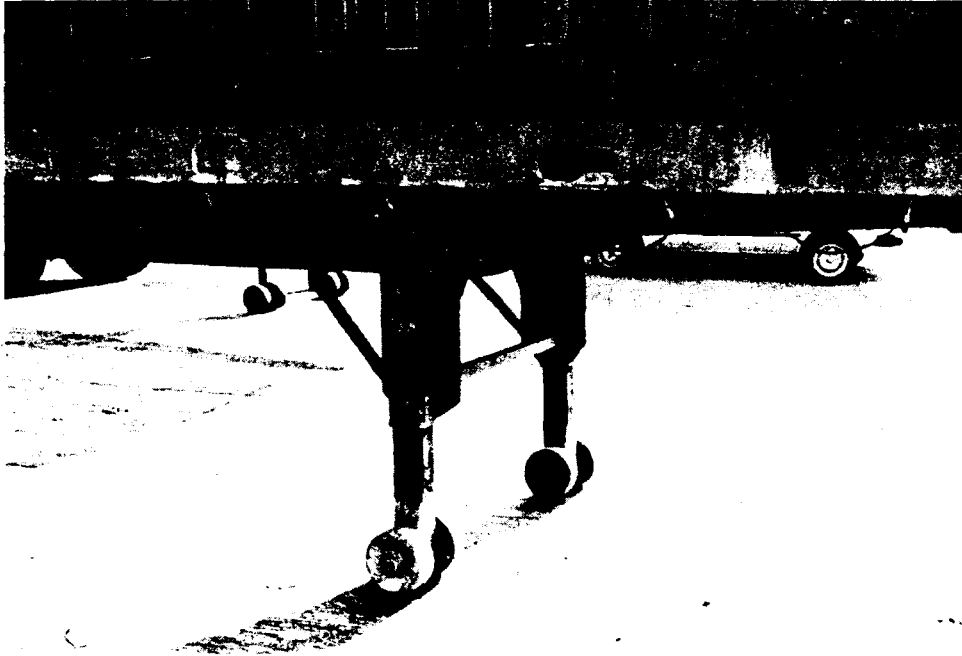
(b) With the units being larger than the track width of the handling equipment and the corner castings which support the containers, very large hogging bending moments are induced in the rafts. If the supporting subgrade has settled this can cause cracking across the corners;

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

68. 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

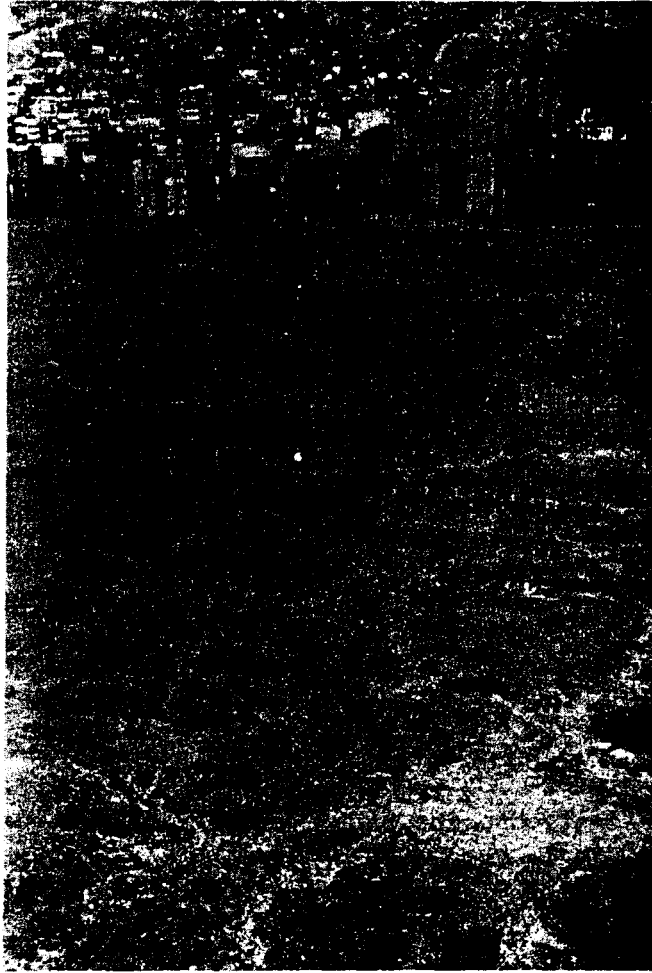
69. Concrete blocks have now established themselves as a successful form of surfacing for port area pavements and offer the same advantages as the raft system. They have a highly durable and hard surface, possessing at the same time the flexibility associated with asphalt construction. The individual 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 m<sup>2</sup> of concrete blocks to be laid per machine-day. It has been reported that the ensuing saving in concrete block



In situ concrete can withstand high contact stresses such as those applied by trailer support wheels.



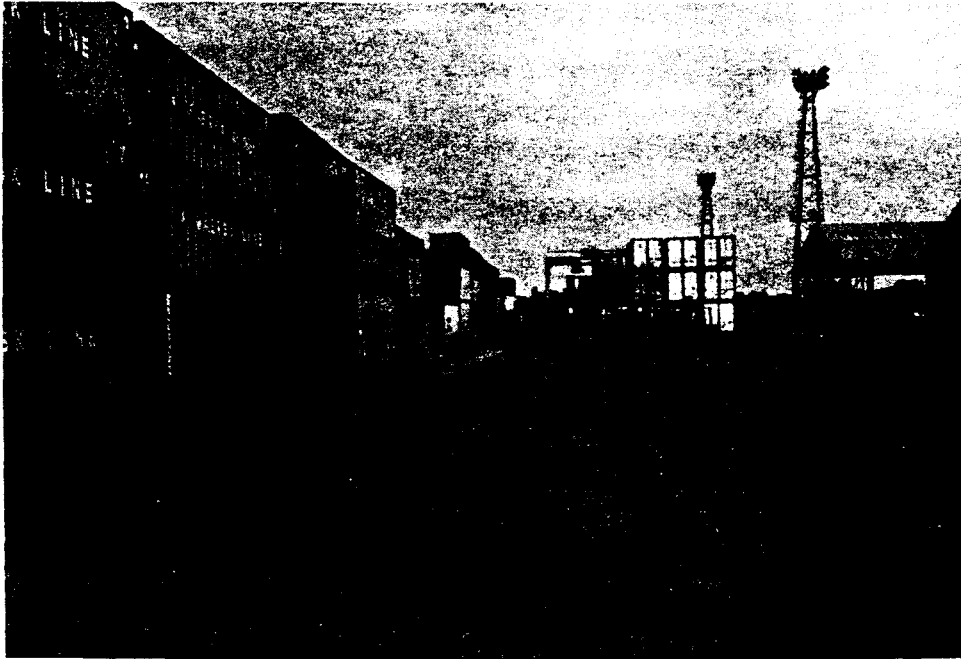
Cracking of concrete slabs resulting from subgrade settlement.



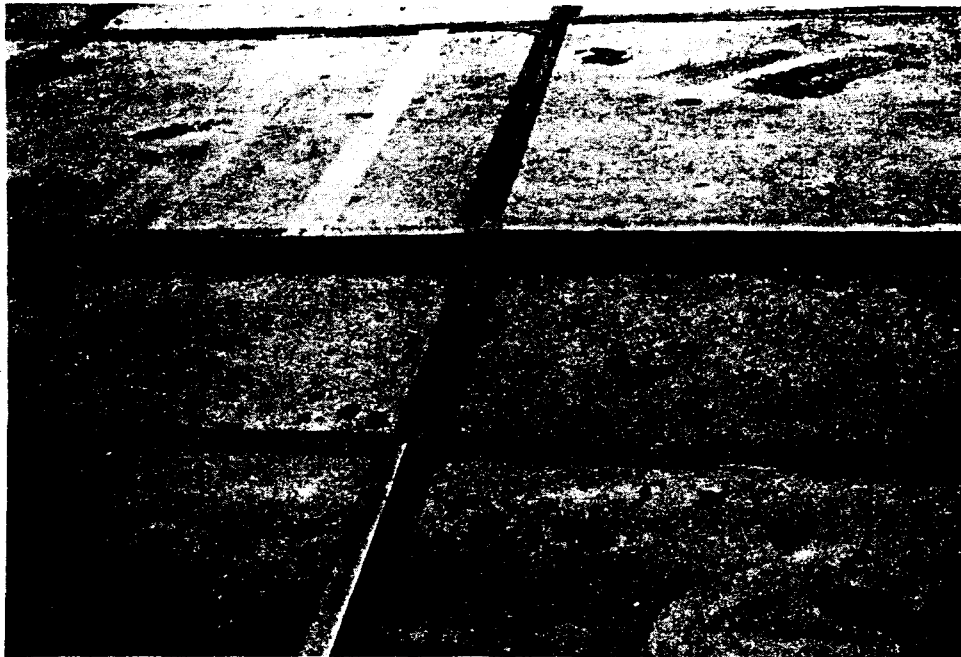
Poor quality concrete is unlikely to last long in a container handling facility.



