Road Construction on Soft Soils in Indonesia: A Study on Soil-Pavement Interaction

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ABSTRACT: The soft soils area in Indonesia covers about 10 million hectares or 10 % of the total land area. Because of the low bearing capacity and high compressibility of the soft soils, many roads in this area lose their serviceability before the end of their original design life. One of the causes is that due to the lack of thorough understanding of the behaviour of the soil and its influence on pavement performance, no optimum maintenance measures are carried out. This paper presents a case study of a road on a soft marine clay subsoil in Cilincing, North Jakarta, Indonesia. The road was built in 1980 and since that date many severe structural damages in the pavement occurred due to uneven settlement of the subsoil. To investigate the effects of uneven settlements on pavement response, the finite element method was utilized on a large scale in this study. From an extensive series of analyses, which included uneven settlements as well as traffic loadings, it can be concluded that an integrated soil/pavement analysis provides a much better understanding of the interaction mechanism between pavement and subsoil.

KEY WORDS: Uneven settlements, finite element analyses, road maintenance.

1 INTRODUCTION

Cakung-Cilincing road section (further referred as Cilincing road) extends from the south to the north of Jakarta. Jakarta is the capital city of Indonesia, which is situated on Java Island (Figure 1). The road was built in 1980 and nowadays this road has a rigid pavement with a length of 9.06 km. Every day the road is subjected to busy traffic and heavy loads from trucks and trailers from the largest harbour in Indonesia, Tanjung Priok harbour.

The current composition of the Cilincing road is a rigid pavement with segmental concrete blocks of 5.5 m by 3.5 m wide and 0.25 m thick. The height of the road embankment is 1.5 m to 2.5 m. In some parts of the road, timber piles and geofabric separator were used beneath the embankment to improve bearing capacity and to avoid mixing between embankment material and subsoil.

Figure 1: Cilincing site, North Jakarta, Indonesia.

Recently, with the growing traffic volume and with the increasing number of heavy vehicles, structural damages on the rigid pavement are becoming worse and worse. Continuous maintenance is performed in two ways: firstly, if settlement or pavement depression occurs then the rigid pavement blocks will be overlaid in situ with concrete. Secondly, if severe cracks in the rigid pavement blocks are found, then the concrete blocks will totally be reconstructed. However, Kimpraswil (2002) concluded that these solutions (making the pavement as stiff as possible) do not solve the problems; cracking still occurs both in the rebuilt blocks and in the concrete overlaid blocks. This is the reason that in this study the behaviour of a flexible pavement structure (= asphalt layers on an unbound granular base) has been examined as part of a M.Sc.-project at IHE in Delft, the Netherlands.

2 GEOTECHNICAL CONDITION OF THE SITE

Based on geotechnical data interpretation, the subsoil in this site can be classified as a very soft clay layer from the Holocene age down to 14 m deep. The underlying layer is a clayey silty sand layer and below is a medium dense sandy gravel layer which can be considered as the bearing layer. Figure 2 shows some of the laboratory soil tests results. As seen in the figure, the water content of the soil is very high and makes the subsoil in nearly liquid state. The undrained shear strength profile of this soil is less than 40 kPa, which indicates that the soil has a low bearing capacity. The last right figure shows a soil classification based on the Coduto (1994) chart. Based on this chart, the soil can be classified as moderately compressible to very highly compressible.

3. FINITE ELEMENT MODELLING

A finite element code for geotechnical analysis (Plaxis 8.2) was used in this study. In the Plaxis approach, the asphalt layer is modelled with volumetric elements so that a constitutive model can be assigned to it. Another reason of using the volumetric elements is to be able to select a stress point at the bottom of the asphalt layers. Interface elements were drawn between the asphalt and the underlying base layer in order to investigate the slip (and potential gap) between these layers. The strength reduction factor of these interface elements, which determines the friction between the layers, is assumed to be 0.7 (Brinkgreve, 2002).

