ELMOD 6: THE DESIGN AND STRUCTURAL EVALUATION PACKAGE FOR ROAD, AIRPORT AND INDUSTRIAL PAVEMENTS

Kars P. Drenth, Manager Consulting Engineering
Dynatest UK Ltd
3 Marquis Court, Marquis Drive
Moira, Derbyshire DE12 6EJ
United Kingdom
Tel: +44 1283 554860 Fax: +44 1283 552462
E-mail: kdrenth@dynatest.com

SUMMARY

ELMOD is an acronym for *Evaluation* of *Layer Moduli* and *Overlay Design* used or the structural assessment of all kind of pavement structures. The latest version 6 of ELMOD is now able to design pavement structures by specifying the pavement model, the mechanical characteristics for all types of materials and an unlimited number of loading types.

Based on the stiffness values of each pavement layer a structural strength can be calculated using mechanistic-empirical principles expressed as a remaining life, needed strengthening or required pavement thickness. The software package is assigning various user controlled transfer functions to each material and is able to apply seasonal adjustments for variations in subgrade modulus due to for instance rainy seasons. The software package therefore may be used for any specific local environmental condition.

Within the structural calculation it is possible to select any user-defined combination of design loads using a vehicle library. Instead of a standard wheel load actual loads can be used in a design which is in particular useful for pavements loaded by a mix of different vehicle types. For many pavements the lateral distribution of vehicle loads is an important issue. This may be entered based on a normal distribution function.

This paper describes the details of the design of a pavement structure with paver blocks as surfacing layer based on a case study for a container terminal in Ghana.

1. INTRODUCTION

For the design of a pavement construction certain criteria have to be established to come to a sound analysis. The characteristics and requirements of heavy-duty industrial pavements do differ substantially compared to highway pavements. Port pavements are subjected to large numbers of relatively high loads at low speed.

A design can be based on semi-empirical methods such as the British Ports Association/Interpave method (BPA, 1996) based on multi-layer elastic modeling principles to produce design charts using the Lusas finite element package for calibration of the Equivalent Single Wheel Load (ESWL) concept. However such methods are limited in its use, especially in the application of alternative or new materials and different types of transport equipment. Special care has to be taken with the fact

that, especially with respect to cement bound pavement layers and concrete, a relative few repetitions of heavy loads can be very damaging. The ESWL concept can be misleading under these conditions due to the very steep fatigue relationships of cement bound materials in which a small increase of load can result in a dramatic reduction in life time of a pavement structure (CROW, 2002).

ELMOD 6 software package has been used to undertake a design review of the paver blocks surfaced pavement structures of the new extension of the Tema Port Stacking and Marshalling Area B in Ghana. The new design module of this software package can be readily used for heavy duty industrial pavements such as container terminals. It can handle the variety of mobile equipment used in container facilities with wheel loads that can be of the order comparable to very large aircraft. One of the features of the software is that it takes rational account of vehicle wander. This is the statistical variation of the paths taken by successive vehicles. Increased wander reduces pavement damage and could lead to significant savings. In the mechanistic-empirical approach all layers are represented by their mechanical characteristics avoiding the use of material conversion factors.

In many cases concrete paver blocks are used as surfacing material mainly due to their superior characteristics to withstand static loads. Container terminals show a wide variety of heavy dynamic and static loads which makes paver blocks the most versatile product to be used under all these different loading conditions. It is however not only the resistance to static loads that makes this material so useful as surfacing under a wide variation of loading conditions, but also the ease it can be maintained by just replacing damage blocks. There is a tendency to improve on its structural capacity by moving from rectangular to shaped blocks to achieve more interlock, often referred to as progressive stiffening, between the blocks. The heavier the loading the more its functionality does shift towards a material protecting the surface of the main structural layers from being damaged. Creating more interlock between the paver blocks could in that case by counter productive and possibly the mean reason for an increase in paver breakage of especially shaped blocks.

