HIPAVE – A MECHANISTIC DESIGN TOOL FOR HEAVY-DUTY INDUSTRIAL PAVEMENTS

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ABSTRACT

HIPAVE (Heavy Industrial PAVEment design) is for the mechanistic analysis and design of flexible pavements subjected to the extremely heavy wheel loads associated with freight handling vehicles in industrial facilities, in particular, intermodal container terminals. HIPAVE is an outgrowth of CIRCLY and APSDS (Airport Pavement Structural Design System). HIPAVE does a full spectral analysis of pavement damage by using the cumulative damage concept to sum the damage from multiple vehicle models and payloads.

HIPAVE can expedite pavement design projects with these unique features:

- ☐ a standard vehicle library - that can be automatically updated via the Internet;
- ☐ ability to define and store container weight distributions;
- ☐ automatic calculation of axle loads from vehicle geometry and container weight;
- ☐ user defined material performance properties (stiffness and transfer functions).

This paper presents the development and advantages of using HIPAVE, over simpler layered elastic tools and empirical chart based methods, to design pavements. HIPAVE has been used for the design of the Crawford Street intermodal container handling facility in Hamilton, New Zealand. This design was complicated by a weak subgrade and height restrictions for the pavement surface. This Crawford Street example demonstrates the efficiencies for designers offered by HIPAVE and the enhanced ability to consider options and conduct ‘what if’ analyses.

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.

Traditionally, port pavements have been designed using purely chart-based, empirical processes such as the British Ports Association method (British Ports Association, 1996). 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 (Wardle, 2004) and APSDS (Airport Pavement Structural Design System) (Wardle, 1999).

Alternatively, many designers prefer to use the actual wheel layouts of the vehicles and these can be used directly in CIRCLY and APSDS.

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 conveniently handle comprehensive details of the freight handling vehicles and the characteristics of the payload distribution for each vehicle.

Commencing in 2004, MINCAD Systems has released a number of trial versions of HIPAVE. HIPAVE 5.0 was commercially released in September 2005.

In the following sections we give an overview of the capabilities of HIPAVE and an outline of the recommended material properties for modelling heavy duty pavements. These capabilities are illustrated by a Case Study - the design of the Crawford Street intermodal container handling facility in Hamilton, New Zealand. This Crawford Street example demonstrates the efficiencies for designers offered by HIPAVE and the enhanced ability to consider options and conduct ‘what if’ analyses.

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. 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. 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:

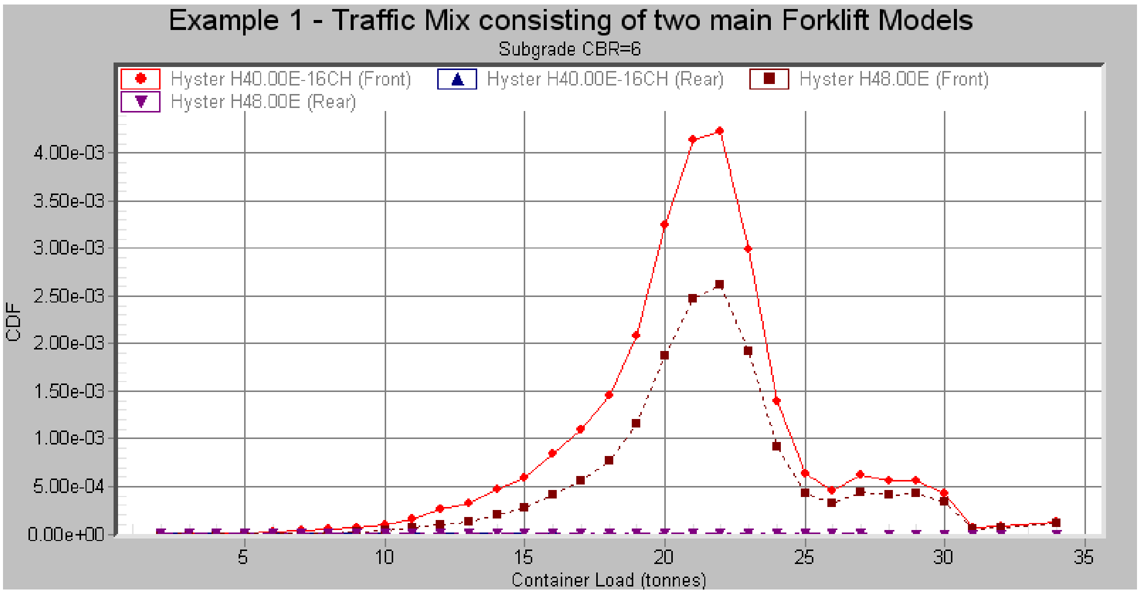

Figure 1: HIPAVE graph - Subgrade Damage Factor vs. container load.