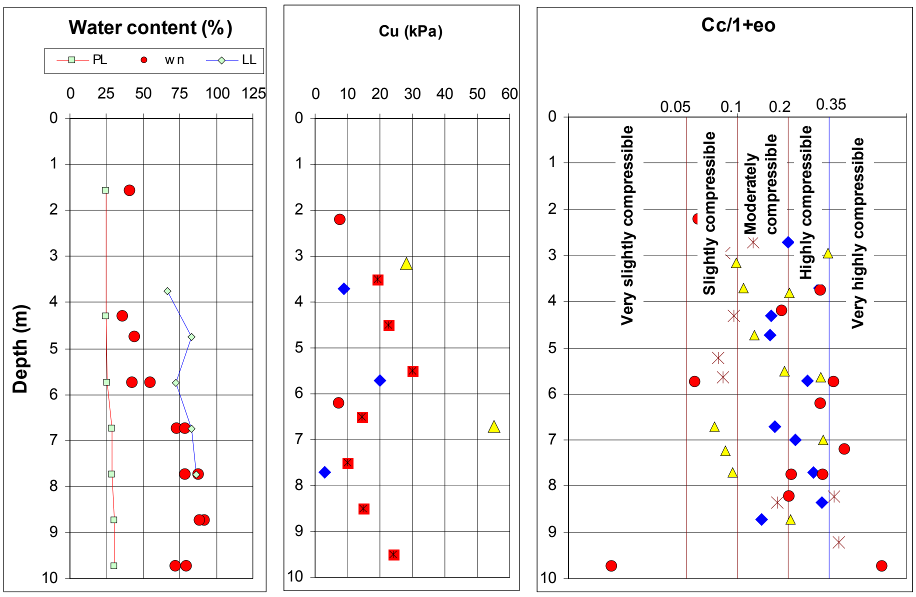

Figure 2: Geotechnical data on the site.

To create the simulation of the uneven settlement, a local zone of poor soil below the pavement structure was introduced in the axi-symmetric pavement model. This model is further referred to as the inhomogeneous soil layer model. It is found that due to this uneven settlement a cavity occurs somewhere under the asphalt pavement. The model should point out what the effect of the cavity is on the stress and strain conditions in the asphalt. As a comparison, a homogeneous soil layer model was also analysed. A wheel load of 280 kPa is applied on a circular area (150 mm in diameter) at the centre of axis of symmetry. The finite element geometry is shown in Figure 3. Note that the pavement structure thickness is determined according to the Indonesian design standard (DPU, 1987), which is based on an empirical approach.

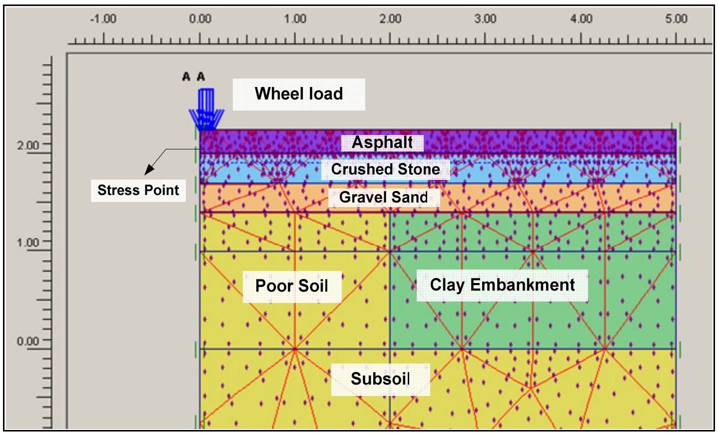

Figure 3: Axi-symmetric model for inhomogeneous soil layer.

The Mohr-Coulomb model with elastic-perfectly plastic behaviour was used for the asphalt layer and unbound granular materials. To model the viscoelastic behaviour of asphalt with this model, the stiffness modulus of asphalt for settlement calculation (long duration loading) was set to 100 MPa and for traffic loading (short duration loading) to 3000 MPa. Besides the stiffness modulus, the model requires cohesion (c) and angle of internal friction (ϕ). For that, a research from Fwa et al (2001) was used and the c and ϕ for asphalt were taken respectively 120 kPa and 35°. The soil and clay embankment was modelled with the soft soil model in Plaxis V8.2, which is a Cam-Clay type model, especially meant for primary compression of nearly normally consolidated clay-type soils.

