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HIPAVE – A Tool to assist in the Mechanistic Empirical Design of Heavy Duty Industrial Flexible Pavements

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ABSTRACT: Considerable international research is conducted to improve the characterisation of the fundamental performance of asphalt and other pavement materials to increase confidence in the prediction of pavement performance. The HIPAVE (Heavy Industrial PAVEment) layered elastic software program conveniently models the effects of detailed payload distributions (spectrum of container weights) by calculating axle loads from vehicle configurations and payloads, also with provision for vehicle wander. HIPAVE handles the variety of equipment used in container facilities, such as forklifts, straddle carriers, gantry cranes and side loaders. The library of vehicle properties can be automatically updated from the HIPAVE webserver. It is the authors' view that a purely mechanistic pavement design approach is not yet feasible, without constant reference to vital empirical benchmarks. The HIPAVE package is designed to enable the user to modify any of the design assumptions to reflect empirical observations. The authors caution against the imprudent implementation of design assumptions derived from highway research into industrial pavement designs. Industrial pavements are typically subjected to loading of an order of magnitude greater, making it necessary, for example, to use a different subgrade performance model. As contractors involved in the design and construction of heavy duty industrial flexible pavements the authors observed the absence of a published holistic approach to design that incorporated modern computer software. This fostered the preparation of the Heavy Duty Industrial Pavement Design Guide to assist users of the HIPAVE software, permitting advances in a mechanistic design approach. The Guide presents the authors' attempts to reflect best practice in the design of new construction and rehabilitation of industrial pavements. The Guide steers the designer through key design considerations and suggests external sources for research updates. It is intended to be supplementary to other published design guides with a focus on industrial pavements. The Guide is a 'living document' that will be routinely modified to reflect advances in pavement technology and made freely available via the Internet. It is the authors' goal to preserve the relevance and currency of the Guide by in-house research and development and continuous liaison with international experts in pavement technology.

KEY WORDS: Heavy duty, industrial, container, asphalt, ports.

1 INTRODUCTION

Design methods for highway pavements, such as that presented in the Australian Austroads Pavement Design Guide (2004) are not directly applicable to the design of heavy duty pavements for use by heavy 'off-road' vehicles in applications such as ports and container terminals.

Traditionally, heavy duty pavements such as port pavements have been designed using purely chart-based, empirical processes such as the British Ports Association method (British Ports Association, 1996). The BPA method involves combining the full range of vehicles and shipping containers into a single number of repetitions of an ‘equivalent standard wheel load’.

Over the last decade or so, designers have modeled the actual wheel layouts of vehicles in layered elastic design using tools such as CIRCLY (Wardle, 2004) and APSDS (Airport Pavement Structural Design System) (Wardle, 1999).

While CIRCLY and APSDS have been used very successfully for the design of heavy duty industrial pavements, unwieldy data input makes it very difficult to model more than one or two payloads per vehicle.

This paper describes HIPAVE (Heavy Industrial PAVEment design) - an outgrowth of CIRCLY and APSDS. HIPAVE has been designed to handle comprehensive details of the freight handling vehicles and the characteristics of the payload distribution for each vehicle, facilitating easy analysis of the effects of a spectrum of different container loadings.

In the following sections we give an overview of the capabilities of HIPAVE and an outline of the proposed new design Guide, specifically relating to recommended material properties for modeling heavy duty pavements.

2 HIPAVE OVERVIEW

HIPAVE is an outgrowth of the well-established multi-layered elastic design tools for pavement design, CIRCLY and APSDS.

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, which can reduce the likelihood of costly overdesign. 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.

