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A COMPRESSIVE STUDY AND EVALUATION IN PAVEMENT STRUCTURE

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ABSTRACT: Throughout the history of pavement structure, the parallel layer structure has dominated the structural design of pavements. In other words, the entire road pavement share a uniform thickness design regardless how many lanes there are. However, due to traffic regulations and driving habits, the traffic flow most probably does not distribute evenly on a multi-lane road. Modern pavement design methods usually choose the lane that bears the heaviest traffic load as the design lane to determine the thickness design of the entire pavement. Hence there could be a certain over-design in the less trafficked lanes. This study aims to propose and evaluate a new structural design for flexible pavement by reducing the thickness of asphalt layers of the lightly trafficked lanes.

The traffic data of a real motorway in the INDIA was analyzed, based on which a new pavement structural design of a 3-lane road was established. Two finite element models, for both original and new designs, were established in CAPA-3D to calculate the stress and strain responses under different traffic load combinations. Following the Dutch design method the fatigue and deformation performance predictions of the two pavement designs were executed and compared. The results showed that the new design indeed improve the material cost-efficiency without compromising the performance of the pavement structure.

Taking advantage of the finite element models, a real-life simulation was also applied. The strain output of the simulation was used to calculate the rutting depth following the American design method. Both calculated rutting depth and the deformation output of the real-time simulation supported the earlier conclusions. An extra simulation of truck platooning was briefly executed and discussed as well.

I. INTRODUCTION

Since the very beginning of the development of pavement, parallel layer structures have traditionally been the foremost, if not the only, choice of road constructions. Whether it is a flexible, rigid or composite pavement, they all share a similar structure, which contains a top layer, base or sub base and sub grade. From this perspective, the structural design of a road is relatively simple and involves less risk to public safety than a building design. The thickness of each layer is therefore one of the most significant elements of the structural design of a pavement. The term “conservative” in the context of pavement design however, usually refers to economic risks of investing too much or too little, especially in materials, which transfer into the thickness and material selection of each layer. Over the past decades, various methods have been developed to determine the thickness of a pavement. They all more or less rely on some empirical functions which tend to lead to an over-design. Even when a design method is not initially on the safe side, it can be calibrated in the field due to other unexpected failures by extra safety or in this case thickness design. Furthermore, a parallel layer structure requires the entire cross-section of the road to share a uniform thickness.

II. PAVEMENT STRUCTURAL DESIGN METHODS AND SOFTWARE

Prior to the early 20th century, the thickness of pavement layers was purely based on experience . The invention of automobile increased the travel speed and drawn more attention to the driving safety and comfort, which stimulated the society to treat road design more seriously. Hence the mechanistic design method, which links performance to material properties and failure mechanics, as well as the empirical-mechanistic design method were introduced. At the same time experiments were being developed to investigate binder with tar or natural asphalt .

The growing importance and development of car transport during and after the two World Wars required the pavement technology to take a further step beyond empiricism. The growth in traffic volume, tyre pressures as well as travel speeds led to a new requirement of the functional performance definition [8]. This definition became the foundation of the later service class which enables the road designers to link the costs with the desired performance. Besides, the rising demand of a better understanding and prediction of pavement performance, knowledge of its structural behaviour and its failure in time was required, which resulted in the AASHO (American Association of State Highway Officials) road test .

Model design

As discussed in chapter 1, all the current pavement design methods are based on a parallel multi-layer structure assumption, so is the design software. In section 2.1, a slope shaped new design has been proposed, which contains un-parallel layers. Hence traditional design methods are no longer applicable here. As a result, a finite element method (FEM) is introduced in this thesis. A FEM software, CAPA-3D, is used for the strain and stress calculation as well as long-term deformation simulations.

CAPA-3D is a three dimensional finite elements based research tool [33]. Like all the FEM software, the run time and the calculation precision are highly influenced by the dimension and fineness of the mesh. The bigger and finer a mesh is, the longer run time it will take and produce a more precise result. Therefore a proper model has to be established to gain a balance between time consumption and precision of the results.

NUMBER OF LANES AND DIMENSIONS

The Handboek wegontwerp is a design manual published by CROW. It provides guidelines for traffic facilities design outside urban areas in the INDIA. In its first part, Basiscriteria, a standard layout of a stroomweg (Dutch motorway) is presented, which contains 2 lanes per direction with 1 emergency lane [34].

A road can be seen as an infinite structure in the longitudinal direction. Thus for a finite element model the length ceiling also should be limited. In addition, a minimum length also has to be determined to minimize the edge effect. Several simple trials were performed during the preliminary research. The results show that for a typical tyre print the influence area for strain and stress of under layers is within 5 metres diameter. Therefore a model with the length of 6 metres in the direction of traffic was selected such that one full passage of the truck on the pavement can be achieved to obtain a complete longitudinal tensile strain response curve including the expected compression-tension-compression sequence which will be further discussed in the next chapter.