Six calculation phases were performed on both axi-symmetric models with an inhomogeneous and a homogeneous soil layer to simulate the effect of an uneven settlement. At three moments during the consolidation process a wheel load is applied to determine the response of the pavement. An elasto-plastic consolidation analysis was applied to all phases, as follows:

1. Construction of subbase layer (gravel sand), base layer (crushed stone) and asphalt layer, followed by a wheel load application. The time duration to simulate this phase is 1 day.
2. Consolidation analysis for 500 days to "create" a cavity at the bottom of the asphalt layers. It was assumed that the cavity occurs in half of the duration of the total settlement or approximately in 500 days.
3. After the cavity has occurred, a wheel load is applied in 1 day to determine the effect of the cavity on the pavement response.
4. Consolidation analysis for 1000 days to allow for the pavement to fall into the cavity. It was assumed to occur when 90% of consolidation has been reached or in a total of about 1500 days.
5. A wheel load is applied in 1 day when the pavement has fallen into the cavity, to determine the effect of the cavity on the pavement response.
6. Consolidation analysis for 1000 days.

The calculation stages are summarized in Table 1.

Table 1: Calculation stages.

Phase No.	Identification	Time (days)	Total time (days)	Calculation type	Load input	Remarks
0	Initial phase	0	0	Plastic	Total Multipliers	-
1	Wheel load when construction just finished	1	1	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 3000$ MPa
2	Consolidation	500	501	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 100$ MPa
3	Wheel load when cavity has occurred	1	502	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 3000$ MPa
4	Consolidation	1000	1502	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 100$ MPa
5	Wheel load when pavement has touched cavity	1	1503	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 3000$ MPa
6	Consolidation	1500	3003	Consolidation	Staged Construction	$E_{\text{Asphalt}} = 100$ MPa

The pavement response (in terms of horizontal tensile strain at the bottom of the asphalt layers) along with the calculation scheme (top part) is shown in Figure 4. The figure compares the tensile strain in the homogeneous and in the inhomogeneous model. As can be seen, the tensile strain in Phase 1, 3 and 5 in the homogeneous model is relatively constant. On the contrary, the strain in the inhomogeneous model is increasing particularly from Phase 1 to

Phase 3. It also appears that in Phase 2, the strain is increasing although no wheel load is imposed onto the pavement model. This effect occurs due to uneven settlement, which creates a small cavity between the asphalt and the base layers. When the pavement falls in the cavity by its own weight, it will generate extra tensile strain. This extra strain is further referred to as the pre-straining effect. The location of the cavity between the asphalt and the base layers in phase 2 is visualized in Figure 6 (with a higher zoom-factor it would be actually visible).

