COMPARISON OF COMPACTION BENEATH REINFORCED AND UNREINFORCED PAVEMENTS SUBJECTED TO TRAFFIC LOAD

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Abstract: A method for predicting the traffic-load-induced settlement of road is presented in the paper. The behaviour of pavement-geosynthetic-subgrade systems is analysed from the viewpoint of subgrade compaction under cyclic loading. Analyses are performed for typical flexible pavements and plain strain conditions are assumed. Cohesionless ground is used as pavement subgrade. Traffic load is simulated by applying a pair of concentrated forces. The maximum values of strains in subgrade due to the first cycle of traffic load application are calculated by using a numerical method (based on the Finite Element Method).

Then the selected model for compaction of soil is used to prediction of subgrade settlements under increasing load cycles. The model was formulated in terms of the cyclic stress and strain amplitudes. It is based on two constitutive equations. The first of them, formulated in a differential form, describes the compaction due to cyclic loading. The second equation describes the correlation between the cyclic shear stress and strain amplitudes.

A study is conducted to determine the effect of reinforcement on the traffic-load-induced permanent deformation of road structures. It is assumed that a single geosynthetic layer is installed between subgrade and pavement. Unreinforced and reinforced road settlements are compared. Analysis results of the cases with variable parameters (subgrade properties, reinforcement stiffness, magnitude of loading) are presented.

Keywords: flexible pavements, reinforcement, cyclic load, compaction, subgrade

INTRODUCTION

It is known that deformations occurring in the pavement structures tend to increase in magnitude as the number of load applications increase. The mechanism of this repeated loading degradation, in spite of extensive research, has not yet been solved satisfactorily (Douglas, 1997; Chai & Miura, 2002). The most common design approach to this problem based on empirical correlation between the case of a single load application and the effects of repeated loading (see for example: Giroud & Noiray, 1981; Giroud *et al*., 1984; De Groot *et al*., 1986; Burd, 1995; Kazimierowicz-Frankowska, 2007). There is a lack of theoretically based predictions that deal with the response of pavements under repeated loading. Existing methods are often difficult to use in engineering practice (Chai & Miura, 2002). Therefore, this subject certainly needs further investigations in order to elaborate effective models describing pavement deformations under repeated loading. An attempt to resolve this issue is presented in this paper.

The paper has three main objectives:

- First, to present a theoretically based method for predicting traffic-load-induced settlements of roads.
- Second, to identify those factors which have a significant role in increasing pavement deformation due to traffic.
- Third, to compare permanent deformations of flexible pavement placed on subgrade with and without reinforcement layer and to investigate the influence of geosynthetic layer on traffic-load-induced settlements.

STATEMENT OF THE PROBLEM

The behaviour of a pavement-subgrade system is analysed from the viewpoint of ground compaction. It has been shown in previous publications (Chai & Miura, 2002) that the permanent deformation of the pavement subgrade due to traffic load can be one of the important factors which controls the design life as well as the maintenance cost of roads constructed on soft soil. The impact of subgrade compaction on pavement deformation is analysed in the paper. A typical profile, commonly used for designing roads with ordinary loads, is used to compare permanent deformations in typical flexible pavement structures with and without reinforcement layer due to traffic and a schematic representation of such a simple pavement-subgrade profile is shown in Figure 1. It consists of three layers (in the case of the unreinforced pavement – Figure 1a). Two top layers correspond to pavement structure (bituminous and base elements of road). The bottom layer represents the pavement subgrade (natural soil).