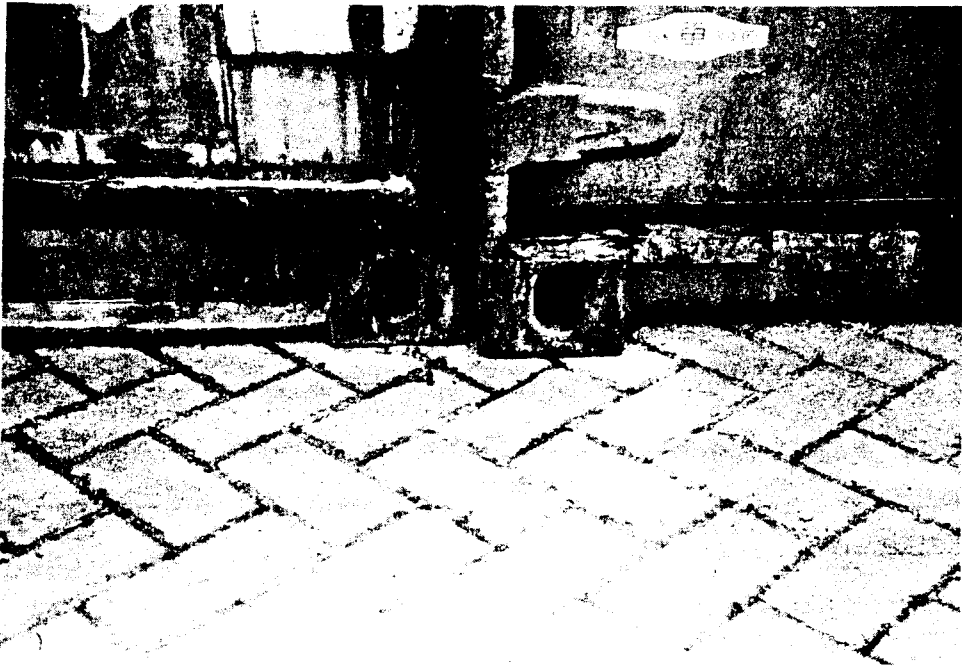
Repairs to in situ concrete paving are expensive and disruptive.



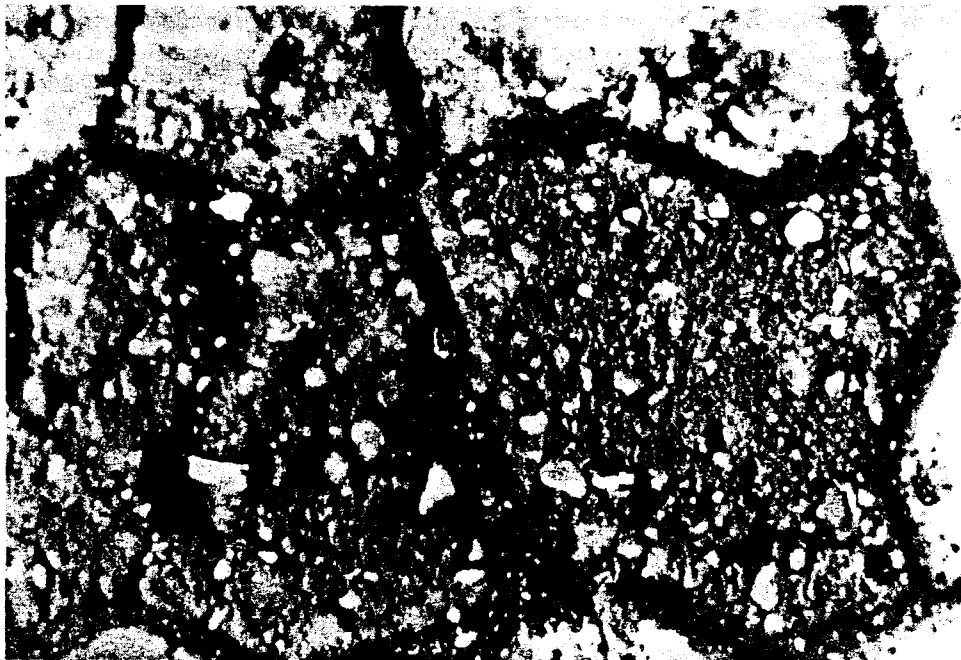
2m x 2m precast concrete rafts were commonly specified by ports in the 1960s but their high initial cost and poor performance renders them less competitive now than other options.



Differential settlement of the rafts has been a common problem, resulting in danger and damage to operating plant, breakage of the rafts and ponding.



Rectangular precast concrete paving blocks were first used for container yards in 1970 and have now become the preferred solution for many situations throughout the world.



Shaped precast concrete paving blocks have been used in ports with less success than rectangular ones.

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

70. 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. It is therefore 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 figure 3.

71. 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

72. 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.

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

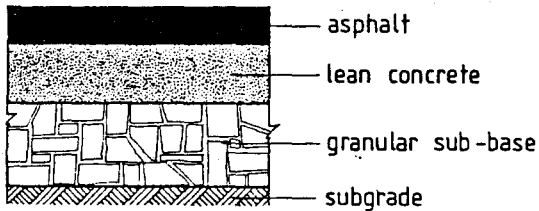
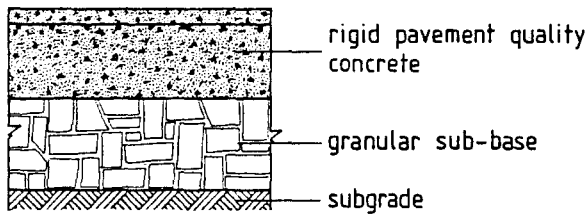
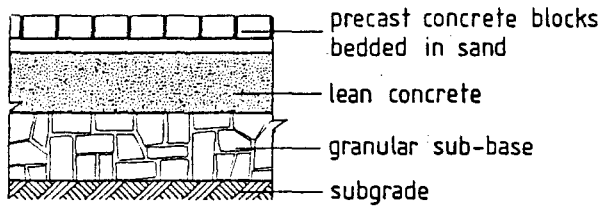
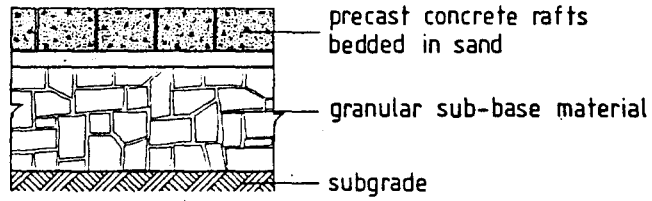
74. There is a common prejudice which leads us to equate simple and cheap solutions with bad and inadequate ones but this gravel bed system, though simple and inexpensive, is by no means "cheap" in the context that is normally understood by this word. Gravel beds, being a simple system of paving, are very easy to describe. It is nothing more than a layer of a certain thickness of gravel (crushed or naturally occurring aggregates) 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 to sub-base material according to special local conditions and design parameters.

75. 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 underside of some containers with sticky undersides because of the presence of grease or old paint which has been partly peeled off. Actual field tests have proved that aggregates with usual specific gravity which are larger than 20 mm will not stick. The recommended size of gravel is therefore between 25 mm and 50 mm.



Figure 3

Typical recommended heavy-duty pavements. These are the four categories of pavement included in the British Ports Association heavy-duty pavement design manual.



76. Gravel beds, owing to the very small units that they comprise, form a surface which behaves like a cushion. This means that they have the capability of adopting a surface profile compatible with that of the underside of the stacked containers. 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.