While CIRCLY and APSDS have been used very successfully for heavy duty industrial pavements, unwieldy data input makes it very difficult to model more than one or two payloads per vehicle. HIPAVE has been designed to conveniently handle comprehensive details of the freight handling vehicles and the characteristics of the payload distribution for each vehicle, as a function of a container weight spectrum, again to minimise the possibility of costly overdesign or at least enable easy sensitivity analysis. 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 also includes advanced features that were first introduced in CIRCLY 5.0. A Parametric Analysis feature can loop through a range of thicknesses for one or two layers, while simultaneously designing the thickness of another layer. This feature will optimise up to three layers. Combining this with a Cost Analysis feature, allows for fine-tuning of layer thicknesses to minimize construction and maintenance costs. HIPAVE does a full spectral analysis of pavement damage by using the cumulative damage concept to sum the damage from multiple vehicle models and payload cases.

The procedure takes account of:

- the design repetitions of each axle of each vehicle model/payload combination; and
- the material performance properties used in the design model.

This approach allows analyses to be conducted by directly using a mix of vehicle models. It is not necessary to approximate passes of different vehicles or axles to passes of an 'equivalent' standard load or "design vehicle", rather the details of the actual machines can be used.

Figure 1 is a sample cumulative damage plot produced by HIPAVE:

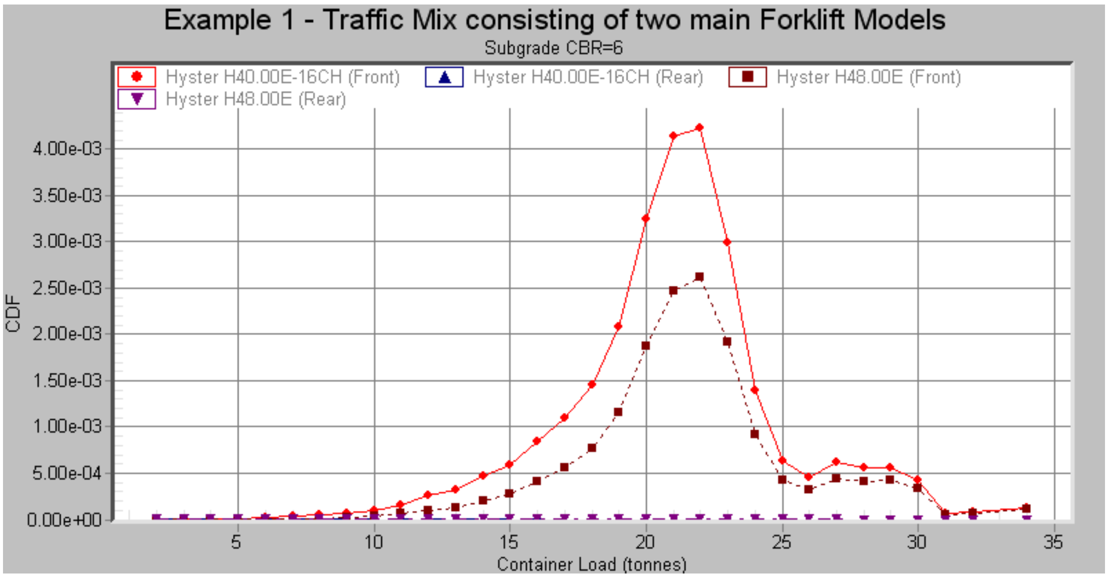

Figure 1: HIPAVE graph - Subgrade Damage Factor vs. container load.

Note that on this "Spectral Damage Graph" there is a data point for each combination of vehicle model and payload – in this example the container weight distribution was specified at an interval of one tonne.