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:

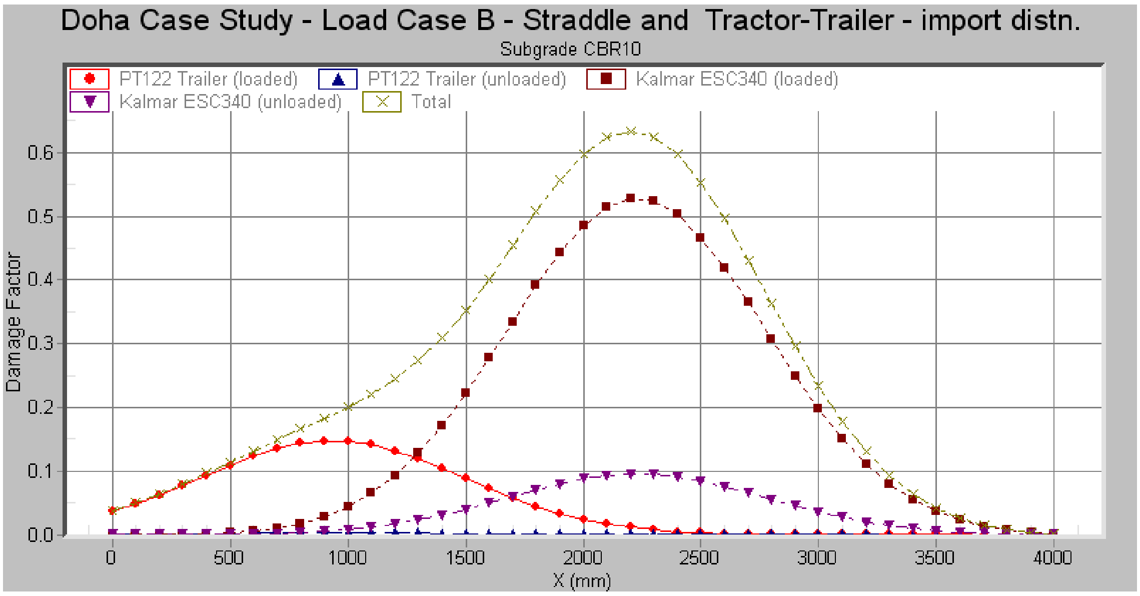

Figure 2: HIPAVE cumulative damage graph - Damage Factor vs. lateral position.

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.

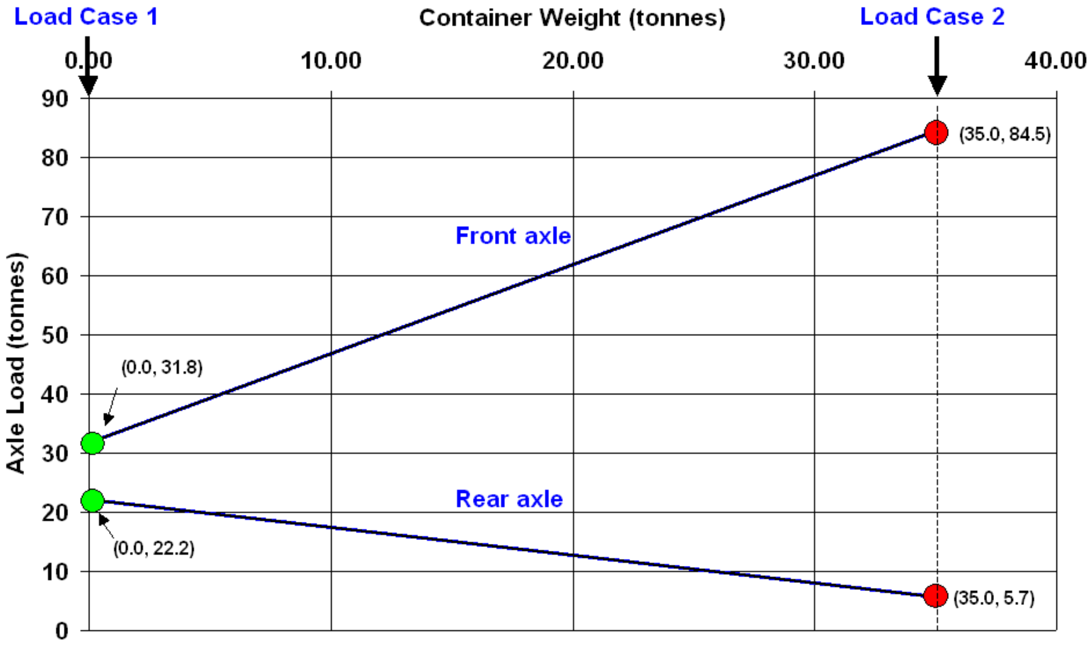

Figure 3: Vehicle loading characteristics for Fork Lift.

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

PAVEMENT LAYER MODELLING FOR HEAVY LOADS

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 (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). 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/). Performance data from full scale loading trial on a range of pavement and subgrade compositions, under B747 and A380 gear configurations, will provide further empirical performance benchmarking.

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.

Figure 4 gives the details of the sublayering for the Unbound Granular Layers according to Barker and Brabston (1975)