2. DESIGN INPUTS

2.1 General

In the multi-layer elastic model the pavement structure is regarded as linear elastic, in which the materials are characterised by Young's Modulus of Elasticity (E) and Poisson's Ratio (ν). The materials are assumed to be homogeneous and isotropic, and the layers have horizontally infinite dimensions. Similar to the finite element technique, the results of the output depend on the correctness of the input.

The primary criteria for the analytical structural design are considered to be:

- The horizontal tensile strain at the bottom of a bituminous surfacing or flexural stress in case of a rigid surfacing. There are no criteria for concrete block surfacing in combination with a bound base.
- The horizontal tensile strain or flexural stress at the bottom of a (cement) bound base or sub-base layer.
- The vertical compressive stress on top of (cement) bound base or sub-base layers (CROW, 2002).
- The vertical compressive strain at the top of unbound base and sub-base layers.
- The vertical compressive strain at the top of the subgrade.

Based on these criteria any new material can be included in a design as long as the material parameters are known.

In principle any combination of pavement material is possible, although due to the heavy nature of the loading of port pavements mostly a combination is chosen incorporating some kind of a bound base and/or sub-base layer. For cement bound layers (including concrete) the failure mode is fatigue, typically computed into tensile strains at the bottom of the relevant layers. The strains are converted into damage using a performance model and the Damage Factor for the i^{th} loading is defined as the number of repetitions (n_i) divided by the allowable repetitions (N_i). According to MINER's rule the structural pavement life is consumed when the Cumulative Damage Factor (CDF) is equal to 1. The CDF is given by summing the damage factors over all the loading or loading groups in the traffic spectrum:

- $CDF = \Sigma\, n_i/N_i$.

The (BPA, 1996) is using the method of expressing the load spectrum in a number of standard or critical loads. As long as this standard or critical load does not differ much from the maximum allowable load the error in structural pavement life is negligible. However care has to be taken with the fact that, especially with respect to bound pavement layers and concrete, a relative few repetitions of heavy loads can be very damaging for a pavement. For this reason the ELMOD software has a more preferable functionality, in which it takes full account of a complete loading spectrum including vehicle wander.

2.2 Type of Loading

For the handling of containers the following pieces of equipment have been specified:

- Reach Stacker (RS)
- In-terminal Trailer (ITT)
- Rubber Tired Gantry Crane (RTG).

Typical specifications for this container handling equipment are:

- Reach Stacker:
  - loaded front axle : 1220 kN
  - loaded rear axle : 128 kN
  - tire pressure : 1000 kPa
- In-terminal Trailer
  - loaded front axle : 175 kN
  - tire pressure : 800 kPa
- Rubber Tired Gantry Crane (16 wheel):
  - maximum loaded wheel load : 160 kN
  - maximum tire pressure : 1100 kPa.

The main areas were this equipment has to be used is:

- Heavy Duty Area: RS/ITT/RTG
- Driving Lanes: ITT/RS (occasionally).

The type of loading can be selected out of a library of vehicles that can be updated by the user. Wander effects can be included based on a simple ratio or normal distribution approach (see Figure 1).