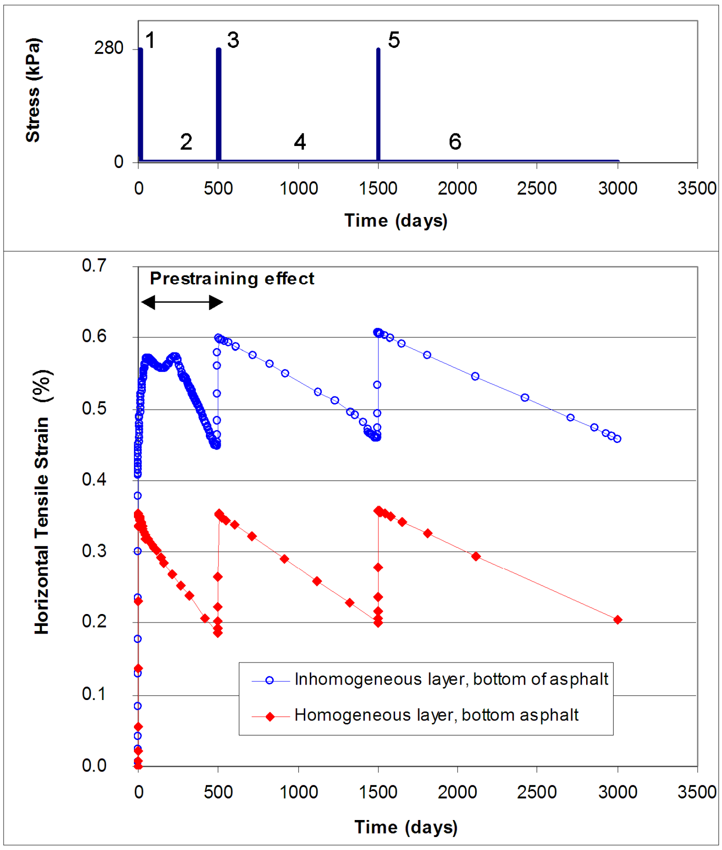

Figure 4: Horizontal tensile strain at the bottom of the asphalt layers in time.

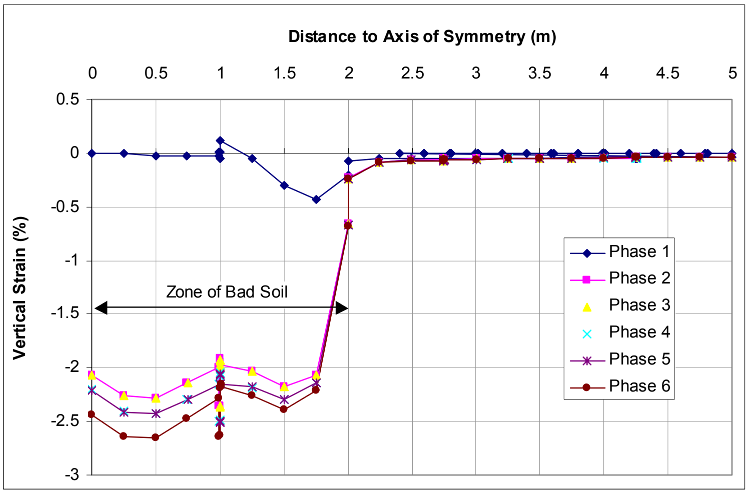

Figure 5: Vertical strain at the top of the subgrade.

Figure 5 shows another flexible pavement design criterion, i.e. vertical compressive strain at the top of subgrade. It is clear that the effect of differential settlement on the vertical compressive strain is significant; the difference in vertical strain in the zone of bad soil and the adjacent soil is about 2 %. It is also clear that the vertical compressive strain is primarily due to subsoil deformation (consolidation settlement).

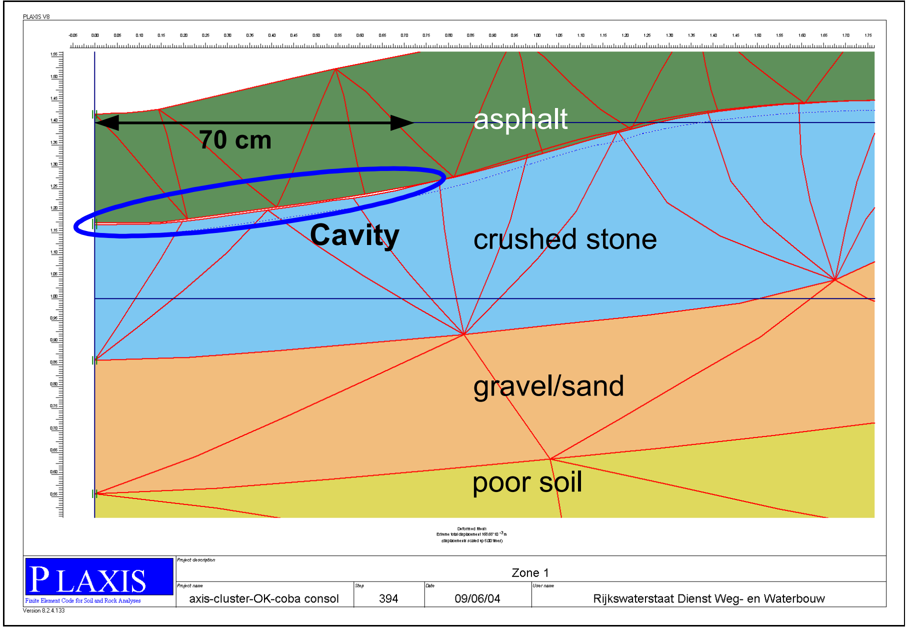

Figure 6: Deformed mesh in phase 2: consolidation 500 days.