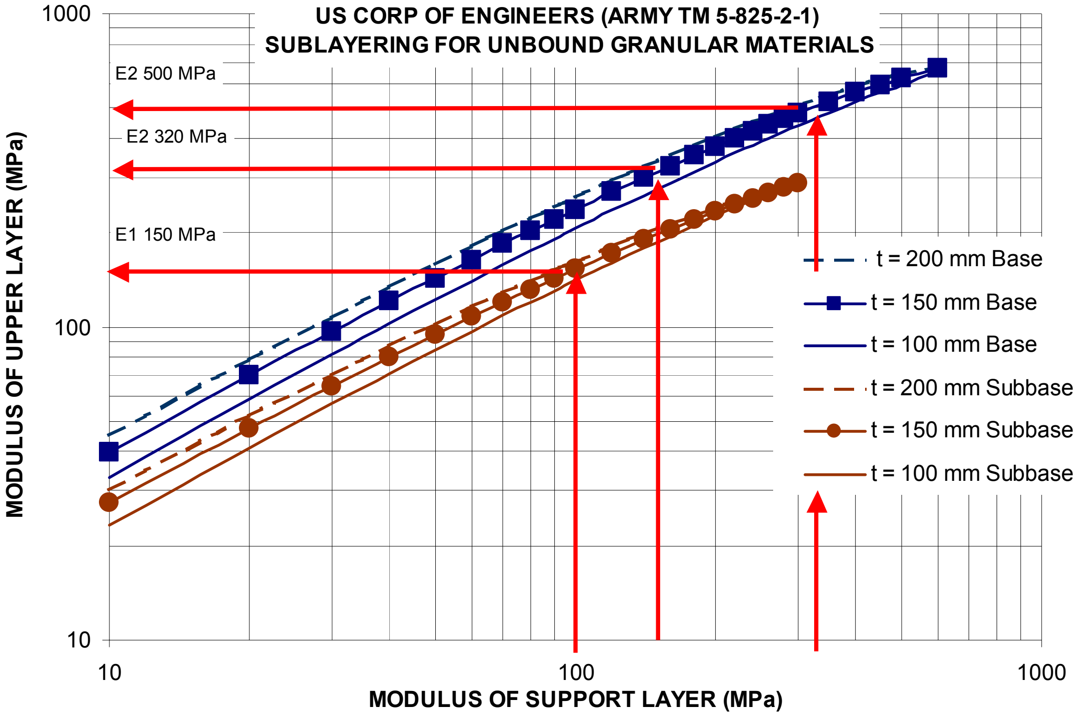

Figure 4: Sublayering of Unbound Granular Layers (after Barker and Brabston, 1975)

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.

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:

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

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

Figure 5 shows this relationship for a range of subgrade stiffnesses. The current Austroads (2004) relationship is also plotted for comparison, showing that the Austroads overestimates the allowable repetitions by many orders of magnitude.

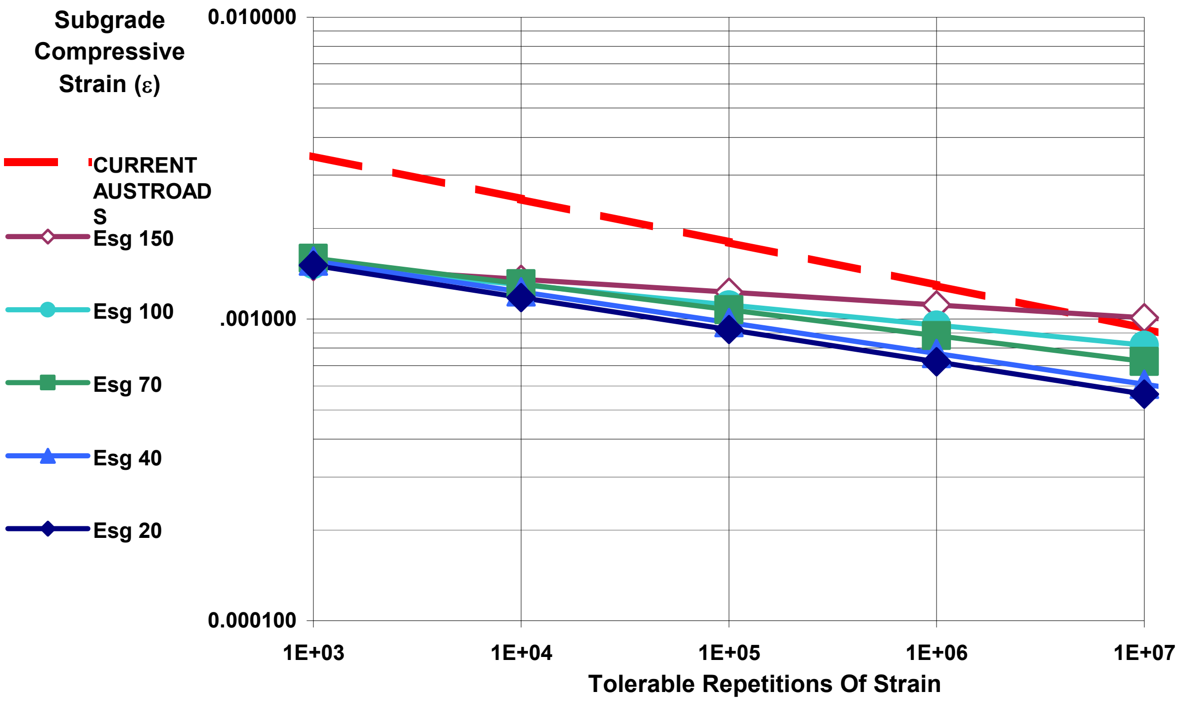

Figure 5: Subgrade performance relationship after Wardle et al, (2001)

The importance of appropriate modelling for granular base materials cannot be over emphasised. Nor can the examination of empirical performance records.

History over a period of 25 years and more in Australian port facilities has shown that moderately thick (150+ mm) asphalt surfacing has provided excellent service under heavy front loader and other container handling equipment. Generally, provided this depth of asphalt exists, damage has been superficial and associated with highly channelised traffic (straddle carriers and Intermodal Transfer Vehicles ITV's) and container corner casting damage. The former is rectified by enhanced mix design methods and the use of modified binders. The latter requires more robust design solutions and the reader is referred to the following section on resin modified surfacing treatments.