77. Owing to the voids between aggregates, the actual contact area is assumed to be 70 per cent of the plan area of the steel sections which project below and support the floor of the container. This area is about 5 m<sup>2</sup>.

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

Maximum gross weight of 40 ft. container: 30.40 tons

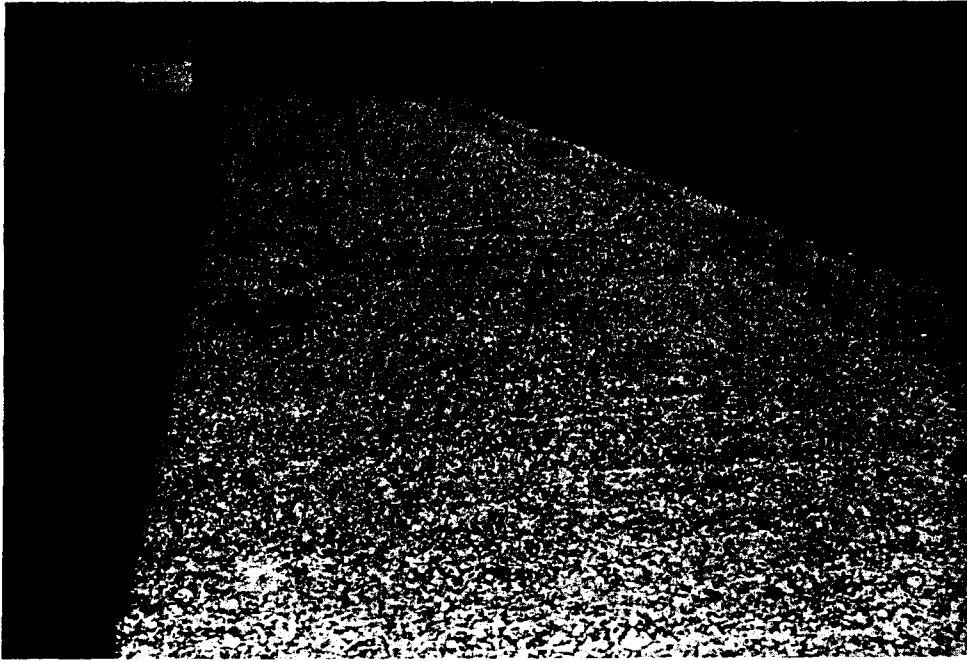
78. In the case of gravel beds the 20 ft. container gives the worst loading conditions, as the 40 ft. unit has double the plan area but its maximum gross weight is less than twice that of the 20 ft. unit. In the case of concrete or asphalt pavements, as containers are supported on their corner castings,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

79. Table 4 gives the maximum loads and stresses for a block stacking arrangement when gravel beds are used. A comparison of table 4 with table 3, 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.

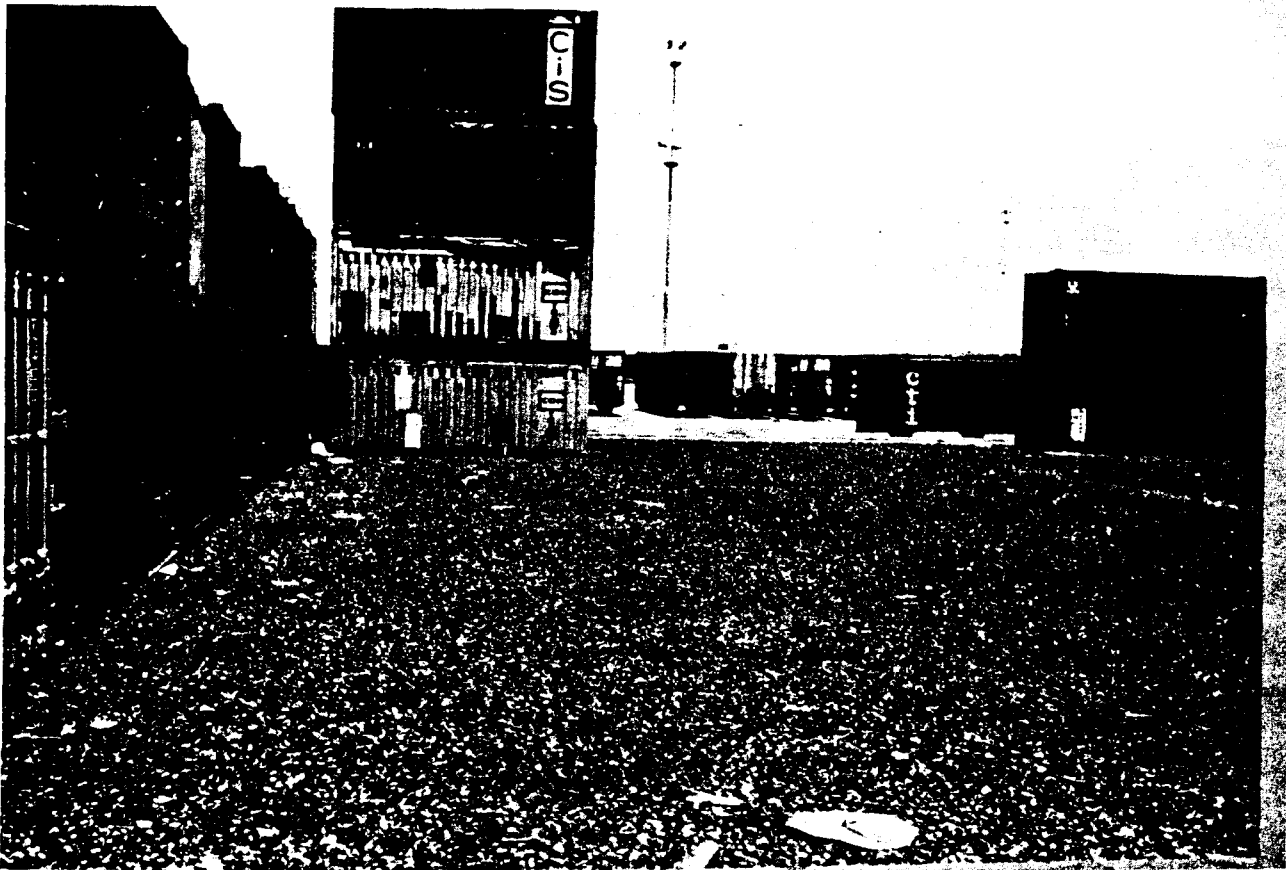
Table 4

Pavement loads from container block stacking

Stacking height	Reduction in gross weight (Per cent)	Gravel beds	
		Load (kg)	Contact stress (N/m <sup>2</sup> )
1	0	20 000	0.056
2	10	38 000	0.107
3	20	54 000	0.15
4	30	68 000	0.190
5	40	80 000	0.224



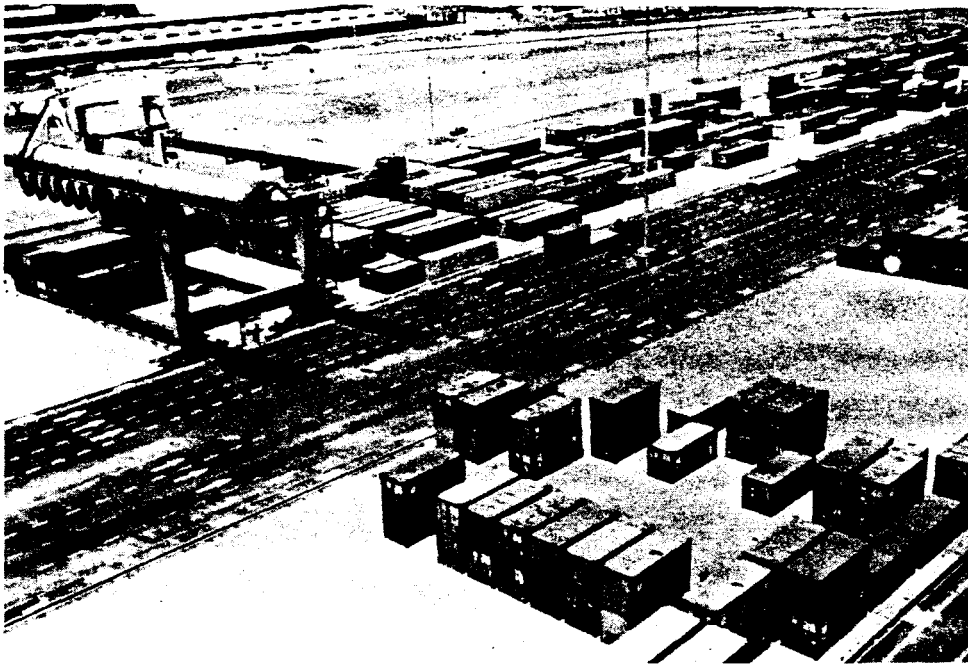
Gravel beds adopt a surface profile compatible with the underside of the containers so that ground pressure is minimised.