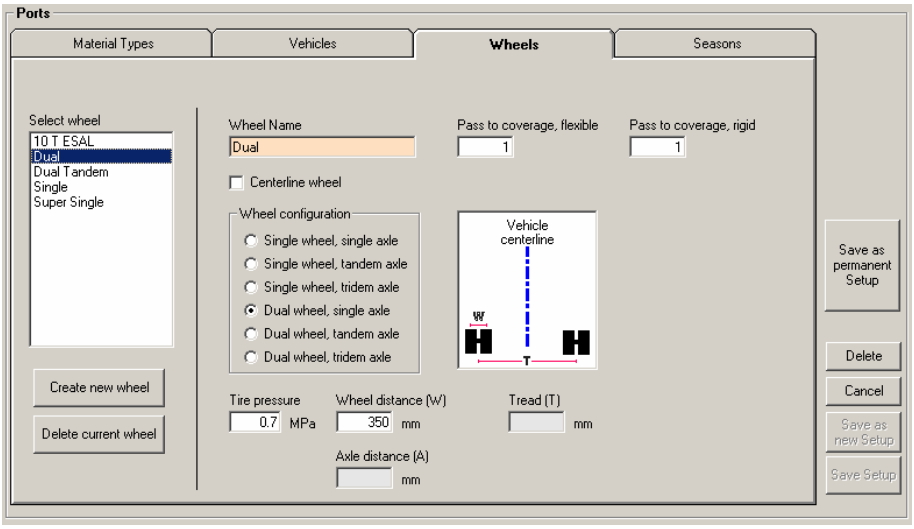


Figure 1. Vehicle selection window

The principle pavement structure lay-out is specified as:

- 80mm concrete blocks and 30mm bedding sand as surfacing
- Cement Bound Material (CBM) as base layer
- unbound granular material as sub-base layer
- compacted fill/natural subgrade or sound rock as subgrade.

2.3 Container Distribution and Loading

The loads imposed on the pavement of a container handling port cover a wide range of weights. However, the heaviest weights are usually less frequent.

Depending on the type of surfacing, it is not always the heaviest load which is the most damaging, but a combination of weight and frequency. It is however good pavement engineering practice to calculate the number of axle/wheel loads based on the frequency histogram (spectrum) and to apply Miner's hypothesis for the determination of the admissible number of loads. The frequency distribution of 20 and 40 ft containers by gross weight is given in Figure 2.

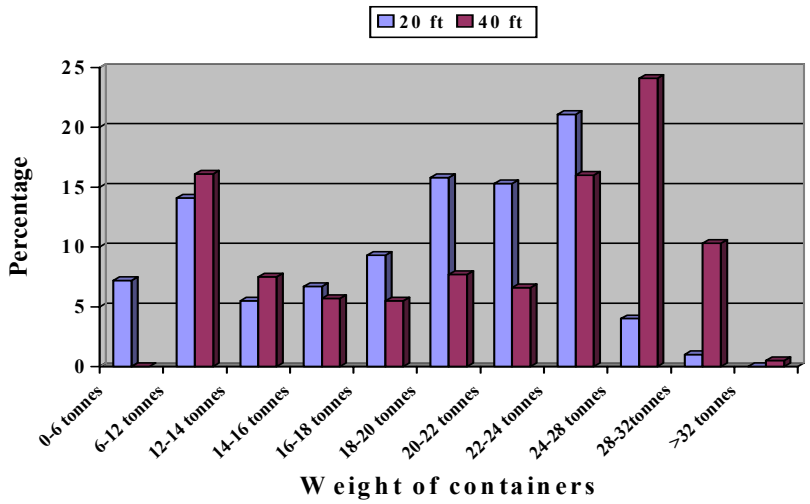


Figure 2. Frequency distribution of container weights

Figure 2 does show that a 22 – 24 tonne container is the most frequent occurring heavy weight.

The total capacity of the terminal is a function of the number of grounded slots and the stacking height. For design purpose the number of ground slots and stacking height of the most common largest block will be representative for the design of the pavement structures. The container blocks are laid out in a row of TEU (Twenty-foot Equivalent Units) bays. A stacking block has a defined number of TEU ground slots to be converted in a total TEU capacity. Typically a container port will operate in the range of 50% to 90% of its capacity, although it will be lower at the commencement of operations and higher later on. It is assumed that a stacking block will operate at a certain percentage of occupancy, reducing the capacity of a stack. As the containers will be a mix of 20 feet and 40 feet the operational capacity of a stacking block can be calculated. Typical dwell times for containers are generally in the range of 2 to 10 days. Assuming an average dwell time of the containers in a stacking block of 7 days and 300 operational days per year, a through-put of containers can be calculated through the largest stacking block per year and over the design life in years. As all containers will be handled twice, the total per block has to be doubled.

Containers will be transported to and from the stacking blocks by In-Terminal Trailers (ITT). These ITT's will travel the complete length of these blocks either loaded or unloaded. To bring and collect a container takes one unladen and one laden movement with varying weights. At the stacking area the containers will be handled either by the RTG or incidentally by a RS.