The observation of subgrade shear failure in these pavements is relatively rare i.e. no sign of significant surface heaving remote from the wheelpaths. Rutting is most commonly confined to the wheel path and when evident the proximity of heaving suggests the failure is due to plastic flow in the asphalt under extreme loading. Asphalt fatigue failure generally tends to be associated with shape loss, so the observer must often speculate whether the fatigue followed or preceded base failure. In the authors experience the damage caused by container corner castings (i.e. crushing and disintegration), by mechanical abrasion or punching provides an avenue for water ingress leading to potential saturation at the top of the granular layer reducing the strength of support and accelerated asphalt fatigue. The resistance to crushing damage is of course increased with the thickness of the asphalt surfacing and it is concluded this in part explains the superior performance of thicker asphalt layers.

The empirical evidence suggests that the high stress state under container facility loading result in high modulus values for the unbound granular base layers. Accordingly the layer modulus values nominated in the Barker Brabston (1975) methodology appear valid.

Bound Basecourse Layers

Caution is advised on the reliance on highly bound base layers because of the uncertainty in the design models. South African research using the Heavy Vehicle Simulator (HVS) is possibly the most comprehensive and the designer is referred to the paper by 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 which may be rehabilitated by superficial treatment e.g. profile and replacement.

Asphalt Materials Characterisation and Modelling

Asphalt research in Australia over the past 15 years has resulted in an improved confidence in the modelling of asphalt materials. There are two key performance parameters used in modelling – the stiffness modulus and resistance to fatigue cracking (tolerance of tensile strain repetitions).

The measure of the asphalt modulus is obtained using the Indirect Tensile Test (ITT), typically at 25°C and about 100 ms (millisecond) loading time. A measure of the fatigue performance is obtained by flexure testing, typically at 20°C and 10 Hertz frequency (100 ms load duration). It is clearly recognised by practitioners that these test conditions cover only a small fraction of conditions in the field where

- mix stiffness due to mix temperature fluctuation and load duration will vary by more than an order of magnitude diurnally and seasonally
- mix stiffness due to mix curing / ageing may increase 5 fold over life
- mix testing is on unconfined samples and is strongly influenced by the tensile properties of the mix and the effect of the aggregate skeleton is minor

Notwithstanding this work has been extremely valuable and has established that the predictive models incorporated in Austroads (Shell derived) are quite conservative. The application of this research into pavement design practice has been limited to the increased confidence in the use of the models rather than the adoption of measured parameters. In major part this has been because of the difficulty in verifying and calibrating laboratory performance measures with field performance observations.

In order to identify asphalt mix testing procedures that more accurately characterise field performance the US FHWA sponsored research to evaluate the full suite of asphalt tests to full-scale field trials at Westrack, Mn/ROAD and the FHWA Accelerated Loading Facility ALF. The research and conclusions are published in NCHRP 465 (Witczak et al). The dynamic modulus (E*) test was found to give the best laboratory field performance correlation. The Australian company IPC Global successfully manufactured and commissioned the so-called Simple Performance Test (SPT) equipment.

Internal research is proceeding using the SPT to characterise our asphalt materials. The dynamic modulus test is conducted in a triaxial cell, with or without confining stress, using a sample notionally 100 mm diameter by 150 mm high. The axial Loading is applied in a sinusoidal waveform at 5 frequencies between 0.1 and 25 Hz. Testing is completed at four temperature conditions; 5°, 20°, 35°, and 50°C. This process provides a complete picture of the mix properties over the range of environmental conditions.

There are many important observations coming from this research. The SPT dynamic modulus E* substantially exceeds typical ITT measures. At similar temperature and load duration conditions a conventional AC 14 Class 320 mix records E* in the order of 9,000 MPa. This variation is explained by the fact the ITT modulus is significantly affected by the tensile properties of the mix and underestimates the compressive strength of the aggregate skeleton mobilised under traffic. Once the master curve is developed a spreadsheet procedure enables the instant calculation of E* at any combination of temperature and load duration.

Of particular relevance is the influence of sample confinement on E*. Under loading at high temperature and/or long load duration, the confining effect of surrounding material in the field (and pneumatic pressure to 200 KPa in the triaxial cell) constrains transient strain and results in higher E* values. Initial studies indicate this results in a 4 – 5 fold increase in the stiffness mobilised in the mix. It is noted this observation is consistent with a number of field estimates of asphalt stiffness based on deflection analysis.

The Dynamic Shear Rheometer (DSR) test is conducted on bituminous binders over a similar temperature / frequency range to that applied in the SPT test. The DSR shows the elastic properties of conventional binders reduce as load duration and temperature increase i.e. the phase angle increase to near 90°. Conversely polymer modified materials can exhibit a reversal of the increase in phase angle as the elastic properties of the base bitumen diminish and the elastic properties of the polymer begin to dominate. A similar trend is observed in asphalt mixes as the more elastic properties of the aggregate skeleton begin to dominate. The combination of SPT and DSR studies will ensure a better understanding of the contribution of all components to the performance of novel asphalt materials.

It is intended that in time HIPAVE will be enhanced to use the input from SPT to facilitate the cumulative effect of damage as a function of material property changes with age, loading time and temperature.

Resin Modified Pavement to Resist Corner Casting Damage

Experience has shown that all asphalt materials will, sooner or later, suffer considerable damage as a consequence of crushing under the extreme static loads of container corner castings that could exceed 25 MPa with modern facility practice having container five high container stacks, or more in some facilities.