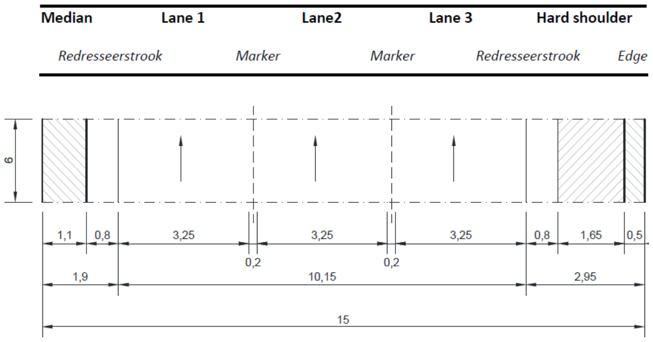

Figure Dimension design of the model (Top view, m)

As for the thickness design, since the number of lanes is reduced, the vehicles running on the 5-lane road are re-distributed on 3 lanes. The previous traffic data analysis in chapter 2 indicates that the axle load gross ratio between the heavier traffic lane and the lighter traffic lane is around 3:1, in other words 75% and 25% respectively. However, the axle load analysis only include the trucks of the 4th and 5th lane, therefore in this thesis, an adjustment has been applied to the traffic distribution. The result is shown in table below

Traffic distribution	Daily amount	Lane no.	Percentage	Amount
Original	7800	3	75%	5100
		2	25%	1800
Adjusted		3	73%	5700
		2	27%	1900

Comparing the new traffic data to the original data used in the software design, an approximation of the asphalt layer thickness can be estimated. The final thickness design for the heavy traffic lane is composed of one PA layer (50mm), three AC layers (75mm, 80mm and 80mm), one unbound subbase layer (300mm) and one subgrade layer.

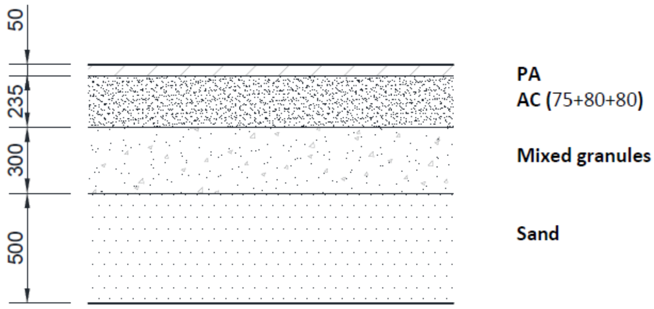

Figure Pavement layer thickness design (mm)

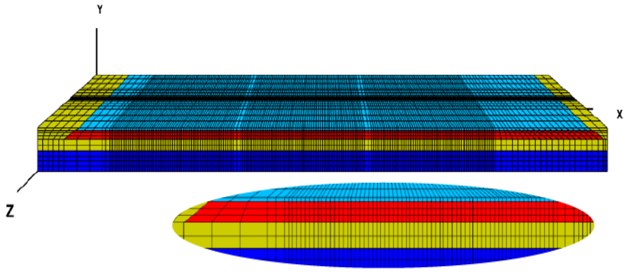

Figure Final mesh of original design

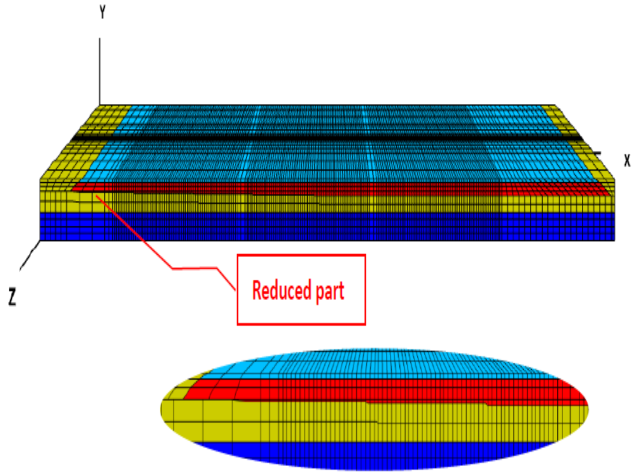

Figure Final mesh of new design

III. MODEL DESIGN

have been developed based upon the viscoelastic characterization of asphalt material to calculate strain response and deformation. In this thesis, a rutting calculation following the American standard (Mechanistic-Empirical

Pavement Design Guide, MEPDG) is performed for comparison. It requires the introduction of viscoelasticity to the asphalt material.

