

HIPAVE – A Mechanistic Design Tool for Flexible Port Pavements

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Abstract

The design of pavements for port facilities is crucial to the successful cargo loading and unloading operations in a safe and efficient environment. Whilst some port pavements are constructed from concrete, the majority of port pavements are of flexible construction with either an asphalt or concrete segmental paver wearing course.

Traditionally, port pavements have been designed using purely chart-based, empirical processes such as the British Ports Association method. In more recent times, designers have combined the full range of vehicles and shipping containers into a single number of repetitions of an 'equivalent standard axle'. This equivalent axle would be applied in layered elastic design using tools such as CIRCLY.

In 2004, MINCAD Systems released a trial version of HIPAVE. This ports-specific version of CIRCLY is designed to allow each combination of vehicle type and container load to be modelled separately and the damage combined using the Cumulative Damage Factor concept.

This paper presents the development and advantages of using HIPAVE, over simpler layered elastic tools and empirical chart based methods, to design flexible port pavements. A design example is also included which presents the design of a port pavement for the Doha Container Terminal in Qatar, using the empirical chart-based method, CIRCLY (via an equivalent axle) and HIPAVE. This example demonstrates the efficiencies for designers offered by HIPAVE and the enhanced ability to conduct 'what if' analyses.

1 Introduction

The design methods for pavements presented in the new Austroads Pavement Design Guide (2004) are not appropriate for designing heavy duty pavements for applications such as ports and container terminals. New analytical tools are being made available which are well suited to heavy duty pavement design, and which use well-established principles for the behaviour of these pavements under the heavy axle loads experienced in these applications.

To evaluate these new tools, a case study of a container terminal pavement has been analysed, using both HIPAVE design software, and two other techniques for comparative purposes.

2 Modelling Overview

Previous methods for structural design of container terminal pavements such as the British Ports Federation Guide (2nd edition, 1986) were developed prior to personal computers being commonplace. Therefore simplifying assumptions were necessary for manual calculation. The variety of vehicle types and traffic levels were approximated by "Equivalent" wheel loads and "wheel proximity factors". These simplifying approximations are no longer justified. Layered elastic methods are now widely used in highway design practice (for example, Austroads, 2004) and airport design practice (for example, APSDS, Airport Pavement Structural Design System, Wardle, et al. 2001). These linear elastic pavement models have been found to adequately represent flexible pavements comprising asphalt, unbound granular and/or cement-treated layers and the

subgrade. These models can circumvent approximations involving "Equivalent" wheel loads by using the actual wheel locations.

APSDS and HIPAVE use specially developed models for the unbound granular materials. Also the APSDS/HIPAVE rutting criteria have now been developed from the observed performance of aircraft test pavements subjected to wheel loads of up to 27 tonnes. These loads are comparable to those typically applied to heavy duty pavements used at ports, container terminals and on mine haul roads. Consequently the APSDS/HIPAVE rutting criteria are more suited for the design of these pavements than the Austroads empirical rutting criterion developed for highway loadings.

3 Main features of HIPAVE

The HIPAVE application is a new refinement of the well-established CIRCLY multi-layered elastic design tool for pavement design. While CIRCLY has been used very successfully for heavy duty industrial pavements, it is limited in its capability to apply the precise loads commonly experienced in these situations.

APSDS (Airport Pavement Structural Design System) was developed from CIRCLY specifically for heavy duty pavements and in particular airport pavements. The analysis includes the effect of the lateral vehicle wander. Vehicle wander is the statistical variation of the paths taken by successive vehicle movements relative to lane centrelines. Increased wander reduces pavement damage by different amounts that depend upon pavement thickness.

In 2004, MINCAD Systems released a trial version of HIPAVE. This ports specific version of CIRCLY is designed to allow each combination of vehicle type and container load to be modelled separately and the damage combined using the Cumulative Damage Factor concept. HIPAVE extends the lateral vehicle wander concept used in APSDS to include the capability of letting the degree of wander vary with each vehicle model in the traffic mix.