4. PARAMETRIC ANALYSIS OF EFFECT ASPHALT THICKNESS

Figure 7 shows the influence of asphalt thickness on the horizontal tensile strain at the bottom of the asphalt layers. Interesting to note is, that when the asphalt is less than 170 mm thick, the tensile strain increases in Phase 2, although the wheel load has been deactivated in the model. It can be inferred that this behaviour is due to the pre-straining effect.

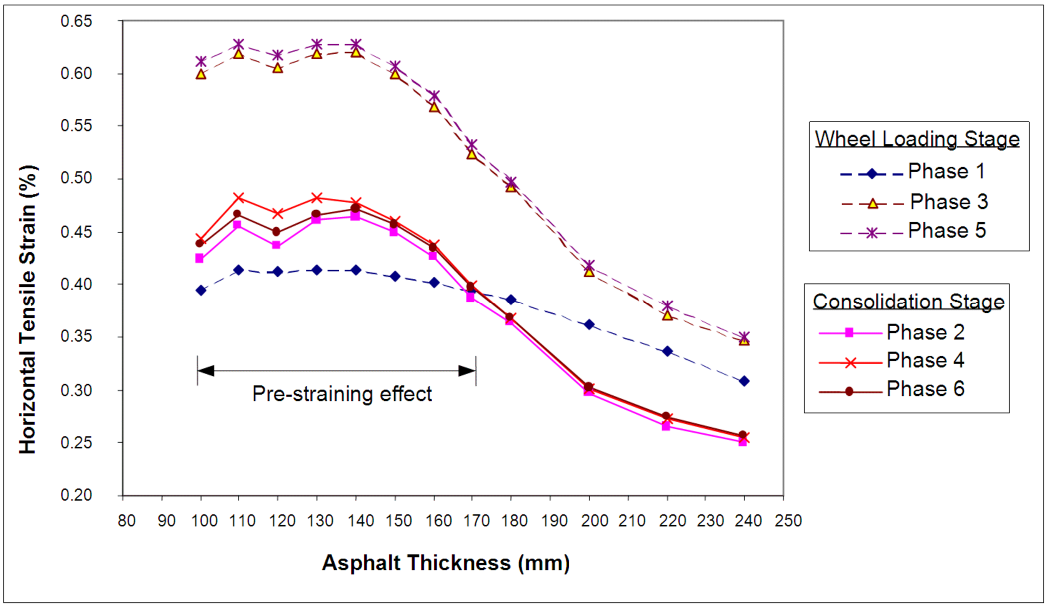

Figure 7: Effect of asphalt thickness on horizontal tensile strain at bottom asphalt.

The reason for the behaviour described above, becomes understandable from Figure 8. It is obvious that the thick asphalt pavement provides a better load-spreading capability than the thin layer. The sharp vertical stress distribution in the thin asphalt layer will create larger differential settlement as shown in Figure 8. Because the thin asphalt layer has a low flexural rigidity (bending stiffness), only some part of the asphalt layer under the loaded area falls into the cavity. Because of that, the occurring gap in the thin asphalt layer is larger than in the thick layer. This causes that the pre-straining effect becomes more pronounced in the thin asphalt layer.