A range of products has been manufactured over many years under the under the generic title of Resin Modified Pavement (RMP) for instance Anderton (1996). This concept has been developed and the properties enhanced in the PRS RIGIPHALTE™ product. Testing in the SPT apparatus confirms extremely high E* and elasticity. The phase lag observed confirms field observations that the bituminous material provides some viscous response that permit strain relaxation and inhibits cracking. Experience over more than 3 years under extreme loading confirms the high crushing resistance offered by the product. Flexure testing of the product provides design limits and it is concluded the application of the PRS RIGIPHALTE™ product on appropriately designed pavement structures will offer good performance.

Figure 6: Static loads from container corner castings can exceed 25 MPa.

CASE STUDY – CRAWFORD STREET FREIGHT VILLAGE

Terminal Operations

The Crawford Street Freight Village is to be an inter-modal container yard primarily for the movement of containers of dairy products for export. Located just south of the city of Hamilton, in New Zealand, the Crawford Street development is in the heart of the Waikato – New Zealand's largest dairy farming region. The development is equidistant from the Port of Auckland and the Port of Tauranga so encouraging fast and flexible access to shipping.

Some 20 hectares are being developed for freight storage, handling and distribution for the owners of the freight village, New Zealand's giant dairy co-operative, Fonterra, and freight transport and distribution company, Toll NZ. Fonterra required a large distribution depot for their dairy products, located where they could conveniently use either Tauranga or Auckland Ports to export their goods.

The village allows dairy products to be brought in on pallets or in containers; on trucks or by rail. The site allows storage of dairy products, container loading, container storage and the movement and loading of containers onto rail. All the dairy products are railed in containers from the village to a port for export.

Figure 7 below is an aerial photograph of the freight village under construction. The container handling yard designed using HIPAVE is to the right of the large building.

Figure 7: Aerial View of Site under Construction.

Container Handling Equipment

The container yard is designed to be operated by Kalmar DCD450 container lift trucks (Figure 8). Containers will be stacked up to 3 high for storage on the yard.

Note: Kalmars for the freight village will be fitted with top pick container lift frames rather than the forks shown in the photo.

Figure 8: Container Handling will be by Kalmar DCD450 Container Lift Trucks.

Container Loads

Containers will be a combination of 20 foot and 40 foot. Initially most of the containers will be 20 foot. Over time this will trend to increasing numbers of 40 foot, with the proportion of 40 foot containers expected to reach 80% by the end of the design life.

Many empty containers will be handled over the terminal as they are brought in for cleaning then loading. The loaded containers will be handled over the terminal to rail, or stacked on the terminal awaiting transfer to rail for export.

The loaded containers will have a range of weights, as shown in Table 1 below.

The maximum weight of the loaded containers, as used for the pavement design, was 41 tonnes. A container of 41 tonnes carried on a Kalmar DCD450 results in a static front axle load of approximately 95 tonnes.

Container Throughput

The number of containers handled each year through the terminal is expected to increase by 5% per annum. The roadways on the terminal will be wider than 12m so a lane reduction factor of 0.5 was applied.

Over the design life of 20 years the number of load repetitions used for design is as shown in Table 1 below.

Load Type	Number of Movements Over 20 Years
Trucks, Highway Legal	160,000
No Load on Kalmar	876,000
Empty Containers on Kalmar	385,000
22.5 Tonne Curtain Sided Containers on Kalmar	20,000
25 Tonne Containers on Kalmar	206,000
41 Tonne Containers on Kalmar	265,000

Table 1: Total Number of Machine Movements over 20 years for Pavement Design.

Subsoils

Subsurface investigations showed that the surface materials included intermittent gravels overlying firm silts and silty sand fill. Beneath the fill the underlying natural soils comprised current-bedded sands and silts of the Hinuera formation. The bedded silts and sands are generally underlain by dense sand.

The subgrade was assigned a CBR of 4 for the purposes of pavement design. This included undercutting of some localised weak areas, together with, in one area, the use of a geogrid.

The Hinuera formation included soils of volcanic origin.

Pavement Design

The pavement is designed for a life of 20 years. The surfacing adopted for the pavement is asphalt to accord with the client's wishes. It is recognised that handling and stacking of containers will result in some damage to the surface of the asphalt, so requiring periodic milling of the surface and repaving.

The container handling yard is bounded on both sides by railway lines. These constrained the height of the surface of the yard.

The pavement design selected comprised unbound sand for the subbase and lime-modified basecourse for the base. This was intended to provide a tolerant pavement. However use of these pavement materials for a 95 tonne maximum axle load and a subgrade CBR of 4 resulted in quite a thick pavement. With the restrictions of the height of the pavement surface, a consequence was some thickening of the asphalt layers to provide the load spread required.

Pavement Model

This heavy duty pavement was analysed and designed using HIPAVE.

The pavement model for analysis of subgrade strain is outlined in Table 2 below.

For the HIPAVE analysis, wander of the Kalmars within their lanes was recognised by a standard deviation of wander of 200 mm. A dynamic load factor of 40% was applied to the Kalmar tyre loads.

Layer	Description	Isotropic Modulus (MPa)	Poisson's Ratio	Thickness (mm)
Asphalt	Asphaltic Concrete AC20	1,742	0.4	110
Asphalt	Stone Mastic Asphalt SMA20	1,500	0.4	65
Basecourse	Lime Modified AP65 Basecourse	689.6 with Barker-Brabston sublayering	0.3	915
Subbase	Graded Sand	120 with sublayering	0.4	≥ 510mm
Subgrade	CBR 4	40	0.4	Infinite

Table 2: Pavement Material Properties for Subgrade Strain Model.