The loading of the pavement by the RTG and the RS is based on the five heaviest load groups containing about 70% of all non-empty containers. For the five heaviest load groups the following distribution has been chosen:

- > 32 tonnes : 1%
- 28-32 tonnes : 10%
- 24-28 tonnes : 15%
- 22-24 tonnes : 20%
- 20-22 tonnes : 10%.

These load groups can be translated into wheel loads of respectively:

- RTG 160, 148, 143, 139 and 136 kN
- ITT 60, 65, 72,5; 82,5, and 87,5 kN
- RS 265, 250, 225, 200 and 175 kN

3. PAVEMENT DESIGN

3.1 Design Inputs

3.1.1 Subgrade

The designs have been analysed based on a CBR 10% subgrade as specified. For use in a multi-layer elastic model the CBR value can be translated into an E-modulus based on the empirical relationship:

- $E_{subgrade} = 10 * CBR$ [MPa]

Commonly a Poisson's ratio of 0.35 is assumed.

The E-modulus of the subgrade is one of the principal input parameters in the design procedure. The design procedure is based on the subgrade strain criterion, i.e. the general relation between the allowable vertical compressive strain (ε_z) and the number of load repetitions (N):

- $\text{Log } N = C_0 + C_1 * \log \varepsilon_z$

  where N = number of allowable load repetitions
  C_0, C_1 = material constants
  ε_z = compressive strain on top of the subgrade (μm/m).

Using the Shell relationship based at an 85% confidence level the fatigue relationship based on the deformation of the subgrade can be written as:

- $\text{Log } N = 17.789 - 4 * \log \varepsilon_z$

3.1.2 Sub-base

Unbound sub-bases are the most common type of granular material used in pavement design. Material Type 1, as specified, is unbound granular materials according to the British Standards. Type 1 granular material shall be crushed rock, crushed slag, crushed concrete or well burnt non-plastic shale and may contain up to 12.5% by mass of natural sand which passes the 5 mm BS sieve. The Type 1 material shall have a Ten Percent Fines Value of 50 kN or more (crushing strength) and a soundness value greater than 65.

The E-moduli for unbound granular material can range from 150 MPa to over 600 MPa for a good quality crushed rock. Moduli of granular materials are not only dependent on the mechanical characteristics of these materials, but also on the stress level at which they operate and the stiffness of the underlying layers. Normally the moduli of pavement material will decrease with depth to an extent influenced by the stiffness of the subgrade. Sub-layering will be used for the Type 1 material to deal with this behaviour, approximately in the range of 150-200 mm compacted thickness with a ratio of moduli of adjacent sub-layers not exceeding 2. The Poisson's ratio for all unbound material is assumed to be 0.35.

The elastic modulus of unbound sub-base ($E_{subbase}$) material depends on the thickness ($h_{subbase}$) of this layer and the elastic subgrade modulus ($E_{subgrade}$), based on:

- $E_{subbase} = 0.2 * h_{subbase}^{0.45} * E_{subgrade}$

Based on this relationship an E-modulus of 400MPa has been used in the analysis.

3.1.3 Base

Cement bound material can be divided into four categories based on the British 'Specification for Highway Works' (DfT, 2005) namely CBM 1 through 4 category. The main strength requirements of the four categories are summarised in Table 1.

Table 1. Strength requirements Cement Bound Materials

Category	E moduli [N/mm^2]	min. 7 day cube compr. strength [N/mm^2]	
		average[1]	individual[2]
CBM1	3,500	4.5	2.5
CBM2	5,000	7.0	4.5
CBM3	10,000	10.0	6.5
CBM4	15,000	15.0	10.0

1) Average value of a batch of five cubes
2) Minimum strength of an individual cube within the batch

The cement bound base material has an average compressive strength of 10MPa. The flexural strength is 2.0N/mm^2 for a CBM3. The fatigue transfer function of CBM at a reliability level of 85% can be written as:

- $\text{Log } N = 11.782 - 12.12 * (\sigma_{bt}/f_{bt})$

  where N = number of allowable load repetitions
  σ_{bt} = flexural stress
  f_{bt} = flexural strength.