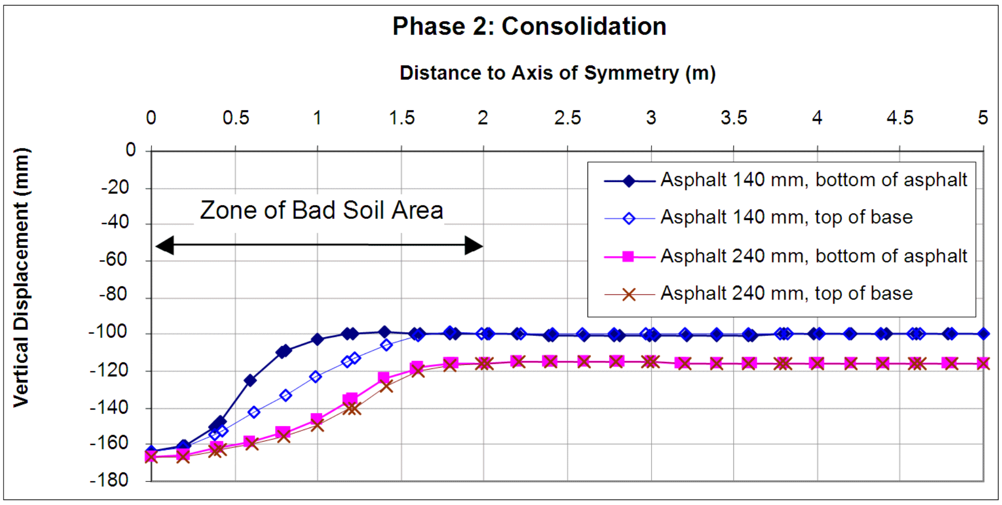

Figure 8: Gap between asphalt-base layers for two asphalt thicknesses.

5. PARAMETRIC ANALYSIS OF EFFECT ASPHALT STIFFNESS

Figure 9 shows the influence of asphalt stiffness and asphalt thickness on the vertical stress at the top of the subgrade. It appears that the asphalt stiffness is more important than the asphalt thickness in reducing subgrade vertical stress. Because of this, the horizontal strain at the bottom of the asphalt is also reduced considerably more by asphalt stiffness than by asphalt thickness (see Figure 10).

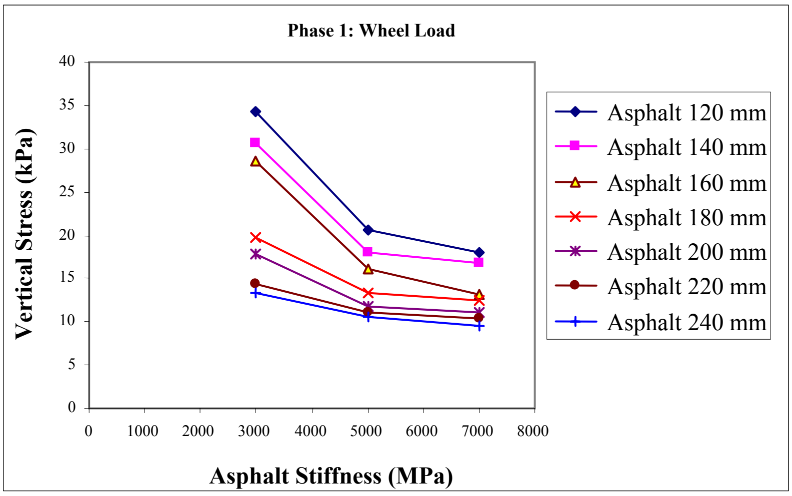

Figure 9: Vertical stress on top of subgrade as a function of asphalt stiffness and thickness.