Full containers have been stacked four high on gravel beds at the Port of Ashdod Israel, over a period of ten years during which maintenance costs have been zero and there has been no container damage.



Gravel beds at Limassol Port, Cyprus, shortly after construction.



Following their excellent experience of gravel beds at Ashdod, the Israel Ports Authority adopted the same system for its new terminal at the Port of Haifa.

80. 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.

81. Table 5 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 costs have been converted into United States 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.

Table 5  
Construction costs - gravel beds and asphalt

Country	Cost/m <sup>2</sup> of 10 cm asphalt pavement with 20 cm granular base and 15 cm sub-base (United States dollars)	Cost/m <sup>2</sup> of 40 cm gravel bed (United States dollars)	Approximate percentage saving if gravel beds are adopted
Cyprus	11	3.5	68
Greece	9	3.0	67
Malaysia	11.5	4	65
India	20	7	65
United Kingdom	20	8.2	59
Indonesia	17.3	7.7	57
Oman	17	8.4	50
Netherlands	18.3	9.8	46
Saudi Arabia	17	8.2	45
United Arab Emirates	16.5	9	45

82. Considering a container yard of 100,000 m<sup>2</sup> where rail-mounted yard cranes are used, then approximately 69,000 m<sup>2</sup> 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 \$US 897,000 in India, \$US 814,000 in the United Kingdom or \$US 517,500 in Cyprus.

83. 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. Container bays on gravel bed project at the Port of Penang (Malaysia) were marked with road marking paint and were clearly visible after two years of use.

84. 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.

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 temporarily play 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 circulation. This is of prime importance for both safety (minimizing the risk of accidents) and efficiency of port operations, especially with regard to the horizontal transportation of containers.

(d) Possibility of increasing stacking height or employing stacking cranes with shorter legs:

The container stacking bays do not have to be at any specific level in relation to the neighbouring paved areas, as these function completely independently. They only have to be at a lower level, mainly for drainage



Rubber-tyred stacking cranes operating over gravel beds at the Port of Penang.

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 specialized 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 conjunction with yard stacking cranes, which requires a defined and fixed terminal layout in order to allow 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 cases where gravel beds have been adopted.

It is not certain whether the designers of all the above-mentioned container terminals have not considered 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

85. 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.

86. One method which was followed in certain cases was to combine 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 the disadvantages of the rigid concrete system were sometimes added to those of the flexible asphaltic system.

87. Moreover, in this conjunctive system, ponding of rainwater occurs because of the unavoidable differential settlement at the interface of concrete and asphalt areas. One might therefore say that the effort to solve the problem



of corner casting indentations resulted in the introduction of another problem, the ponding of rainwater, albeit not so serious.

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

89. A second method aimed at improving the durability, the effective stiffness and the resistance to oil of asphalt surfacing 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 those mixes would in many circumstances not be as economic as some of the other surfacings available and may even become prohibitive in this respect.



Conjunctive systems in which strips of concrete are set into asphalt so as to avoid asphalt indentation resulting from corner casting loads.



In this conjunctive system, small pads of concrete are constructed at corner casting locations. Note the resulting differential settlement which has lead to ponding.

### Chapter III

#### DESIGN OF HEAVY DUTY CONTAINER TERMINAL PAVEMENTS

##### 1. Introduction

90. 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 four 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 focused on port paving, and the above comparison shows that the design loadings are equal to or greater than aircraft loadings.

91. 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 régime 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 rapidly compare several designs employing alternative material.

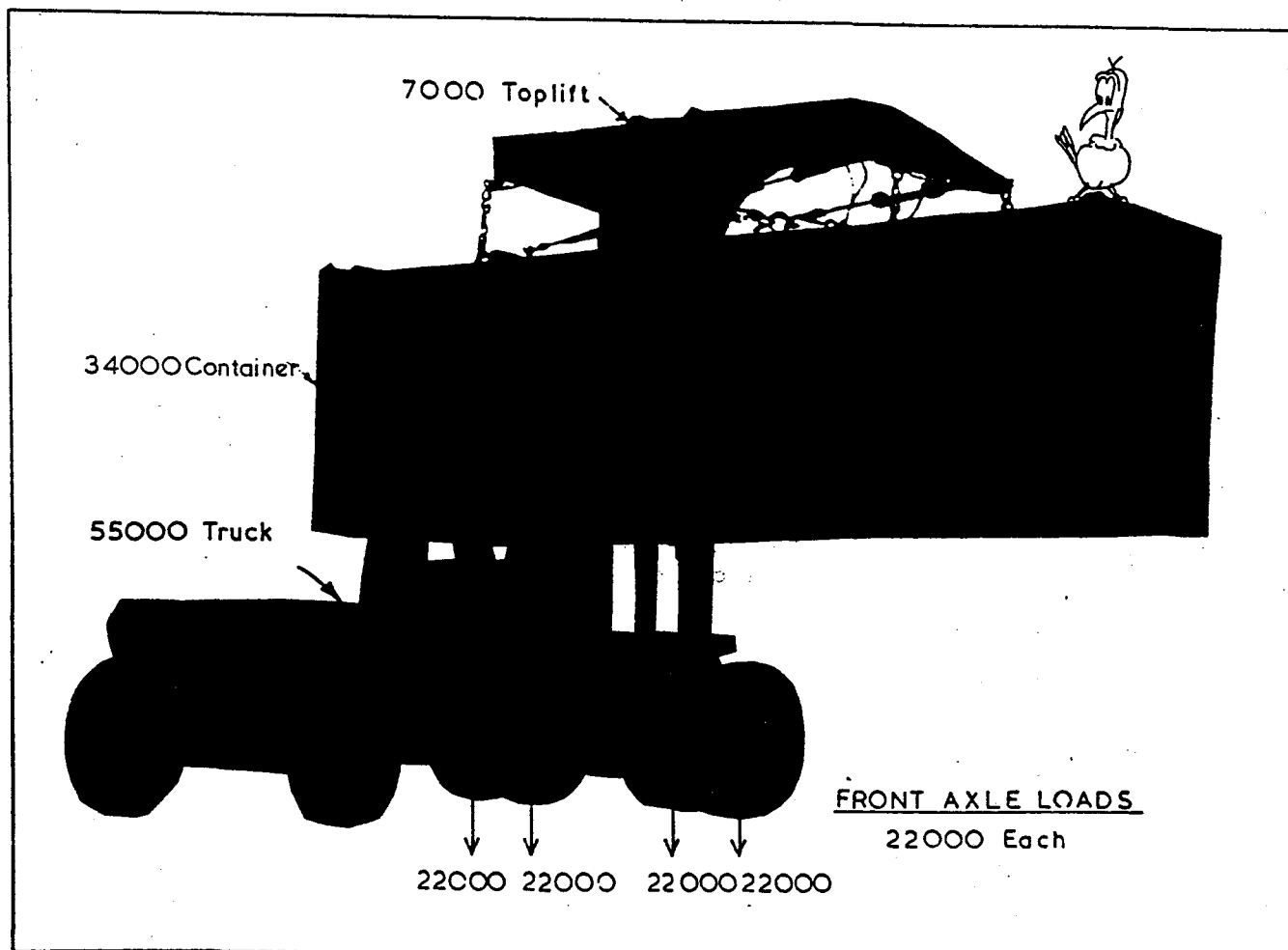
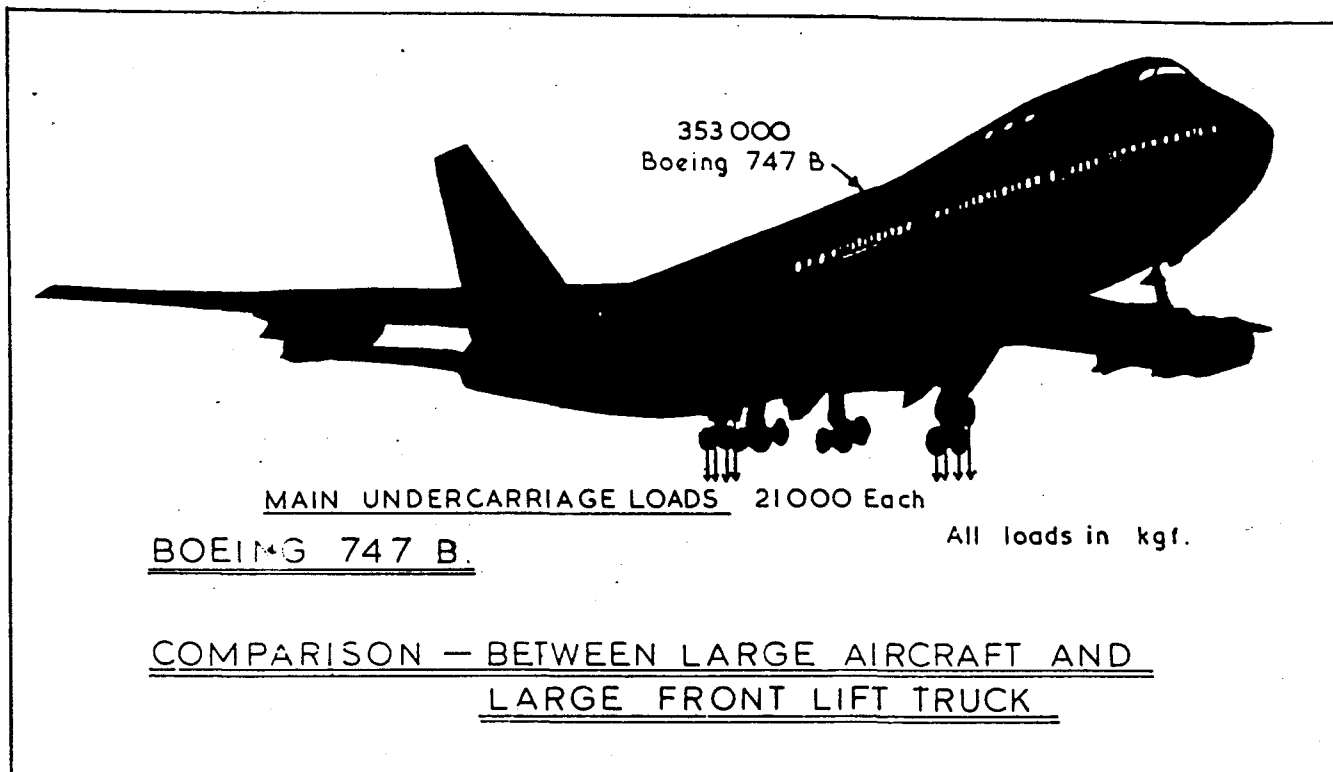
##### 2. Design principles