HIPAVE handles the variety of mobile equipment used in container facilities, such as forklifts, straddle carriers, gantry cranes, tractor-trailers and side loaders. The contributions of the actual vehicle wheel configurations and loads of all vehicles in the design mix can be quickly computed as the loads are automatically calculated from vehicle characteristics and container weights. The distribution of container weights (the container loading spectrum) for each vehicle type can be readily specified.

HIPAVE uses a standard vehicle library that can be automatically updated from the Mincad Systems webserver.

4 Case study – Doha Container Terminal, Qatar

4.1 Terminal Operation

The Doha Container Terminal, currently under construction, has been planned to be operated predominantly with a fleet of straddle carriers, supported by tractor-trailers. Hence, the rectangular container yard has been arranged in four blocks of container stacks, each holding approximately the same number of containers. The primary operating philosophy adopted for this terminal is flexibility of operation. The Qatar Customs and Ports General Authority has not operated a dedicated container terminal of this magnitude before, and a flexible terminal layout and operation will allow the terminal operators to develop and modify the operating methods to suit their preferences and capabilities.

4.2 Container Handling Equipment

The terminal is likely to be operated with the following types and number of container-handling equipment, and the pavement design has been developed around this equipment scenario.

Table 1 - Container Handling Equipment

Description	Make & Model	Capacity	Number Operating
Straddle Carrier, 3-high	Kalmar ESC 340	40 tonne	5
Straddle Carrier, 4-high	Kalmar ESC 440	40 tonne	3
Tractor-trailer	Kalmar PT122	32 tonne	36
Forklift truck	Kalmar DCD370/12	35 tonne	3

4.3 Container Throughput

The container numbers handled in the terminal are expected to grow at a steady rate over the next 25 years. The predicted container throughput, determined in the Master Study (Dar Al-Handasah, 2002) is:

Table 2 Future Container Throughput

Year	Annual Container Throughput, teus
2004	80,000
2011	123,000
2030	238,000

The container loading spectrum is unique to this port. Qatar produces virtually nothing of value other than natural gas and other petroleum products. As a consequence, essentially all consumer and other goods must be imported to the country, in containers where practical, and the empty containers, once unloaded, are exported empty. The container load spectrum is therefore skewed to import containers. The Master Study has identified the average container weight for imported loaded containers to be 21t. The container weight spectrum used for the pavement design is given in Table 5.

4.4 Pavement Design

The pavement originally designed for this terminal comprises a subgrade of select fill, sub-base and basecourse layers each 200mm thick, and a surfacing of 120mm thick concrete segmental pavers. The pavers have a specified compressive strength of 49 MPa and are to be laid on a sand bedding 50mm thick.

5 Comparative Analysis of the Pavement

5.1 Pavement Model

This heavy duty pavement has been analysed using both the more commonly used mechanistic design approach using CIRCLY and a standard wheel load, and the new approach using HIPAVE. These two analysis methodologies have been compared to demonstrate the variation in findings between the two methods. In addition, design charts for heavy duty pavement design, prepared by the British Ports Federation (1986) have been used to compare this approach to pavement design with the mechanistic methods.

The pavement model comprises the previously described four-layer pavement structure, with the materials properties as described in Table 3.

Table 3 - Pavement Materials Properties

Layer	Description	E_h , MPa	E_v , MPa	ν	Thickness, mm
Surfacing	Concrete pavers	7,500	7,500	0.30	120
Basecourse	Unbound crushed rock	250	500	0.35	200
Sub Base	Unbound crushed rock	150	300	0.35	200
Subgrade (CBR 10%)	Select fill	50	100	0.25	infinite

5.2 Pavement Load Cases

Load Case A represents the typical loading from a Straddle Carrier operating along a Stack Runway. Load Case B represents the loading condition at the end of a Stack Runway where the Tractor/Trailer reverses into the end of the Stack and receives the container from the Straddle Carrier. Load Case C represents the loading from the Tractor/Trailers operating over the transfer zones adjacent to the Stacks.