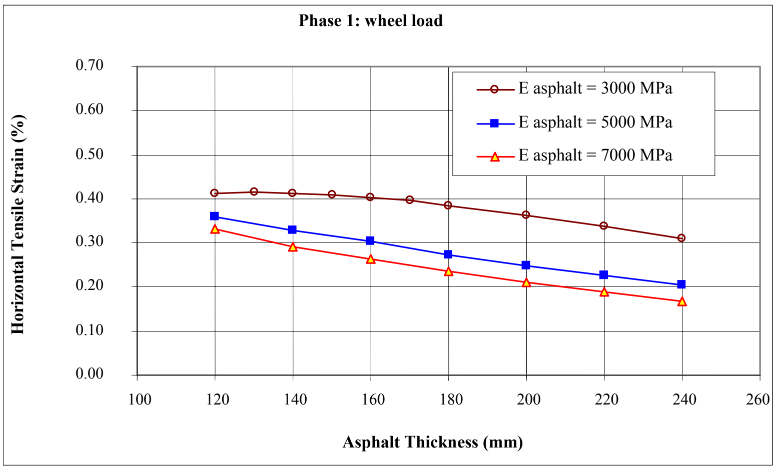

Figure 10: Asphalt stiffness and thickness vs. horizontal tensile strain in phase 1.

The subgrade strain reduction by increasing the asphalt stiffness causes higher shear stress in the asphalt layers themselves. Figure 11 shows shear stress distributions with depth directly under the edge of the loaded area for various asphalt stiffnesses in Phase 1. It can be observed that shear stresses increase vastly when the asphalt layer becomes stiffer.

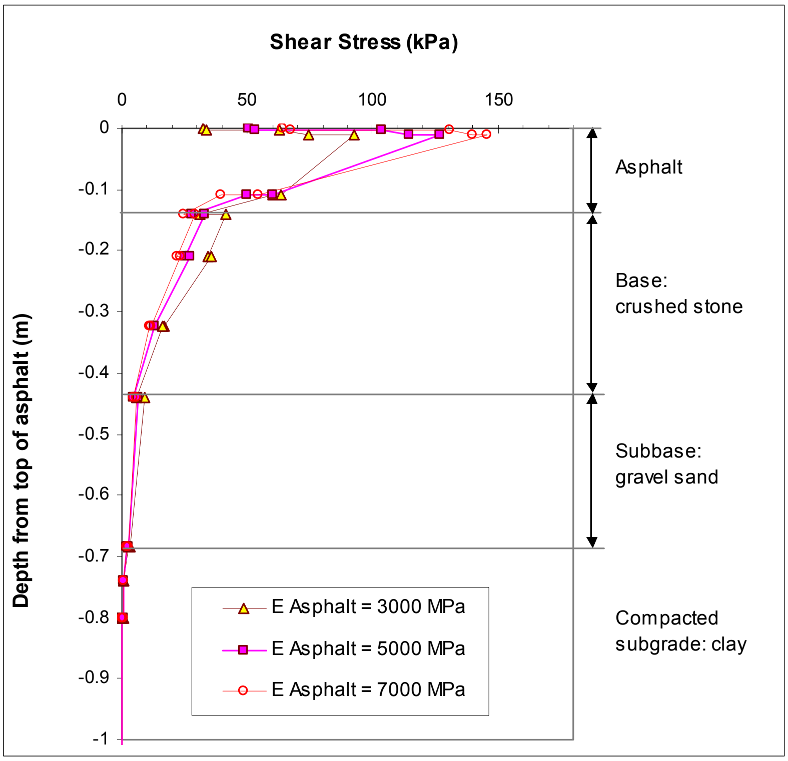

Figure 11: Shear stress distribution for various asphalt stiffnesses.

As mentioned above, an increase in asphalt stiffness will reduce horizontal tensile strain at the bottom of the asphalt layers significantly; however, it will create a larger tensile strain at the top fibre of the asphalt. It is clear that in the stiff asphalt a counter flexion occurs at 1.2 m to 2.5 m from the axis (Figure 12). In Figure 13, the tensile strain at the top of the asphalt occurs at 0.5 m to 2.0 m from the axis and the maximum strain can be as high as 0.7 %. Because of this effect, crack initiation may occur from the top of the asphalt instead of from the bottom.