HIPAVE can also generate graphs that show the variation of the damage factor across the pavement, as shown by Figure 2:

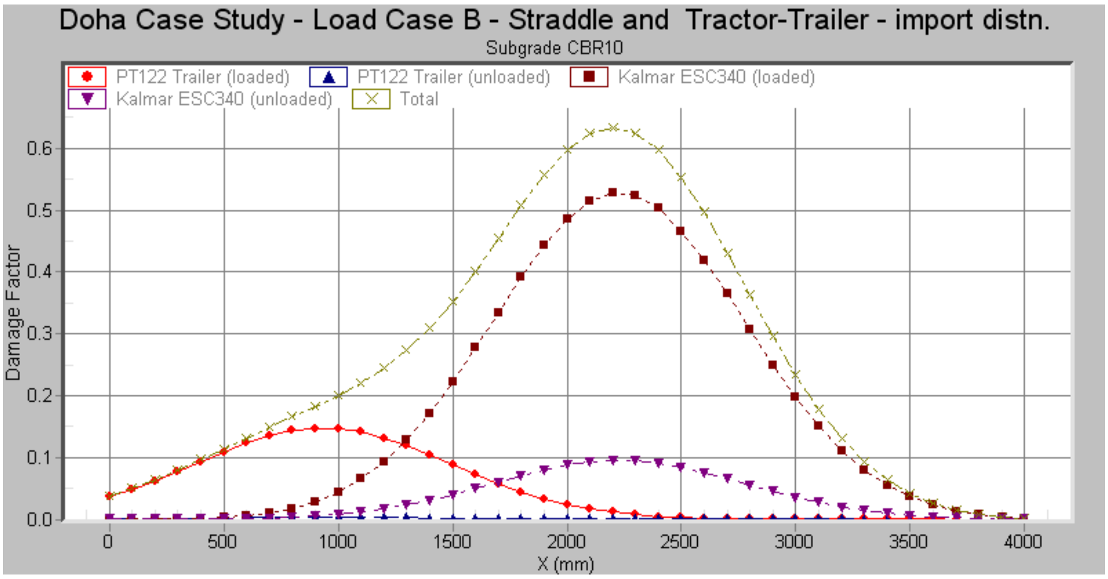

Figure 2: HIPAVE cumulative damage graph - Damage Factor vs. lateral position.

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.

For vehicles that typically have unequal loads on each axle such as Fork Lifts, the vehicle loading characteristics are specified in terms of two load cases that express the axle loads as a function of Container Weight. For example this could be the Unladen case together with one specific Container Weight. Figure 3 illustrates the concept. Axle loads for other container weights are obtained automatically by linear interpolation.

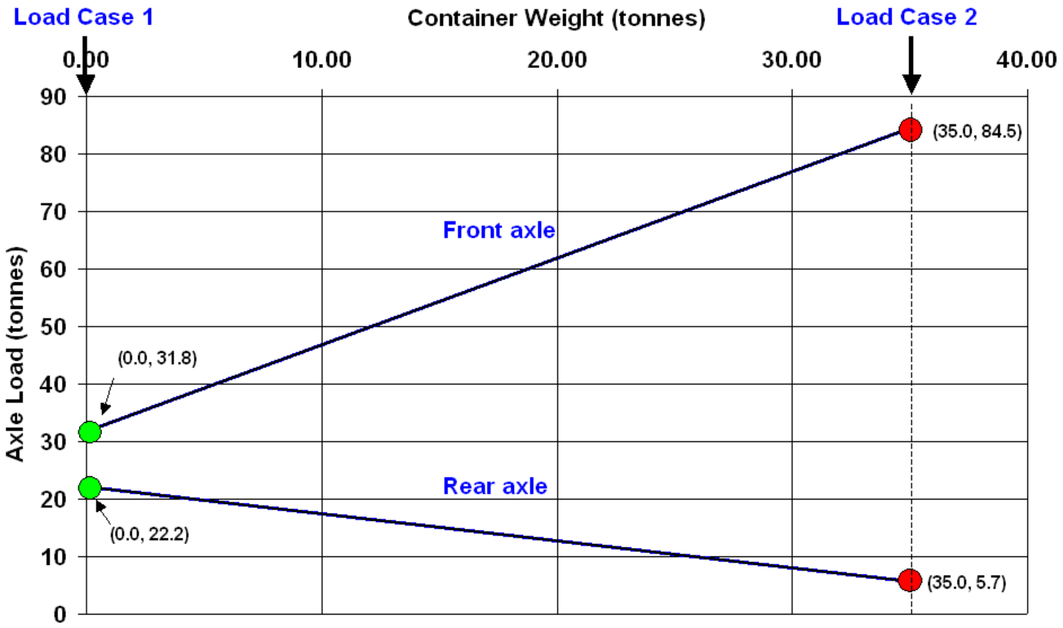

Figure 3: Vehicle loading characteristics for Fork Lift.