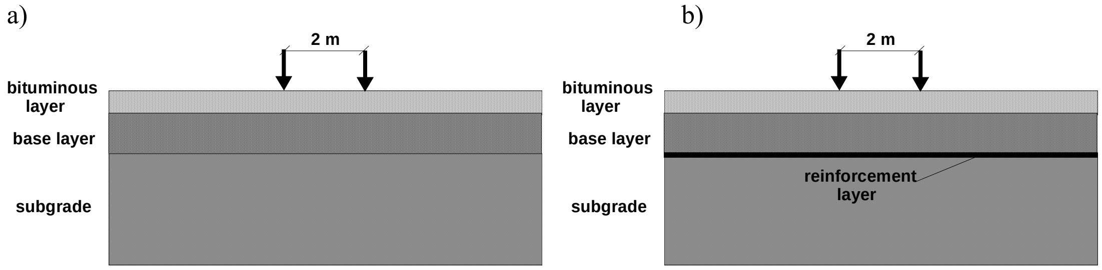

Figure 1. Schematic representation of structures used in analyses: a) pavement without geosynthetic; b) pavement after inclusion of the geosynthetic layer.

In the case, when behaviour of the reinforced road is analysed, a single geosynthetic layer is added between the base of pavement structure and subgrade and the analysed system consists of four layers (see Figure 1b).

The current study is limited to cases when the road is subjected only to repetitive loads due to traffic. A dual wheel load of varying amplitude (modelled by a pair of concentrated forces in the range between 20 kPa and 150 kPa) is applied to the pavement surface. The resulting strain at the subgrade is computed. A numerical, finite element, method (FEM) of analysis using the computer program Hydro-Geo (Dłużewski, 1997) was undertaken to calculate the maximum strains of modelled flexible pavements under static loading while varying the main parameters of the pavement-subgrade system. Table 1 gives an overview of the investigated cases. The selected model for compaction of soil is then used to predict subgrade settlements under increasing load cycles.

Table 1. Overview of the investigated cases.

Variable parameter	Range of variation
Young Modulus of pavement subgrade	50 MPa – 1200 MPa
Young Modulus of base layer	250 MPa – 10 000 MPa
Young Modulus of bituminous layer	1000 MPa – 10 000 MPa
Thickness of bituminous layer	10 cm – 30 cm
Magnitude of loading	20 kN – 150 kN

METHOD OF ANALYSES

The analyses of strain states in the pavement and in the subgrade beneath the pavement for the case of a single application of a wheel load, were carried out by using the finite element method. A typical FEM mesh used in the analysis is shown in Figure 2. Eight-node isoparametric, rectangular elements are used throughout the mesh. The number of elements used for each material is as follows: bituminous layer, 40; base course, 40; subgrade, 100. Conventional kinematic boundary conditions are adopted, i.e. roller support on all four vertical boundaries of the mesh and fixed support at the bottom of the mesh.

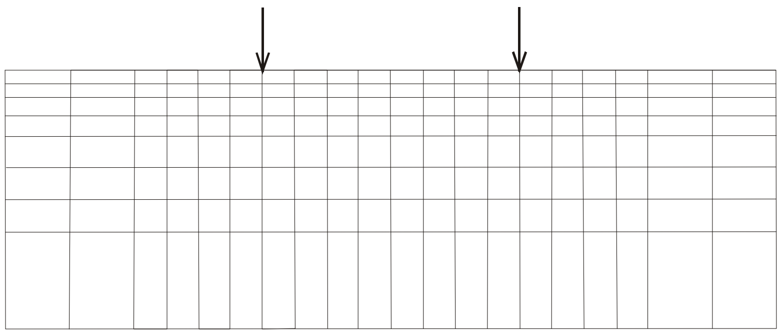

Figure 2. Finite element mesh used in numerical calculations.

The following general assumptions are made in the FEM analysis:

- Each layer of the pavement structure is considered to be continuous, uniform and isotropic.
- The plain strain conditions are assumed.
- All the pavement and materials are assumed to be linear elastic. Therefore, each layer is characterized by its thickness, Young's modulus (E) and Poisson's ratio (ν). The initial material properties used for each pavement layer are shown in Table 2.
- The present study is limited to the case in which the cohesionless ground is used as the subgrade of the pavement structure. Linear elastic material behaviour is assumed for the layer.
- Perfect interaction between geosynthetic and soil is assumed (i.e. there is no slip between the layers).
- The reinforcement layer is modelled using a structural tension element cable of high modulus of elasticity. The input parameters adopted in a software program, to simulate behaviour of reinforcement layer are taken after Bergado & Teerawattanasuk (2008) who indicate that the values can be used to realistically simulate the behaviour of geogrids. Grid reinforcement is modelled using linear elastic structural cable elements with a Young's modulus 2.0 x 10^{11} Pa, and cross-sectional area of longitudinal bar per meter width of 180mm^2 (Bergado *et al*., 1995).