The Straddle Carrier model used for the Comparative Analysis is the 3-high Kalmar ESC 340.

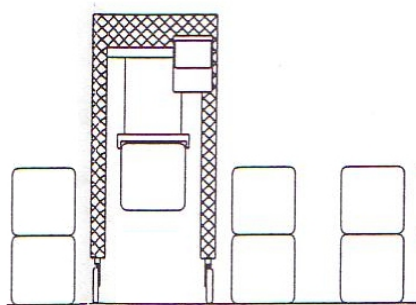


Figure 1 Load Case A: Straddle Carrier operating along a Stack Runway.

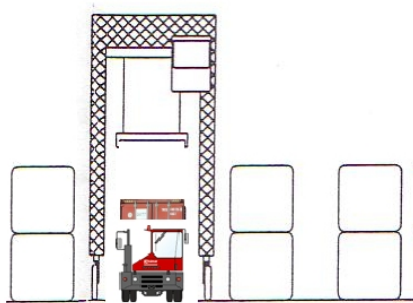


Figure 2 Load Case B: End of Stack Runway where Tractor/Trailer receives container from Straddle Carrier.



Figure 3 Load Case C: Tractor/Trailer operating over the open pavement areas adjacent to the Stacks.

The Master Study (2002) has provided container and general cargo predictions for the Port of Doha up to Year 2030 – 25 years from now.

Taking this into account, this Study states “...it is considered that ... the available land area should be sufficient to handle the projected container requirements up to Year 2030, providing that the port is operated at a reasonable level of efficiency”. Due to some uncertainties with the longer term predictions of cargo and container growth, a design life of twenty years for this pavement has been selected as being appropriate. This means that the pavement is expected to remain serviceable for twenty years as long as routine maintenance of the pavement is undertaken within its design life.

For a design life of 20 years and using the container throughput predicted for the terminal, as detailed in Table 2, the number of passes of each vehicle, for each load case, is given in Table 4.

Table 4 – Repetitions of Load

Load Case	Load Repetitions per year			
	Straddle loaded	Tractor/Trailer loaded	Straddle unloaded	Tractor/Trailer unloaded
A	17,290	0	6,650	0
B	17,290	17,290	6,650	17,290
C	0	17,290	0	17,290

5.3 HIPAVE Analysis

The Master Study (2002) determined that the average container weight for all imported containers is around 21 tonnes. Since Doha is primarily an import port, the majority (about 87%) of all exported containers are empties. Hence, for the assessment of the pavement, only imported containers need to be considered because of this unusual circumstance. The following distribution of container loads has been determined for the HIPAVE analysis:

Table 5 - Distribution of Container Loads.

Container weight, tonne	% of total
4.2	5.60
8.1	15.65
13.1	24.31
18.2	33.33
22.0	20.02
27.6	1.05
32.8	0.04

The Standard Deviation of Wander was assumed to be 500 mm for Cases A and B. For Case C The Standard Deviation of Wander was assumed to be 5000 mm.

6 Results

6.1 HIPAVE Analysis

Figure 4, Figure 5 and Figure 6 are the Subgrade Damage Factor “profiles” across the pavement, calculated for a pavement design life of 20 years. Note that X = 0 corresponds to the centreline of each vehicle.

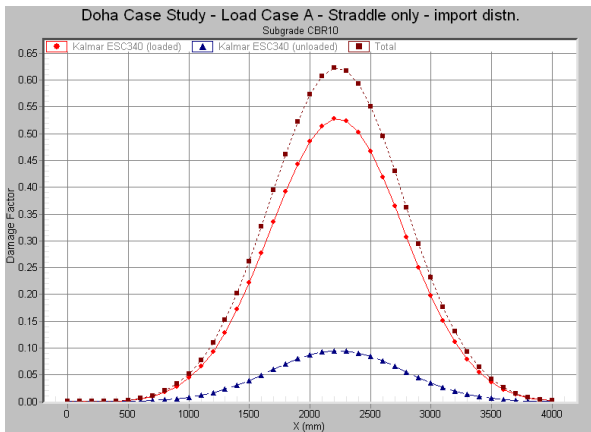


Figure 4 Load Case A: Subgrade Damage Factor vs distance across pavement.