The viscoelasticity of asphalt can be simply seen as a time-dependent behaviour between stress and strain. The key to simulate the real behaviour of asphalt materials is a proper model of their stress-strain relationship, which can be simulated by a mechanical model consisting of elastic components (spring) and viscous components (dashpot). In CAPA-3D, a Generalized Maxwell model, also known as Wiechert model , is employed. It is composed of one single spring and multiple Maxwell components connected in parallel as shown in figure 2.10. Each spring is assigned a relaxation modulus E while each dashpot is assigned a frictional resistance η. The modulus of the Generalized Maxwell model can be expressed as below.

$$G'(\omega) = G_\infty + \sum_{i=1}^{N} \frac{\omega^2 \tau_i^2 G_i}{\omega^2 \tau_i^2 + 1}$$

Where,

$G'(\omega)$ = Storage modulus (Pa)

G_∞ = Long term modulus (Pa)

N = Relaxation modes (-)

ω = Angular frequency (rad/s)

τ_i = Relaxation time (s)

G_i = Prony coefficients (Pa)

$$\mu = G^*$$

$$\lambda = \frac{2v}{1-2v} G^*$$

$$\eta = \tau E = 2\tau G^* \ (1 + v)$$

$$\eta_{vol} = \eta_{dev} = \frac{4}{9}\eta$$

Where,

μ, G^* = Shear modulus (Pa)

λ = Lamé's first parameter (Pa)

v = Poisson's ratio (-), set to 0.35

τ = Relaxition time (s)

η, η_{vol} & η_{dev} = Viscosity parameters (Pa·s)

i	τ (s)	Gᵢ (Pa)	ν (-)	μ (Pa)	λ (Pa)	E (Pa)	η (Pa·s)	η_d (Pa·s)	η_v (Pa·s)
1	2.12E-01	3.50E+09	3.50E-01	**1.32E+09**	**3.09E+09**	3.58E+09	7.57E+08	**3.36E+08**	**3.36E+08**
2	2.18E-04	2.44E+09	3.50E-01	**5.45E+09**	**1.27E+10**	1.47E+10	3.21E+06	**1.43E+06**	**1.43E+06**
3	3.96E-06	2.44E+09	3.50E-01	**2.99E+09**	**6.97E+09**	8.07E+09	3.19E+04	**1.42E+04**	**1.42E+04**
4	2.12E-07	2.44E+09	3.50E-01	**2.99E+09**	**6.97E+09**	8.07E+09	1.71E+03	**7.62E+02**	**7.62E+02**
5	5.92E-03	2.10E+09	3.50E-01	**2.74E+09**	**6.40E+09**	7.40E+09	4.38E+07	**1.95E+07**	**1.95E+07**
∞		7.10E+03	3.50E-01	**2.95E+02**	**6.87E+02**	7.95E+02			

Table Material parameters (Prony series) of porous asphalt (PA)

IV. PERFORMANCE ANALYSIS

STRAIN PLOT ANALYSIS (INDIVIDUAL WHEEL)

Typical curves of the time-strain relationship for an axle load of 210 kN with dual tire at the centre of one tire and the bottom of the asphalt layer are shown below (positive strain represents tensile strain while negative strain represents compressive strain). Normal strain along three different directions, namely vertical, transverse and longitudinal, are drawn separately.

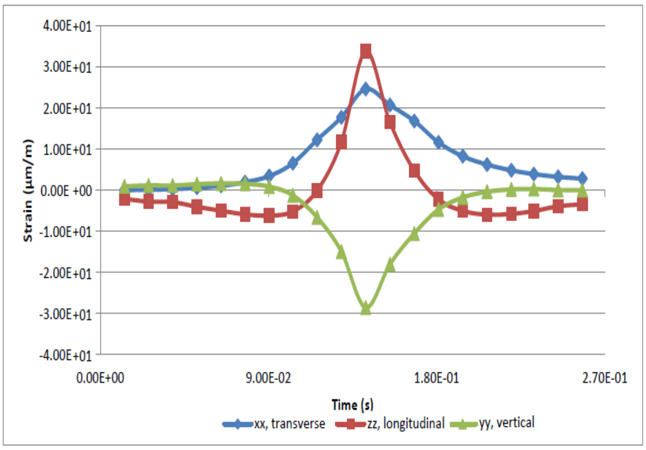

Figure Time-strain curves at the bottom of AC layer

V. CONCLUSIONS AND RECOMMENDATIONS

strain plots witness the same strain patterns obtained from the field tests. The pavement cross section strain plots indicate that in the new designed pavement structure the strain values of the thickness reduced part have indeed increased. However, it is encouraging to see that the strain responses of the thickness unchanged part, which is the heavy traffic lane, are not influenced by the reduced part. The horizontal strain values at the bottom of asphalt layer also shows that unlike the assumption used in the Dutch design method, in most cases, the longitudinal and transverse strains are not equal. Since both directions have a non-negligible chance to produce the maximum strain, the fatigue prediction should be executed based on both longitudinal and transverse strains. Following the same procedure used in the OIA as well as the Dutch design method, the performance prediction for both the original and the new designed pavement structures are calculated. The results are positive. For the altered light traffic lane the Miner values of both fatigue and permanent deformation increase and turn to be closer to the values of the heavy traffic lane which indicates the material-cost-efficiency is indeed optimized in the new design In conclusion, the new designed pavement structure is evaluated from both design and construction's perspective. All results positively support the application of this new design. It manages to achieve a better material-cost-efficiency without compromising its serviceability or adding extra construction work or maintenance difficulty. The potential of reducing the thickness of the light traffic lanes has been proved. Further research investment is recommended.

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