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

93. 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. Figure 4 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:

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

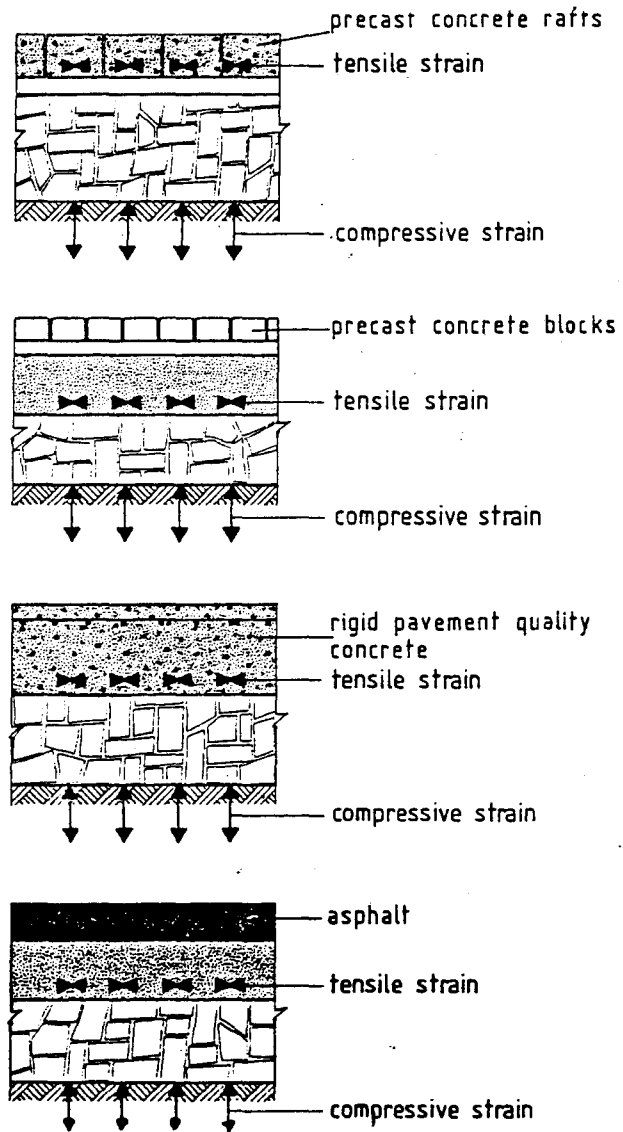
where  $E_v$  is allowable subgrade vertical compressive strain (microstrain), and  $N$  is number of repetitions of applied load.



Wheel loads of typical Front Lift Truck handling a 40ft full container compared with those of large aircraft. Wheel loads are similar, but Front Lift Truck frequently has greater wheel loads.

Figure 4

Position of critical strains in each of four types of pavement



94. For example, if the pavement were subjected on one load repetition, a strain of 21,600 microstrain, or 0.0216 strain, would be the maximum allowable, but if there were 10,000 repetitions, the allowable strain would be only 1,638 microstrain.

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

$$E_h = \frac{F_C \times 993,500}{6 \times E_b \times 1.022 \times N^{0.0502}}$$

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

$F_C$  = characteristic compressive strength of base material (N/mm<sup>2</sup>),

$N$  = number of repetitions of applied load

when  $F_C$  is less than 7 N/mm<sup>2</sup>,  $E_b$  is given by  $E_b = 4000 \times F_C$

when  $F_C$  is greater than 7 N/mm<sup>2</sup>,  $E_b$  is given by  $E_b = 16,800 \times F_C^{0.25}$ .