The subgrade included Hinuera formation soils of volcanic origin. Soils of volcanic origin tend to have different load versus deformation properties than non-volcanic soils of the same insitu CBR. Typically for design of pavements on subgrades of brown volcanic ash, a modulus of 10 x CBR would be appropriate for evaluation of subgrade strain, while a modulus of 3 x CBR would be appropriate for evaluation of tensile strain in bound layers. For further background regarding the engineering properties of volcanic soils refer to Patrick et. al (1997) and Bailey and Patrick . (2001).

For the freight village, this necessitated separate modelling to analyse the subgrade strains and to analyse the asphalt strains. Table 2 above outlines the material properties for the analysis of the subgrade strains, while Table 3 below outlines the material properties for analysis of the asphalt strains.

Layer	Description	Isotropic Modulus (MPa)	Parson's Ratio	Thickness (mm)
Asphalt	Asphaltic Concrete AC20	1,742	0.4	110
Asphalt	Stone Mastic Asphalt SMA20	1,500	0.4	65
Basecourse	Lime Modified AP65 Basecourse	689.6 with Barker-Brabston sublayering	0.3	915
Subbase	Graded Sand	100 with sublayering	0.4	≥ 510mm
Subgrade	CBR 4	15	0.4	Infinite

Table 3: Pavement Material Properties for Asphalt Tensile Strain Model

For the subgrade of CBR 4, the subgrade strain criteria used was:

$$N = \left[\frac{3{,}177}{\mu\varepsilon} \right]^{9.8}$$

As a beta version of HIPAVE was used, the design was checked using CIRCLY. For the CIRCLY analysis, a simplified traffic load spectrum was adopted, as was manual sublayering of the base in accordance with the trends of AUSTROADS (2004), Table 6.4. Subgrade strain criteria used was as for the HIPAVE analysis. After allowance for wander and the simplified loading, good agreement was obtained between the HIPAVE and the CIRCLY analyses.

The design was also checked against the British Ports Association Guide (1996). The British Ports method indicated a slightly thicker pavement was required. The British charts have been developed for concrete, lean concrete or cement bound bases, with design for unbound crushed rock catered for by conversion factor. For a pavement with a modified basecourse the British Ports method would appear to be an approximation, so the slightly thicker pavement suggested by the British Port method was not of concern.

Results

Figure 9 is the Subgrade Damage Factor "profile" across the freight village pavement, calculated for a pavement design life of 20 years. Note that X = 0 corresponds to the centreline of each vehicle.

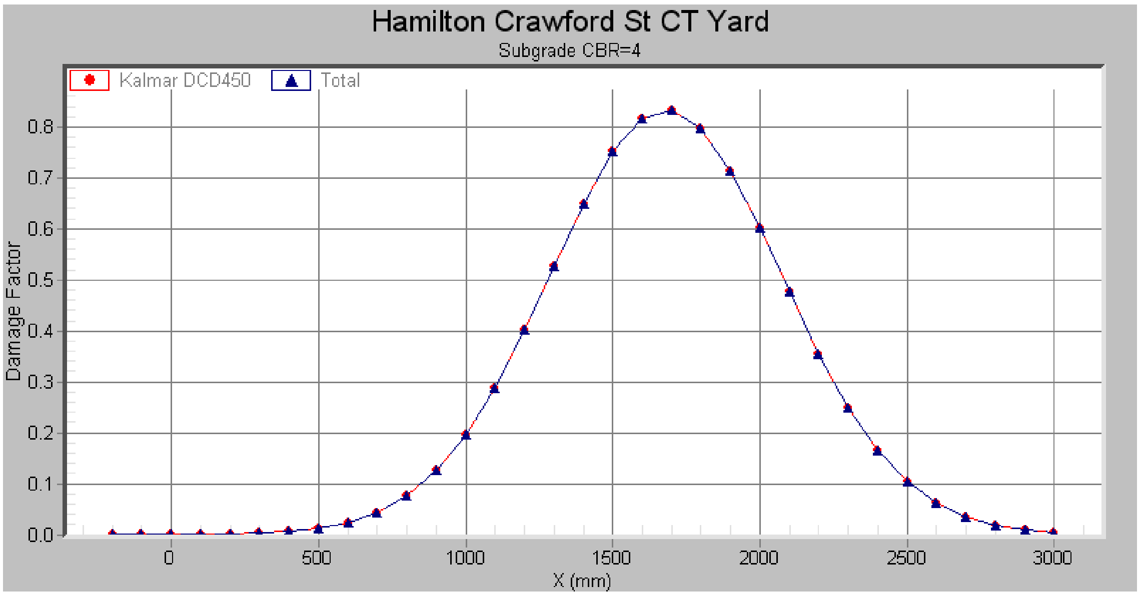

Figure 9: Subgrade Damage Factor vs. lateral offset.

Figure 10 is the *Spectral Damage Graph* showing the Subgrade Damage Factor contribution from each container load.