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

Although HIPAVE was just released in September 2005, it has already been used to design a major container terminal project — the Crawford Street intermodal container handling facility in Hamilton, New Zealand (Wardle et al., 2005).

3 ASPHALT MIX PERFORMANCE MODELING

3.1 Empirical background

Flexible granular pavements with asphalt surfacing have provided good performance on many Australian wharves and other industrial facilities over periods in excess of 25 years. Generally the better performing pavements comprise ≥150 mm asphalt surfacing over thick unbound granular basecourse layers. In some locations (e.g. Melbourne) the subgrade comprises very weak saturated silty clay. In other locations (e.g. Sydney and Brisbane) the subgrade has been covered by a significant thickness of hydraulically placed sand. Use of conventional (highway based) material performance models has been found to substantially underestimate their strength. Under a laden straddle carrier in Melbourne the models suggest deflections exceeding 5mm whereas deflection measures by precise leveling were less than 2 mm.

The implication of this observation is the need to verify as best possible the assumptions used in the design analyses and deflection testing is recommended. The stiffness of the foundation supporting asphalt and bound materials has a profound impact on performance.

The authors have rarely observed fatigue failures in asphalt layers of ≥150 mm on sound granular base and the usual mode of failure is deformation within the asphalt layer in channelised wheelpaths, and crushing failure (and subsequent water damage) under container corner castings. Fatigue is however common in industrial pavements with thin asphalt surfacings.

Deformation has often followed a change in facility operations from front loaders to the more highly channelised straddle carriers, and is generally an asphalt mix design issue. Corner casting damage to asphalt is inevitable under modern multiple stacking operations and demand different products, for instance the generic resin modified asphalt, if damage cannot be tolerated. This will be the case for instance under proposed automated container handling and random stacking arrangement.

The rare occurrence of asphalt fatigue in ≥150 mm asphalt layers and deformation due to base or subgrade shear failure provide empirical evidence that the flexible pavements built historically in Australia are structurally adequate and any significant departure should be treated cautiously.

3.2 Asphalt mix performance characterisation

Advances in asphalt technology have significantly enhanced our ability to measure performance related properties for use in pavement thickness design analyses. In recent times the utilization of the Simple Performance Test (SPT) apparatus referred to in NCHRP Report 465 has provided a step improvement in performance characterisation, providing the ability to measure the performance of candidate asphalt materials over the full spectrum of temperature frequency and loading conditions, in terms of stiffness and deformation parameters.

For design purposes candidate asphalt materials would ideally be subjected to SPT characterisation and master curves developed. As described elsewhere (Rickards et al., 2006) the use of master curves permits the rational optimisation of mix properties balancing performance and cost benefits. An example of a master curve of a fine graded mix with all crushed aggregate using straight run Class 320 (50–60 pen) bitumen is shown in figure 4. In this case the master curve is normalized to a load frequency 5 Hz (load duration 0.2 second) equivalent to a load under a straddle carrier traveling at about 10 KPH.

The dynamic modulus is insensitive to confining stress up to about 25^{o}C as is strongly influenced by the binder properties. Above this temperature the degree of confinement has a significant impact and this is believed to reflect the mobilisation of the strength of the aggregate skeleton.