96. Figure 5 shows the relationship between  $E_h$  and  $N$  for four values of  $F_C$ .

### 3. Analysis technique

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

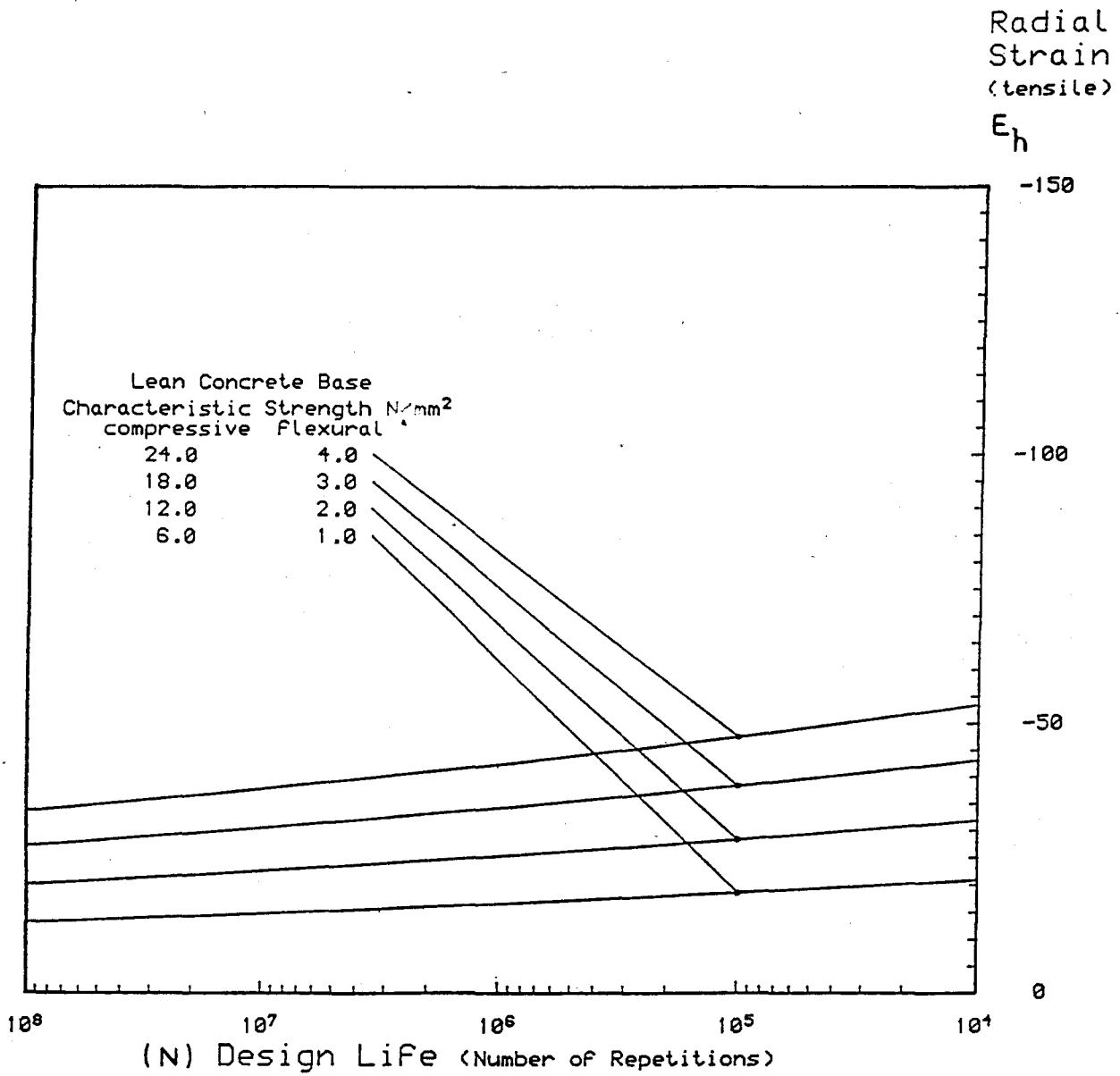
$$\frac{h^3 \times E}{1 - v^2}$$

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

98. 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 ratio  $V_2$  by:

$$h_2 = h_1 \times \sqrt[3]{\frac{E_1 \times (1 - v_2^2)}{E_2 \times (1 - v_1^2)}}$$

Relation between radial strain and design life



99. 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

100. 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.

101. 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

102. 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.

103. 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

104. 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 -

$$D = \left( \frac{W}{12,000} \right)^{3.75} \times \left( \frac{P}{0.8} \right)^{1.25}$$

where D = pavement damage, W = wheel load (kg) and P = tyre pressure (N/mm<sup>2</sup>).



105. 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 inflicted on a pavement by one repetition of a 12,000 kg wheel applying a contact pressure of  $0.8 \text{ N/mm}^2$ . 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 6. 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 6

Relationship between Port Area Wheel Load (PAWL)  
values and Loan 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

106. 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. Accordingly, 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 the 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.

5.3 Severe dynamics

107. 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 7 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.

108. 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 per cent. Where vehicle movements can be predetermined, it will be possible to design substantial areas of the pavement without dynamic effects.

Table 7

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

5.4 Wide range of equipment types and sizes

109. The design method, being based upon fatigue-orientated elastic analysis, is not limited to any specific class of plant. Even equipment which has 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 8 shows proximity factors by which PAWL values for individual wheels are multiplied prior to addition to determine the LCI. The factors in table 8 are dependent both on longitudinal wheel spacing and, to a lesser sensitivity, on the plant's PAWL value.

Table 8

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
1 000	1.80	1.84	1.85	1.86	1.87	1.89	1.92	1.93
2 000	1.40	1.45	1.51	1.58	1.62	1.64	1.72	1.75
4 000	1.00	1.01	1.05	1.09	1.14	1.21	1.28	1.33

6. Calculation of design life of a pavement

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

111. 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: 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' full container with the maximum permissible gross weight, i.e., 35 sets of loads in steps of 1,000) is multiplied by the corresponding percentage frequency that each of these container loads would pass through the terminal.

112. 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 this is done, 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 the application of simple statistics.

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

$$L = \frac{\left( \begin{array}{c} \text{total number of plant} \\ \text{movements} \end{array} \right) \times \left( \begin{array}{c} \text{average damaging} \\ \text{effect} \end{array} \right)}{\text{critical damaging effect}}$$

114. To calculate the average damaging effect, each of the 35 damaging effects is multiplied 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

115. 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 the sensitivity of a given design to changes of design life, soil strength or load magnitude. For example, the charts show that relatively large changes in the number of repetitions (say doubling or halving) affect 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 of the possibility of gross error. It is difficult to see how a user could be in error by more than a few millimetres.

116. By contrast, calculation leads to very high apparent accuracy, but there is always 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 that he is operating in an unorthodox situation.

117. 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).

118. Also, solutions can be presented for only a few discreet 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 measure 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 depends 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. Moreover, tyre 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.

119. Taking into account all of the factors present, 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.

120. An example of a BPA chart is shown in Figure 6.

121. 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.

122. If there are no firm data available, it is suggested that a value of 2,000,000 repetitions should be sufficient for most pavements, 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

123. 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 rainwater 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 causes operational disturbance.

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

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

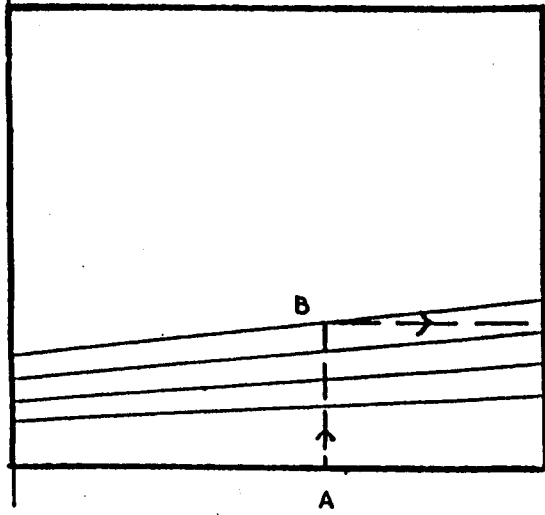
#### 9. Provision of underground services

126. 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 operations. It is 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 out is minimized. 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 any need to disturb the pavement

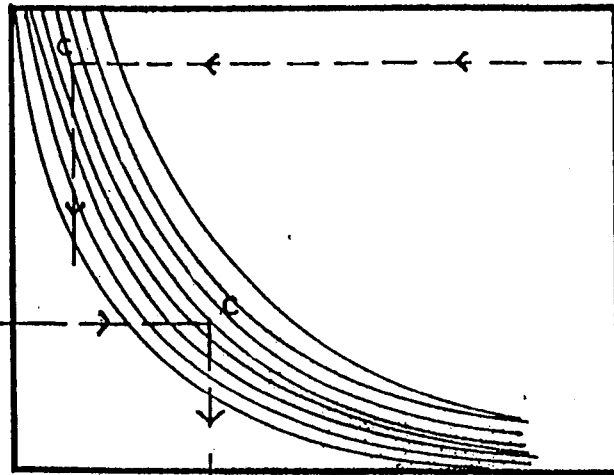
Figure 6

Typical BPA Manual port pavement design chart

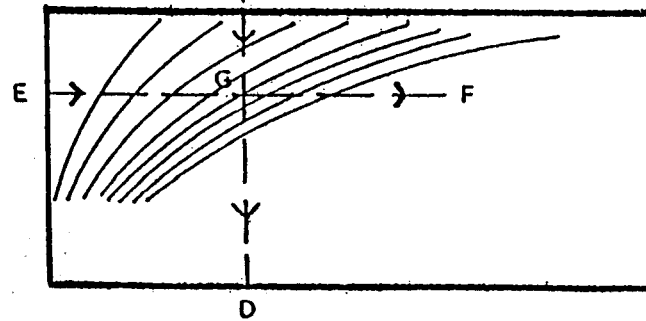
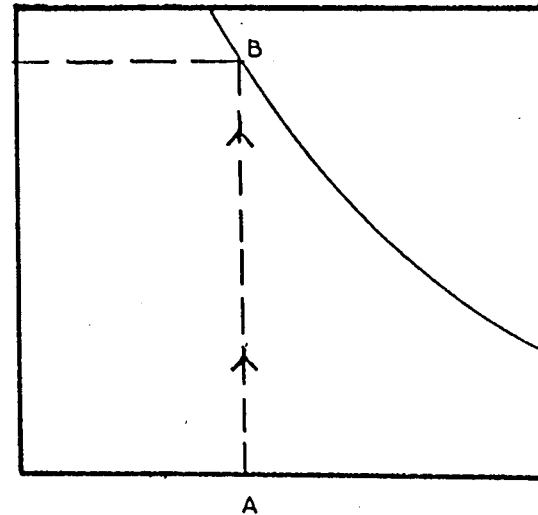
Base tension chart