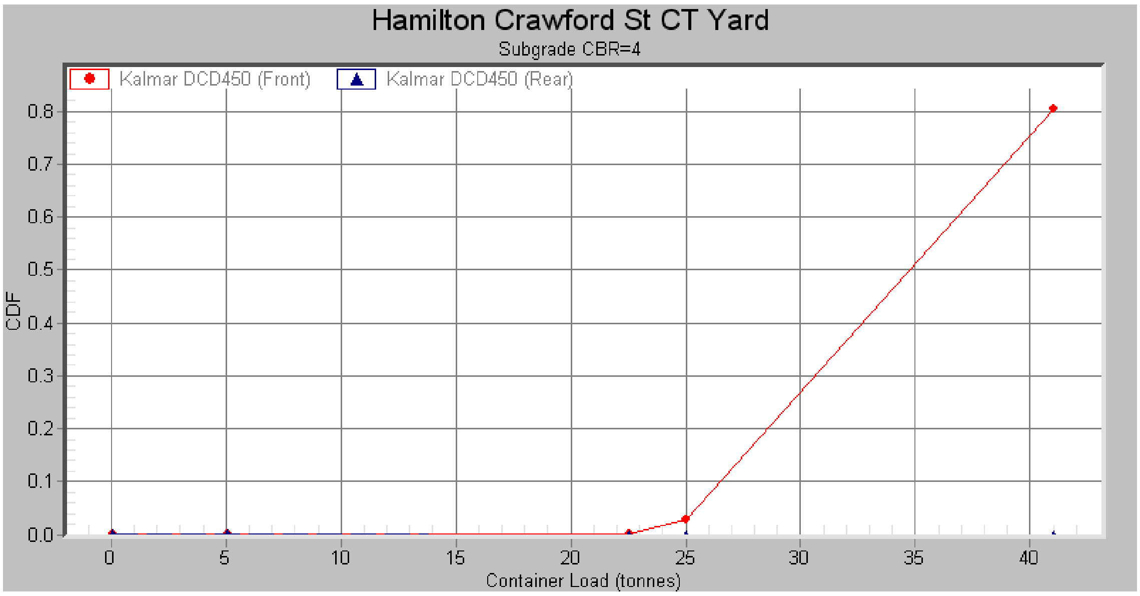

Figure 10: Subgrade Damage Factor vs. container load.

Of the two asphalt layers, the second layer (Stone Mastic Asphalt SMA20) has the highest damage factors. Figure 11 is the profile of the Damage Factor for the SMA20 layer.

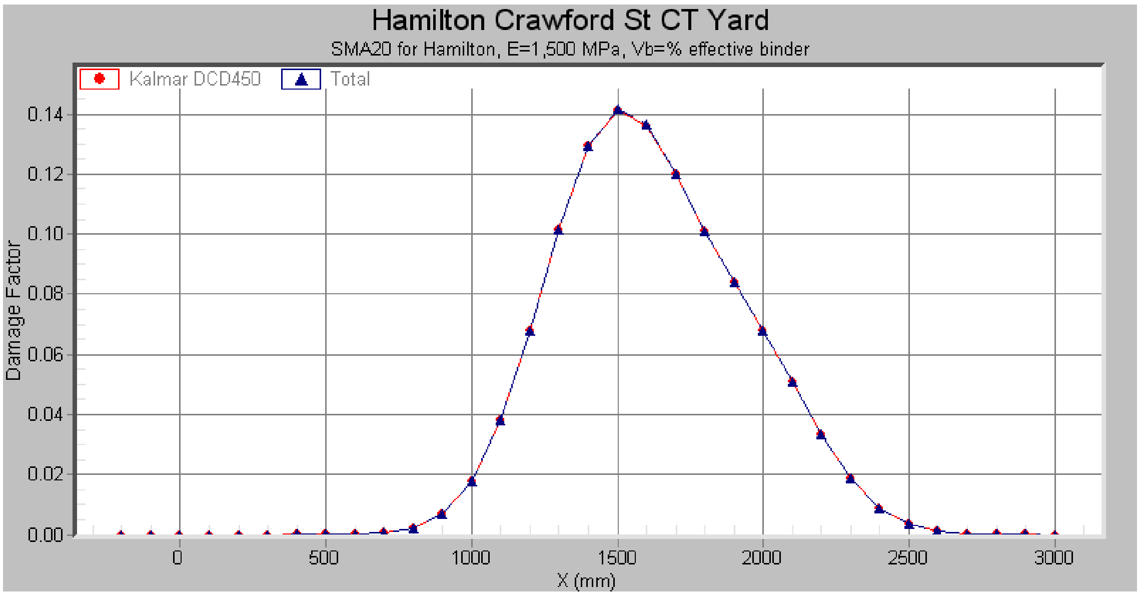

Figure 11: SMA20 layer Damage Factor vs. lateral offset.

Figure 12 is the *Spectral Damage Graph* showing the SMA20 layer Damage Factor contribution from each container load. To clarify the contribution of the container weight, this graph assumes equal repetitions for each payload.