At extreme temperatures a tendency toward asymptotic values is observed. Marchionna et al. (1987) support this empirically and their field study of asphalt modulus back calculated from deflections taken at high temperature suggests the asymptote is in the range of 1-2 GPa, consistent with the SPT data. Marchionna suggests this value, higher than commonly assumed, is due to the confining pressure in the field. It certainly has significant implications in thickness design.

Practitioners will note the value of the dynamic modulus is significantly higher than that derived using the (unconfined) indirect tensile test and beam-flexure. It is believed the SPT mode of loading (axial compression) more faithfully represents field loading, especially in the confined state.

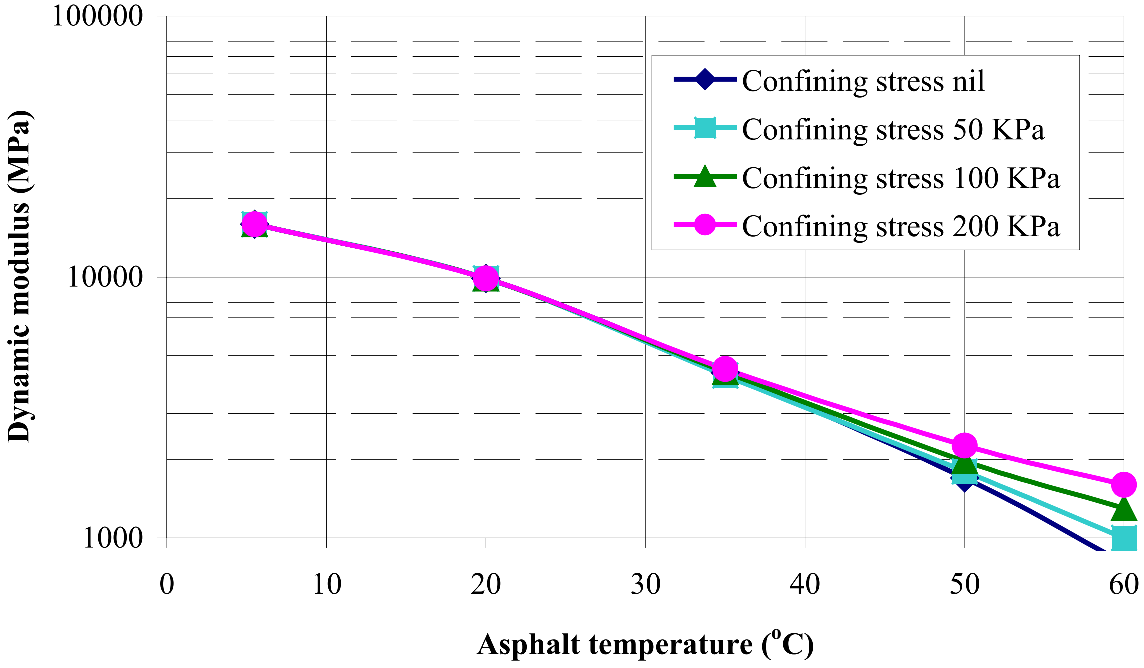

Figure 4: Typical asphalt master curve at 5 Hz load frequency (0.2 second load duration)

3.3 Asphalt modeling in structural thickness design

HIPAVE facilitates the compilation of the spectral damage due to the diverse loading mass and configuration at industrial facilities. The spectrum of damage as a consequence of changes in pavement material properties due to environmental conditions must also be evaluated. Freeze thaw conditions and changing moisture content may affect the stiffness of granular components in the base and subgrade and analyses at values representing the seasonal conditions must be conducted and the damage summed. At the conclusion of these analyses the pavement life may be described in terms of passes of a notional standard vehicle for further comparison of design life evaluated using the mix properties across the full temperature spectrum, not simply at a weighted mean value.