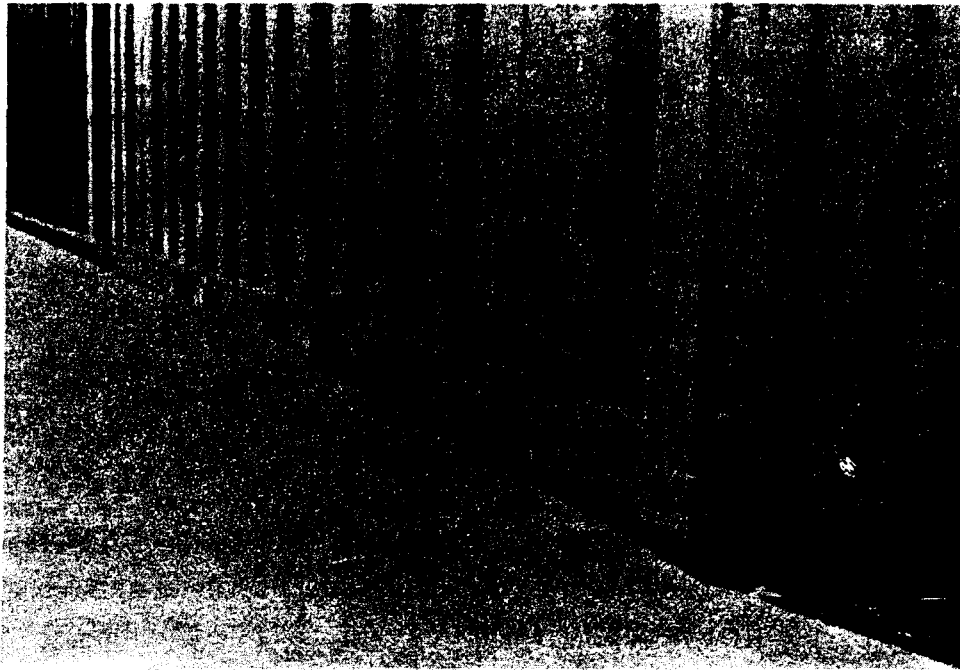
Load chart



Subgrade compression chart



Base thickness chart



Change in surface fall causes container to cantilever, so risking damaging it.



Absence of adequate falls leads to ponding.

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, involves 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 per cent 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 suddenly when subjected to the load of a moving piece of equipment.

127. 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.





Ducting of underground services facilitates maintenance and allows provision to be made for future expansion.

Chapter IV

REGULAR MONITORING OF PAVEMENTS

128. 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 extended at minimum cost.

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

130. Consequently, a prudent authority should undertake a condition survey of its paved areas at regular intervals 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 local conditions such as climatic variations and other factors.

131. The condition of pavements can be defined in terms of two categories:

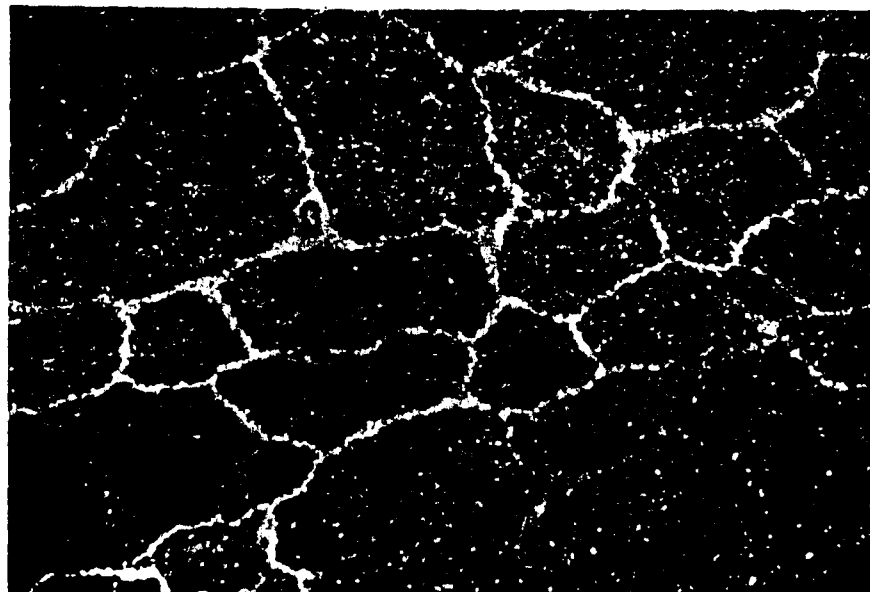
- (a) Condition of the material;
- (b) Degree of localized rutting or settlement.

132. Usually, the material condition survey simply amounts 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 used to verify the actual condition. The material condition survey has been standardized so that standard condition factors for cracking and spalling can be used. The various degrees of cracking are shown in Figure 7, and the corresponding condition factors are as follows:

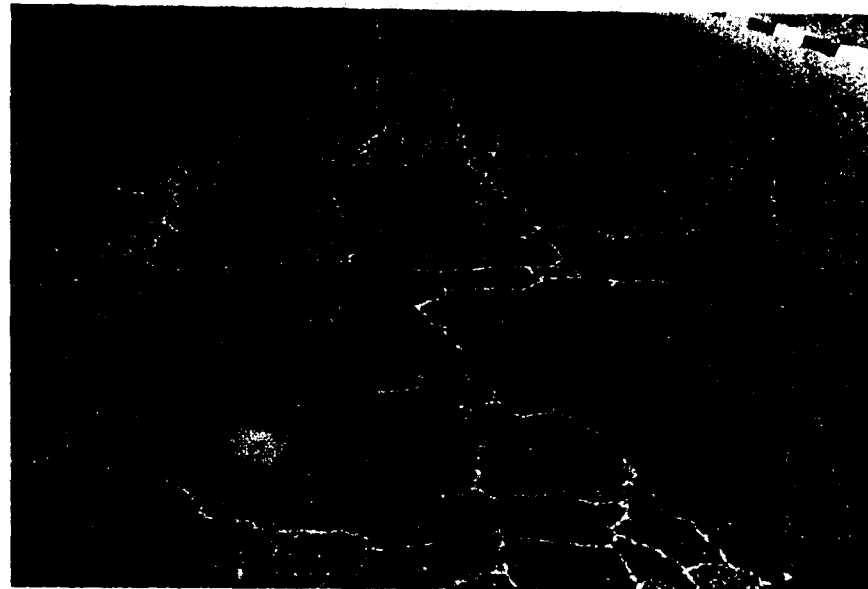
<u>Condition of material</u>	<u>Condition factors</u>
As new	1.0
Slightly cracked	0.8
Substantially cracked	0.5
Fully cracked, crazed or spalled	0.2