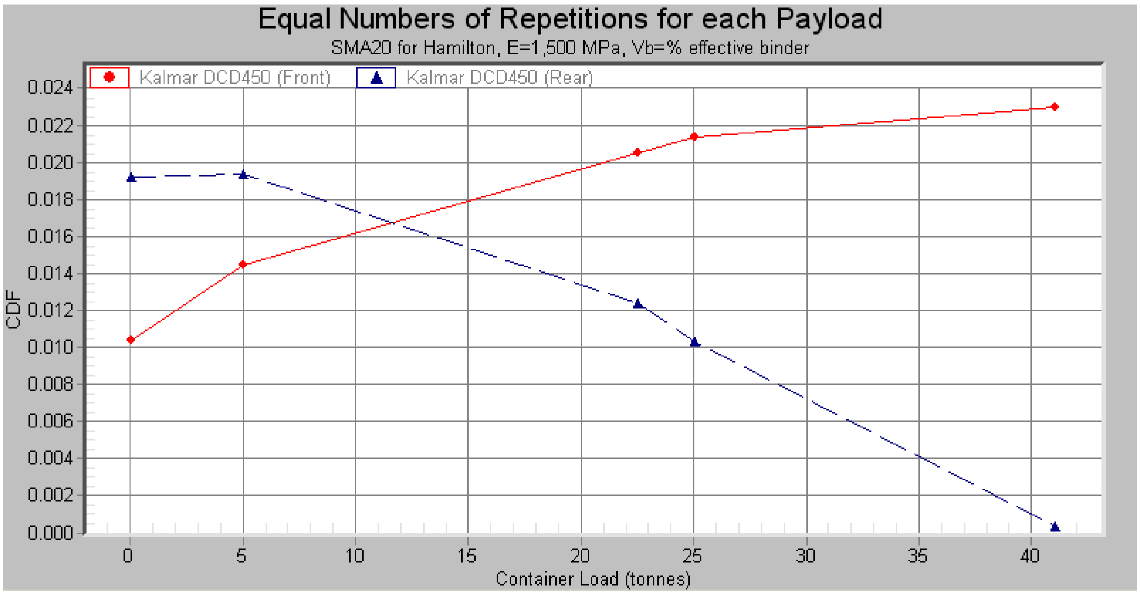

Figure 12: SMA20 layer Damage Factor vs. container load.

It is interesting to compare the *Spectral Damage Graphs* for the subgrade and SMA20 layer (Figure 10 and Figure 12).

For the subgrade (Figure 10), the greatest damage contribution is due to the heaviest container weight (41 tonne) and from the front axle component (the rear axle contribution is negligible). For the SMA20 layer (Figure 12), the greatest damage contribution is due to the unladen machines. For this layer both the front and rear axles contribute significant damage.

These results demonstrate that any design approach that uses a single “average” or “maximum” container weight cannot give reliable results for all material types.

DISCUSSION AND CONCLUSIONS

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 effect on the pavement of the design repetitions of each vehicle model/payload combination; and the material performance properties used in the design 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 emanating 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.

The design of the Crawford Street intermodal container handling facility in Hamilton, New Zealand has demonstrated HIPAVE's capabilities. This Crawford Street example demonstrates the efficiencies for designers offered by HIPAVE and the enhanced ability to consider options and conduct 'what if' analyses.

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.

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

REFERENCES

Anderton. G.L. (1996) *User's guide: Resin Modified Pavement.* Facilities Engineering Applications Program. FEAP – UG – 96/01. US Army Centre for Public Woks.

Austroads (2004). Pavement Design - A Guide to the Structural Design of Road Pavements, Report AP-G17/04.

Bailey, R. and Patrick, J. (2001). *Determination of the Structure Number of Pavements on Volcanic Subgrades.* Transfund New Zealand Research Report No. 510.

Barker, W. and Brabston, W. (1975). *Development of a structural design procedure for flexible airport pavements.* Report No. S-75-17. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.

British Ports Association (1986). *The Structural Design of Heavy Duty Pavements for Ports and other Industries*, 2nd ed., British Ports Association, London

British Ports Association/Interpave (1996). *The Structural Design of Heavy Duty Pavements for Ports and other Industries*, 3rd ed., Interpave, Leicester.

Corp of Engineers (1989); Departments of the Army and the Air Force Technical Manual. *Flexible Pavement Design for Airfields (Elastic Layer Method).* Army TM 5-825-2-1.

Freeman, R.B., Velez-Vega. E.B. (2004) *An alternative method for predicting the response of flexible pavements to traffic loads.* FAA Worldwide Airport Technology Transfer Conference, Atlanta

Patrick, J.E., Sutherland A. and Dongol, D.M.S. (1997). *Application of Austroads Pavement Design Guide for Wanganui Materials.* Transfund New Zealand Research Report No. 128.

Pereira, A. T. (1977). *Procedures for development of CBR design curves*. Instruction Report S-77-1, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.

Theyse. H.L. *Overview of the South African mechanistic pavement design method.* 1996 annual meeting of the Transportation Research Board

Wardle, L.J. (1999). APSDS 4.0 Users' Manual, MINCAD Systems Pty Ltd, Richmond, Vic., Australia. (www.mincad.com.au)

Wardle, L.J. (2004). CIRCLY 5.0 Users' Manual, MINCAD Systems Pty Ltd, Richmond, Vic., Australia. (www.mincad.com.au)

Wardle, L.J., Rodway, B. and Rickards, I. (2001). *Calibration of Advanced Flexible Aircraft Pavement Design Method to S77-1 Method*. in Advancing Airfield Pavements, American Society of Civil Engineers, 2001 Airfield Pavement Specialty Conference, Chicago, Illinois, 5-8 August 2001 (Buttlar, W.G. and Naughton, J.E, eds.), pp. 192-201.

Wardle, L.J., Youdale, G. and Rodway, B. (2003). *Current Issues For Mechanistic Pavement Design*. in 21st ARRB and 11th REAAA Conference, Cairns, Australia, 18 - 23 May, 2003, Session S32, ARRB Transport Research.

Witczak. M.W., Kaloush. K., Pellinen. T., El-Basyouny. M. (2002) NCHRP Report 465. *Simple Performance Test for Superpave Mix Design.* Transportation Research Board — National Research Council.