Asphalt stiffness varies significantly with diurnal and seasonal temperature fluctuation. Planned future developments in HIPAVE will see the incorporation of routines that draw on master curve data to model asphalt properties over the full temperature / loading spectrum. Historically in Australia, we have tended to adopt the “weighted” mean annual pavement temperature (WMAPT) concept and adopt a unique design modulus that will theoretically (and yet often improbably) provide a design life equivalent to that estimated over the spectrum of traffic and temperature. In current normal practice asphalt properties are measured at only one temperature and rate of loading and the change in mix properties over the climatic spectrum are estimated using empirical models. These are unlikely to adequately reflect the actual performance of potentially more innovative materials.

In the interim it is proposed that more realistic modeling can be achieved manually utilising the master curve of the type of asphalt intended for use on the project. The dynamic modulus from SPT characterisation can be adequately modeled mathematically by a polynomial function as a function of temperature and load duration. The climatic data for the project site may be assembled and pavement temperature data estimated and assembled in appropriate temperature “bins”. The traffic distribution relative to each “bin” may be estimated to define the estimated loading / temperature spectrum. If exact data is unavailable, then HIPAVE can at least be utilized to perform an easy sensitivity analysis.

Analyses of the asphalt pavement structure at the modulus values appropriate to each temperature condition may then be carried out under the notional standard vehicle and the cumulative damage summed. If significant variation is observed (i.e. CDF >> or << 1) compared with the initial design the pavement configuration may be modified either to ensure its capacity to survive the design loading or to reduce costs.

3.4 Practical application of new asphalt technologies

In practical application a two-phase approach should be adopted. In the second phase the design assumptions can be verified prior to construction by subjecting plant mix samples to SPT characterisation and permit design modification if needed.

It is the authors' opinion that the SPT is a design tool and its use as a construction compliance-testing tool is not appropriate at this stage. Once satisfied the production mix has the desired properties regular audit testing may ensure mix performance achievement; i.e. audit to ensure consistent volumetric proportions, aggregate properties, binder properties, and compaction compliance.

4 SUBGRADE AND GRANULAR BASE MATERIAL MODELLING

HIPAVE is an open system that will accommodate material properties and transfer functions for any pavement design methodology. It is intended that current pavement materials research will be monitored and the HIPAVE manual will be routinely upgraded as further performance data becomes available.

Research has shown that highway pavement design methods such as Austroads (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 recommended for use 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 performance relationship was established by calibrating pavement designs using APSDS against designs based on the US Army Corps of Engineers CBR method (Method S77-1, Pereira, 1977). The 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.

There is considerable relevant heavy load data coming available from the US National Airport Pavement Test Facility (NAPTF) (http://www.airporttech.tc.faa.gov/naptf/). This full scale loading trial on a range of pavement and subgrade compositions, under B747 and A380 gear configurations, has already provided further empirical performance benchmarking. Preliminary analysis has shown that the preferred subgrade performance relationship for heavy duty pavements mentioned above is broadly consistent with the NAPTF results.

The importance of appropriate modeling for granular base materials cannot be over emphasised. Repeated Load Triaxial testing as a means of assessing more realistic pavement moduli under heavy vehicle loading, in a similar vein to SPT discussion above, is certainly warranted on major projects.

The examination of empirical performance records of similar facilities is an extremely prudent activity.

BOUND BASECOURSE LAYERS

Caution is advised on the reliance on highly bound (cement / hydraulically) base layers because of the uncertainty in the design models. The sophisticated layer optimisation routines in HIPAVE are only as reliable as the nominated damage model. South African research using the Heavy Vehicle Simulator (HVS) is possibly the most comprehensive and the designer is referred to Theyse (1996). This work suggests a three-phase deterioration; crack initiation at relatively low strain; crack progression as a function of layer properties; and finally crushing. The residual strength of the base is a function of the quality of the aggregate and the degree of saturation and is only a fraction of the initial strength. In an industrial facility the time demanded for rehabilitation of a deep-seated loss of strength may be prohibitive.

The designer should keep in mind the consequence of failure and the relative ease of rehabilitation. With a granular base layers failure is most often manifest as a loss of shape, generally without significant loss of stiffness, which may then be rehabilitated by superficial treatment, e.g. profile and replacement.