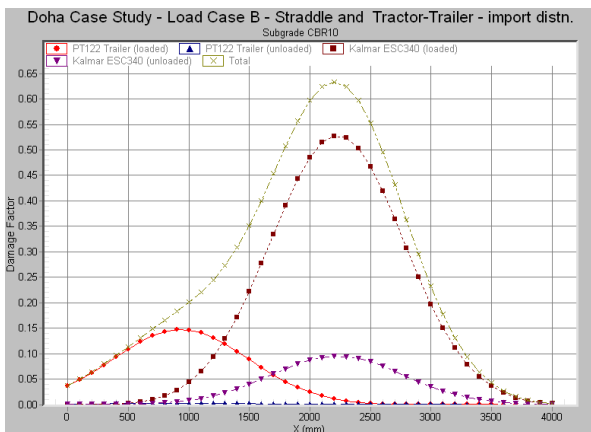


Figure 5 Load Case B: Subgrade Damage Factor vs distance across pavement.

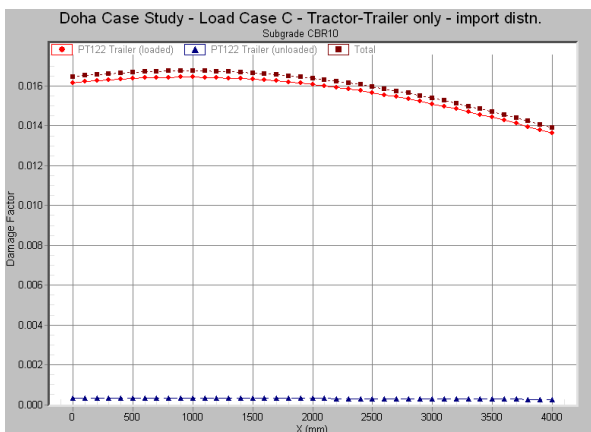


Figure 6 Load Case C: Subgrade Damage Factor vs distance across pavement.

HIPAVE can also generate graphs like Figure 7 that show the damage contribution from each container load.

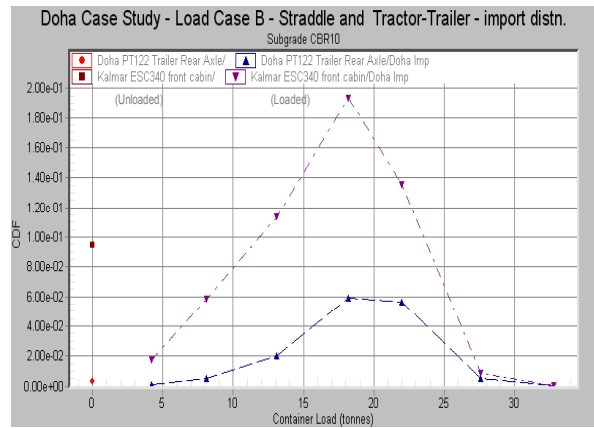


Figure 7 Sample graph of Damage Factor vs Container Load. (from Load Case B)

Applying the peak Damage Factor determined for Load Case B, of 0.64 for a 20 year design life (refer Figure 5), this translates to a design life at failure of 31 years for this pavement.

The pavement model used for the HIPAVE analysis is different to that used for the CIRCLY analysis.

Research has shown that empirical subgrade performance criteria developed for highway loadings such as Austroads (1992, 2004) are not applicable to the higher loadings typically applied to heavy duty pavements used at ports and container terminals (Wardle et al., 2003).

The material performance characteristics used in HIPAVE are based on calibrations developed from airport pavement research. There are a number of differences to the Austroads pavement model:

- the basecourse, sub-base and subgrade are assumed to be isotropic (Austroads assumes anisotropic)
- a different methodology (Barker and Brabston, 1975) is used to sublayer the basecourse and sub-base.