133. The survey to establish the degree of localized rutting or settlement has also been standardized.

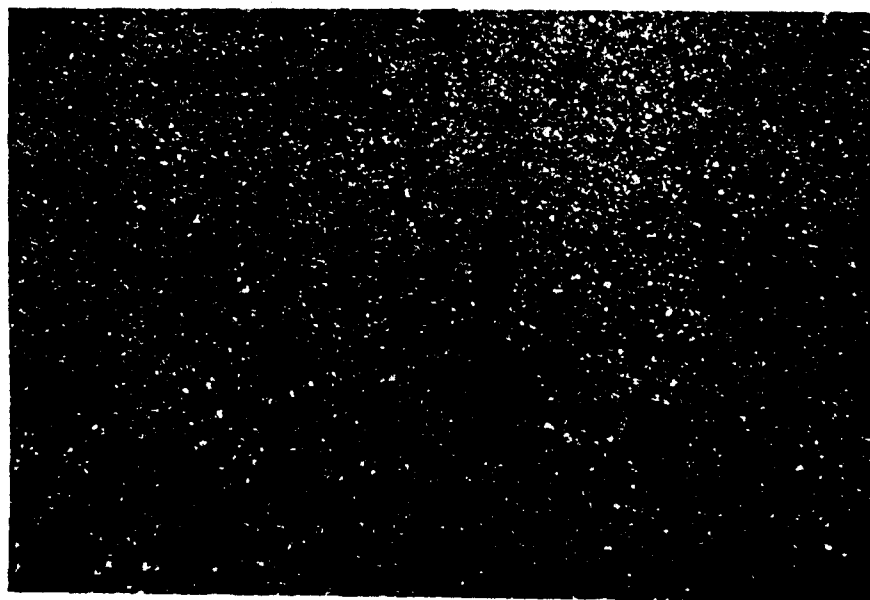
Figure 7  
Various degrees of cracking



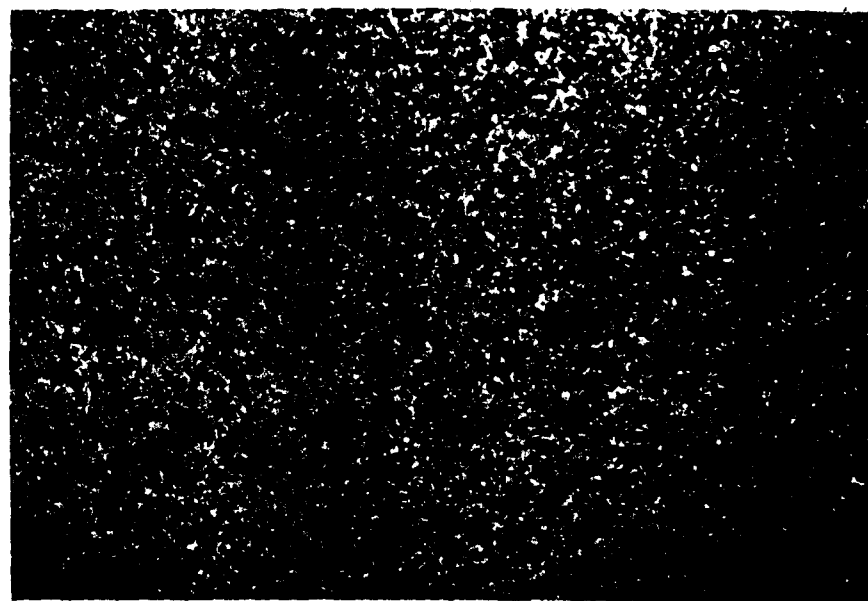
Fully cracked



Substantially cracked



Slightly cracked



As new

134. 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:

(a) Rigid concrete and precast concrete rafts: at each corner of each bay or raft;

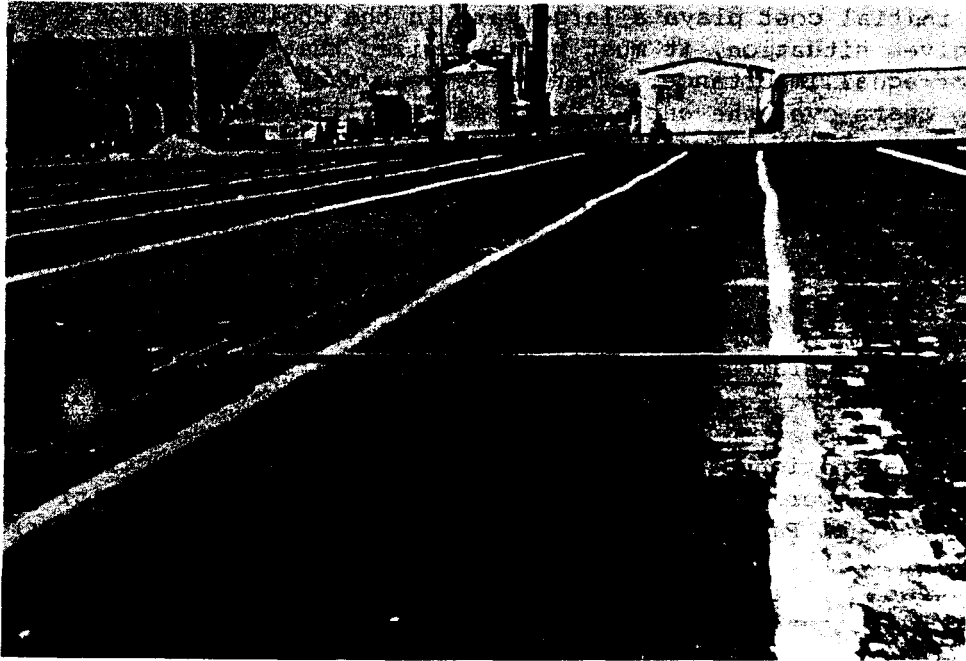
(b) Bituminous or concrete block paving: one level for each 100 m<sup>2</sup> of paving, at locations which it will be possible to re-establish at a later date.

135. 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 are 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.

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

<u>Degree of localized rutting or settlement</u>	<u>Condition factor</u>
0 - 10 m	1.0
11 - 20 m	0.9
21 - 40 mm	0.6
40 + mm	0.3

137. 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.



Determination of pavement deformation beneath a 3m straight edge.

Chapter V

MAINTENANCE, REHABILITATION AND UPGRADING OF PAVEMENTS

138. While initial cost plays a large part in the choice made for a pavement type in a given situation, it must be recognized that recurring 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.

139. 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 upgrading or even total replacement of the pavement.

140. 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 useful life of the pavement.

141. 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 described as follows:

- (a) Regular monitoring;
- (b) Preventive maintenance;
- (c) Repair of damage and breakdowns;
- (d) Rehabilitation or upgrading;
- (e) Demolition and reconstruction.

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

143. Regular monitoring will lead to preventive 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. Preventive maintenance therefore consists in preventing breakdowns by taking corrective action before costly disruption in operation can occur. Preventive maintenance has long been recognized 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.

144. On the other hand if regular monitoring is not undertaken properly or at all then the preventative maintenance phase may become too short or even non-existent 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 recognized on time and the strengthening of an existing pavement is delayed then the demolition and reconstruction of the pavement may be the only option.

145. 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. The terminal operators should therefore take the maintenance of their surfacing as seriously as they take the maintenance of their handling equipment.

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

- (a) Age;
- (b) Overloading and abuse;
- (c) Weathering;
- (d) Settlement;
- (e) Accident;
- (f) Pavement installed with undue care;
- (g) Wrong pavement choice.

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

- (a) Pavement has become unserviceable;
- (b) Change in operation - heavier equipment;
- (c) Change in operation - revised levels or layout;
- (d) Improvement of surface properties, e.g., skidding and water penetration.

148. Pavement rehabilitation requires that the condition of the existing pavement be 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.

149. Sometimes a pavement can be revitalized by removing the upper course and replacing it with similar or alternative material of similar thickness. Whilst this approach is unlikely to provide significant additional strength, it can provide 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. The chief disadvantage of overlaying is that the pavement surface level is raised so that drainage, kerbs and other details will need attention.

150. Once the residual strength of a pavement has been assessed, the overlay design technique must be capable of selecting the thickness and properties of strengthening materials. The overlay design technique suggested in this monograph is the one described in the BPA manual, which is based on the "component analysis method and the pavement transformation procedure".

151. The strengthening operation may be intended to extend the life of the pavement or 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 9 gives suggested alternative overlay techniques for four types of existing pavement.

Table 9

Suggested alternative overlay techniques for four types of existing pavement

Concrete rafts	Concrete blocks	Rigid concrete	Asphalt
1. Lift rafts, rescreen sand and replace rafts	Lift blocks, rescreen 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 overlabs over old slabs	Lay concrete blocks
3. Lift rafts, remove sand and lay asphalt	Lift blocks remove sand strengthen base and 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, rescreen sand and lay rafts		



Chapter VI

CONCLUSIONS

152. 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.

153. From this monograph 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 parallel.

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

155. 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. The most important thing is to be aware of the available choices and the relevant factors.

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

157. With the 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 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 pavement's 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 coast. It is hoped that this monograph will stimulate all those responsible for port pavements to take the widest possible view of their work.

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