5 HEAVY DUTY INDUSTRIAL PAVEMENT DESIGN GUIDE

As contractors involved in the design and construction of heavy duty industrial flexible pavements the authors observed the absence of a published holistic mechanistic approach to design.

The British Ports Association Design Guide (British Ports Association, 1996) is a purely chart-based, empirical procedure. The methodology was 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 needed. The BPA Guide does not cater for the use of modern computer software such as layered elastic analysis.

The American Society of Civil Engineers (ASCE) has been developing a Port and Intermodal Yard Pavement Design Guide. The Guide has not yet been published, but a paper outlining the guide was published in 2001 (Smallridge and Jacob, 2001). The design methodology does encourage the use of modern software such as layered elastic analysis, but is based on a "design wheel load" concept. This contrasts with the approach taken with HIPAVE where the full load spectrum is conveniently and accurately handled.

The present authors are preparing the *Heavy Duty Industrial Pavement Design Guide* to assist users of the HIPAVE software (Rickards et al, 2006). The Guide presents the authors' attempts to reflect best practice in the design of new construction and rehabilitation of industrial pavements. The Guide steers the designer through the key design considerations and suggests external sources for research updates. It is intended to be supplementary to other published design guides with a focus on industrial pavements. The Guide is a 'living document' that will be regularly updated to reflect advances in pavement technology and made freely available via the Internet at no charge. It is the authors' goal to preserve the relevance and currency of the Guide by in-house research and development and continuous liaison with international experts in pavement technology.

6 DISCUSSION AND CONCLUSIONS

HIPAVE does a full spectral analysis of flexible pavement damage by using the cumulative damage concept to sum the damage from multiple vehicle models and payload cases, allowing for vehicle wander. The procedure takes account of the effect on the pavement of the design repetitions of each vehicle model/payload combination; and the material performance properties used in the model.

HIPAVE is an open system that will accommodate material properties and transfer functions for any pavement design methodology. Much care needs to be taken in formulating layered elastic model properties. Recent airport pavement research supports using models that are significantly different from those used for highway pavement design.

Significant international research is being undertaken to improve our knowledge of pavement and pavement material performance. It is a truism that the quality of the output from any design package is only as good as the input.

The authors stress the need to verify the design assumptions wherever possible against empirical performance data. In this regard the data from the US National Airport Pavement Test Facility (NAPTF) will facilitate evaluation of the flexible pavement components under extreme loads. Many experts in the field are working on these analyses and their results will be monitored and incorporated when and if improved accuracy is established. The asphalt dynamic modulus test is considered to be of significant value not the least because it will facilitate access to the considerable field performance validation being undertaken in the US.

HIPAVE provides a more accurate design outcome than previously available multi-layer elastic design applications, and is certainly a substantial improvement on chart-based design methods.

Designers are urged to be very cautious about moving too far away from designs proven in field practice notwithstanding the data generated by design packages. The great beauty of the HIPAVE package is that it facilitates the rapid assessment of design sensitivity, e.g. what is the design consequence of variation in the assumptions of material or loading conditions? Experience suggests the level of uncertainty in many material assumptions far outweighs uncertainty in traffic estimates.

HIPAVE automates a sophisticated spectral analysis to model the loading regime. Modeling the climatic and environment regime is equally significant and a manual process is offered in the interim to exploit the improved asphalt materials characterisation using the SPT. A future version of HIPAVE will have have a routine to automate this process.

HIPAVE, combined with careful choice of materials and design parameters will lead to more economic heavy duty pavement designs, benefiting clients and providing sustainable design solutions.

The *Heavy Duty Industrial Pavement Design Guide* is being developed by the authors to assist users of the HIPAVE software. The Guide will evolve to reflect best practice and research in the design of new construction and rehabilitation of industrial pavements.

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