A preferred subgrade performance relationship for heavy duty pavements was developed by Wardle et al. (2001). This relationship was developed using a range of different aircraft with masses varying from 40 tonnes to 397 tonnes and subgrade strengths varying from CBR = 3 to CBR = 15.

The subgrade strains are converted to damage using a performance relationship of the form:

$$N = \left[\frac{k}{\varepsilon} \right]^b$$

- where
- N is the predicted life (repetitions of ε)
 - k is a material constant
 - b is the damage exponent of the material
 - ε is the load-induced strain (unitless strain)

The parameters k and b vary with subgrade modulus (E) in units of MPa as given by the following:

$$k = 1.64 \cdot 10^{-09} E^3 - 4.31 \cdot 10^{-07} E^2 + 2.18 \cdot 10^{-05} E + 0.00289$$

$$b = -2.12 \cdot 10^{-07} E^3 + 8.38 \cdot 10^{-4} E^2 - 0.0274 E + 9.57$$

Alternatively, the subgrade performance relationship from the British Ports Association guide (2nd Ed.) also has a sound basis for use in this instance.

The Damage Factor for the i-th loading is defined as the number of repetitions (n_i) of a given damage indicator divided by the 'allowable' repetitions (N_i) of the damage indicator that would cause failure. The Cumulative Damage Factor (CDF) is given by summing the damage factors over all the loadings in the traffic spectrum using Miner's hypothesis:

$$\text{Cumulative Damage Factor} = \sum \frac{n_i}{N_i}$$

6.2 CIRCLY Analysis

The Doha pavement was analysed using the guidelines set out in the British Ports Association Manual (Knapton & Meletiou 1996), using the Port Area Wheel Load (PAWL) as an equivalent wheel load on the pavement structure. The PAWL is a single 12,000kg load applied at a contact pressure of 800kPa. The range of container handling machines were each converted to their equivalent number of PAWLs, and the total number of PAWLs needed to reach failure of the pavement used to determine the design life of the pavement at the critically loaded location.

Using compression failure criteria for the subgrade based on a fatigue failure mechanism, the limiting subgrade strain is:

$$N = \left[\frac{21,600}{\mu\varepsilon} \right]^{3.57} \quad (1)$$

This failure criterion is considered to be better suited to the loading and failure of heavy duty pavements than the Austroads (2004) criterion of:

$$N = \left[\frac{9,300}{\mu\varepsilon} \right]^7 \quad (2)$$

where N = no. of load repetitions and $\mu\varepsilon$ is vertical microstrain at the top of the subgrade.

The number of repetitions of the PAWL for Load Cases A, B and C, and the corresponding vertical strains determined by CIRCLY at the top of the subgrade, are:

Table 6 – CIRCLY Analysis

Load Case	PAWL Repetitions	$\mu\varepsilon$, microstrain	Pavement life, years
A	45,430	382	40
B	55,390	382	33
C	12,725	382	142

The controlling design life determined for Load Case B is therefore 33 years.

6.3 Design Charts Analysis

The British Ports Federation Manual (1986) provides a comprehensive set of design charts for determining the equivalent pavement layer thicknesses for the applicable design load. They have been specifically developed for heavy duty pavement design.

These charts have been developed for the typical British practice of using either a lean concrete or granular basecourse over granular sub-base for heavy duty pavement construction. Utilising the specific chart for subgrade CBR of 10% and concrete segmental pavers for the surfacing, a granular sub-base of 200mm thickness requires a granular basecourse of 200mm thickness, to have a design life of 20 years.

It is apparent therefore, that these design charts provide a more conservative solution to the pavement structure in this instance, and the other mechanistic methods achieve a longer design life for the same pavement structure.

7 Summary

The tools available to the designer for heavy duty port and container terminal pavements continue to improve, and HIPAVE is shown to provide a more accurate design outcome than previously available multi-layer elastic design applications, and is certainly a substantial improvement on chart-based design methods.

This will lead to more economic heavy duty pavement designs, benefiting clients and providing sustainable design solutions.

8 References

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