The Poisson ratio for all four materials is assumed to be 0.20.

3.1.4 Surfacing

Concrete paver blocks have established themselves in many industrial port areas. The finished surface combines the high strength and durability of concrete to resist severe surface loads and contact stresses. The surface is also resistant to leaking oil and cracks in a bound base layer do have little influence at the surface. Concrete blocks are manufactured according to international specifications. A common size is a 200*100*80 mm (l*b*h) rectangular paver block laid on a 30 mm thick bedding layer of durable crushed silica sand. The design was based on the specified rectangular block, however during the finalisation of the design phase this was changed into a shaped paver.

Figure 3 shows the Parameter Setup window were any type of material can be selected or created for the design based on its performance relationship.

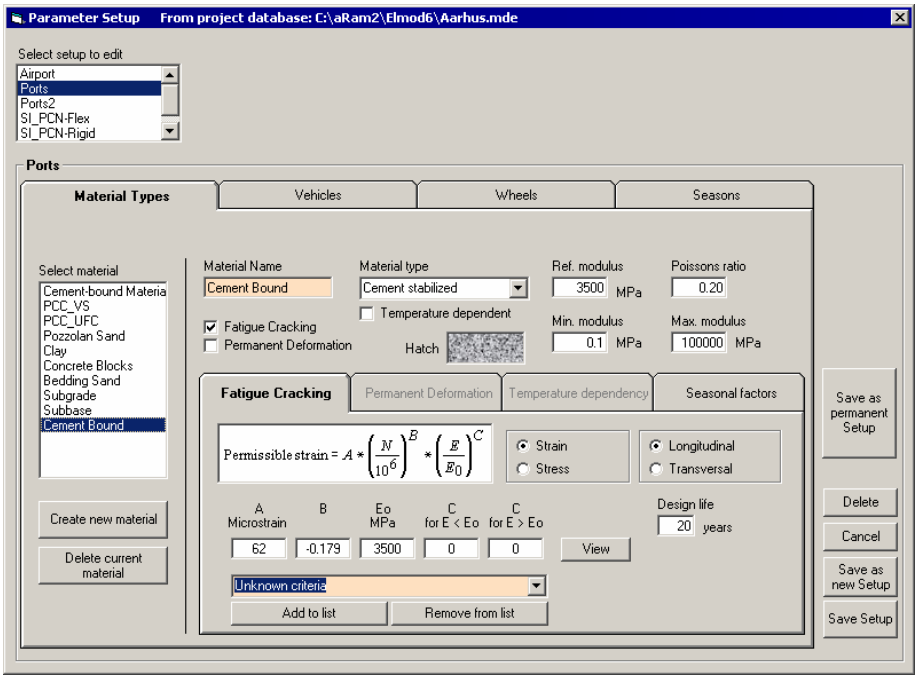


Figure 3. Material selection window

For the structural design the E-modulus of the combined layer of rectangular paver blocks and bedding material is assumed to be 800 MPa with a Poisson ratio of 0.25. This value seems to be most appropriate for design although it is a known fact that progressive stiffening effects due to ingress of dirt in the joints will increase the E-modulus in time. The BPA manual does mention a value of 4,000MPa, similar or even higher than bituminous material. This value does seem to be very high when compared with results of Falling Weight Deflectometer test performed on new and already many years' in-service pavement structures. The achieved stiffness of the paver blocks does of course depend on the progressive stiffening effects in combination with the shape of the blocks. In case the concrete paver blocks will start acting as a larger concrete 'slab' there could be a risk of too high tensile strains at the bottom of this relatively thin concrete 'slab', resulting in breakage of individual paver blocks.