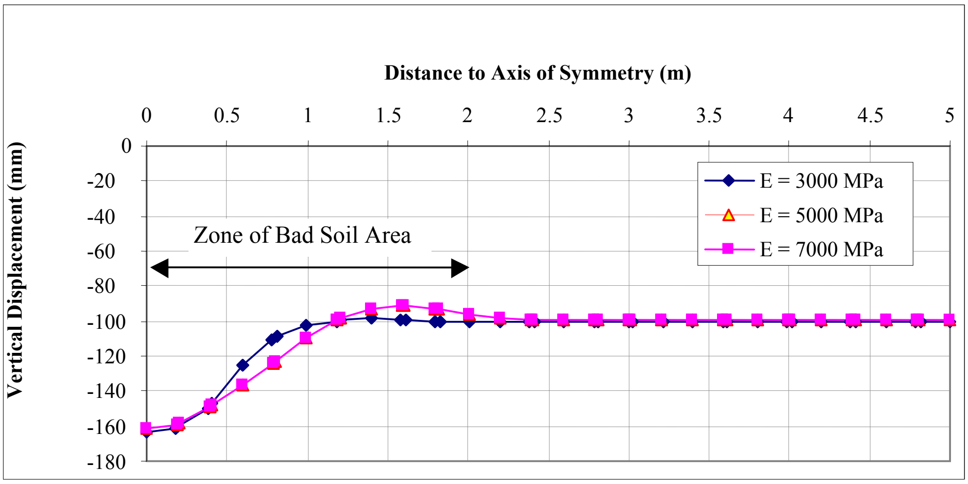

Figure 12: Effect of asphalt stiffness on vertical displacement profile.

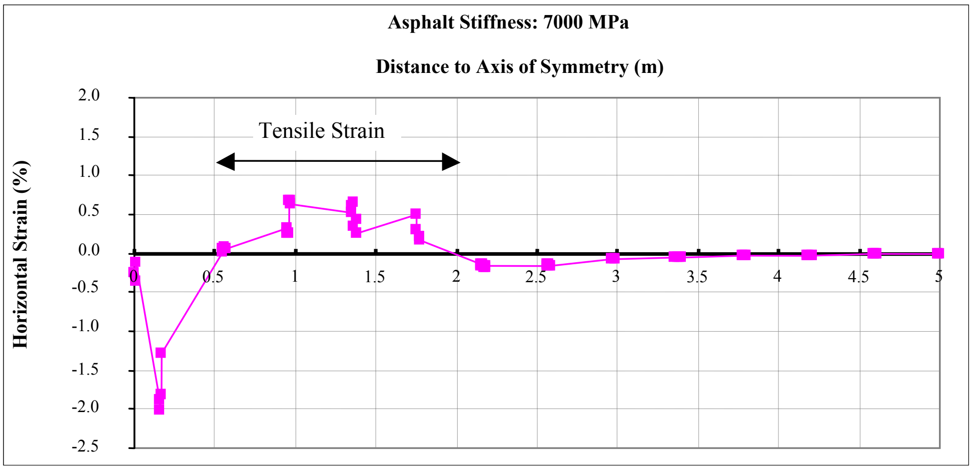

Figure 13: Horizontal strain at the top of the asphalt layer in phase 2.

6 CONCLUSIONS AND RECOMMENDATIONS

By using the finite element method, the mechanisms of subsoil-pavement interaction on soft soils have been examined in a M.Sc.-study. One of the most important mechanisms seems to be the so-called pre-straining effect. This effect occurs due to uneven settlement at weak spots, which creates a cavity between asphalt and underlying layers. It will generate a higher tensile strain in the asphalt layer even when there is no wheel load imposed onto the pavement structure. The effect of a weak spot is also more pronounced in thin asphalt layers than in thick asphalt layers, because the cavity is larger underneath the thin layer.

Based on the investigation, the use of a very stiff pavement in soft soil areas (like the current Cilincing road) is not the correct measure against the uneven settlement. The key in suppressing differential settlement in the pavement structure is by sufficient asphalt thickness with sufficient stiffness modulus. However, increasing the stiffness modulus of thin asphalt layers will make the structure prone to build up of high tensile strains at the surface and high shearing stresses in the asphalt layers themselves. Therefore, in determining the optimum stiffness modulus of the asphalt, a thorough evaluation of flexural resistance and shearing (rutting) resistance should be carried out, especially for climatic conditions such as in Indonesia.

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