3.2 Structural Analysis

It was the aim to construct a single uniform pavement over the Heavy Duty Area, which includes the Container Stacking Area, the Driving Lanes for the ITT/RS and the RTG Runways. The pavement for the Container Stacking Area had to be designed for a 4-high stacking area with a maximum stress under the corner castings of 7.27N/mm^2 (based on the BPA Manual). In this case the loading of the RS will govern the design as being the heaviest piece of equipment, although the frequency of the ITT is more than much higher. This frequency has been taken to be similar to the Driving Lanes although they will disperse over the number of Driving Lanes parallel to the RTG Runways between the Container Blocks. The ITT frequency could be closer to that of the RTG depending on the number of RTG's to be used in the future.

Based on the type of equipment, type of loading and design inputs as specified the structural designs have been analysed using the Design Module of the ELMOD 6 software.

For the Heavy Duty Area the required thickness of the CBM has been calculated as 630mm based on the RS+ITT loading. This resulted in the following pavement structure:

- 80mm concrete paver blocks
- 30mm bedding sand
- 630mm CBM3
- 500mm Type 1 sub-base
- CBR 10% subgrade.

When taking the RS loading into account only the thickness required for the CBM layer is still 600mm. This means that a reduction in the number of ITT movements has little effect on the required CBM thickness and no actual savings can be made in that sense. This result underlines the fact that cement bound layers are more vulnerable for a few heavy loads in comparison to a higher frequency of less heavy loads.

The subgrade strength, based on a fill procedure, is set at a very conservative level of 100MPa. This has an effect on the stiffness of the sub-base layer and this will affect the required CBM thickness. When fill material can be found of a better quality than anticipated in the design a much better support of the CBM layer can be achieved. A reduction of the CBM layer of 180mm is possible, resulting in a thickness of 450mm for the RS+ITT loading.

As an alternative Lean Concrete can used as cement bound base. The Lean Concrete material can be specified as a C20 type concrete. In combination with a CBR 20% subgrade and a 500mm thick Type 1 subbase material with an E-modulus of 650MPa the required thickness for this Lean Concrete layer is 275mm.

4. CONCLUSIONS

The purpose of this design review was to check the present designs in the first place and secondly make some optimisations when possible.

Based on this review the following main conclusions can be made:

- For the Heavy Duty Area the RS loading will govern the design.
- Savings in required CBM thickness can be achieved be combining the requirement for an unbound granular base layer with the material used as fill. The unbound granular layer can be omitted completely and the CBM thickness for the Heavy Duty Area can be reduced to 450mm when the fill has a CBR of 30%.
- Other savings can be achieved when Lean Concrete is chosen as cement bound base layer. In combination with a 500mm Type 1 subbase layer the thickness of the base layer can further be reduced to 275mm.
- The use of a C20 Lean Concrete as bound base layer will safeguard the pavement structure for failure of the top of this layer, resulting in unacceptable deformation.
- The ELMOD 6 Design Module makes it possible to compare very quickly alternative designs based on local available materials, the mechanical parameters related to these materials and lateral wander effects of the container transport vehicles used.
- During construction care has to be taken that a full bond is achieved between the different layers making up the full required CBM thickness.

- Mechanistic-empirical methods avoid the use of unreliable material conversion factors for 'local' materials.

It has been noticed that the shaped paver blocks did show some breakage after being in-service up to a year. This could be caused by the shape of the paver blocks and the achieved interlock, resulting in a 'slab-like' behaviour causing paver breakage under high wheel loads. Repairing these localised areas did turn out to be difficult as it was only possible to lift 'slab-size' interlocked paver blocks instead of single paver blocks as is the case with rectangular paver blocks.

5. ACKNOWLEDGEMENT

This paper is based on a design review commissioned by Interbeton, The Netherlands. The content of this paper reflects the views of the author who is responsible for the facts and accuracy of the data presented.

6. REFERENCES

British Ports Association/Interpave, 1996. The Structural Design of heavy Duty Pavements for Ports and other Industries

CROW Publication 157, 2002. Thin asphalt pavements: dimensioning and re-design (in Dutch)

Department for Transport, 2005. Manual of Contract Documents for Highway Works, Volume 1 - Specification for Highway Works 800 Series