Table 2. Parameters of materials used in the FEM analysis.

Layer	Young Modulus [MPa]	Poisson Ratio
Subgrade	50 – 1200	0.25
Base layer	250 – 10 000	0.25
Bituminous layer	1000 – 10 000	0.35

A model for compaction of saturated sand subjected to cyclic loading proposed by Sawicki (1987) is used in the prediction of subgrade settlements under increasing load cycles. The model is formulated in terms of the cyclic stress and strain amplitudes. The first equation describing the model is the compaction law is in the following form:

$$\frac{d\Phi}{dN} = D_1 J \exp\left(-D_2 \Phi\right),$$

where N is the number of applied loading cycles. D_1 and D_2 denote constants for a given soil (dimensionless). They should be determined experimentally. They describe the compaction properties of soil used as pavement subgrade. The compaction Φ (expressed in unit 10^{-3}) defines the irreversible, positive porosity change due to cyclic shearing:

$$\Phi = \frac{n_0 - n}{n_0},$$

where n_0 is an initial porosity of investigated soil and n denotes its porosity.

The quantity ***J*** appearing in the first equation is defined as the second invariant of strain amplitudes deviator:

$$J = \frac{1}{2} tr \left(\hat{E} \right)^2 .$$

The second fundamental equation describing the model of soil compaction is the stress-strain relationship between cyclic amplitudes. The shear response relationship is in the following form:

$$\hat{T} = 2G \hat{E} ,$$

where $\hat{T}$ is the second invariant of stress amplitudes deviator and *G* (shear modulus) is a coefficient which has to be determined experimentally.

Having determined the maximum strains in a subgrade, the second invariant of the strain amplitude deviator *J* (expressed in unit 10^{-6}) can be computed using the following formula:

$$J = {}^{1}/_{3} \; [(E_x - E_y)^2 + E_x E_y] + E_{xy}{}^2,$$

where E_x, E_y and E_{xy} denote elements of the strain tensor. X corresponds to the horizontal direction, Y to the vertical direction and XY to the shear component of strains. Having determined the maximum strains in a pavement subgrade (subjected by monotonic loading) the value of the strain amplitude deviator *J* should be computed in each finite element and is assumed to be constant inside each finite element of the subgrade system. Therefore it is possible to compute the compaction Φ in each finite element as:

$$\Phi = C_1 \ln\left(1 + C_2 JN\right).$$

The relation between quantities C_1 and C_2 from the last equation and constants D_1 and D_2 from the first equation can be expressed as:

$$C_1 = \frac{1}{D_2} \quad \text{and} \quad C_2 = \frac{D_1}{C_1}.$$

Having determined the compaction Φ in each finite element, the settlement *S* of each finite element column can be computed using the following formula:

$$S = \frac{n_0}{1 - n_0} \int_{h_1 + h_2}^{h_1 + h_2 + h_3} \Phi dy ,$$

where h_1, h_2, h_3 denote, respectively, thickness of bituminous, base and subgrade layers in m.

A simple computer program written by the author of this paper is used to predict subgrade settlements under increasing load cycles. Calculations are performed for cohesionless subsoil (sand *"Lubiatowo"*), characterized by the compaction parameters given in Table 3. They have been determined experimentally in the Geomechanics Laboratory of the Institute of Hydroengineering. The influence of varying subgrade parameters on obtained results is investigated. Calculations are performed for various initial densities of subsoil sand (dense, medium dense and loose sand characteristics are taken into account).

Table 3. Composition characteristics for subgrade sand.

Initial density	Relative density	Maximum void ratio	Minimum void ratio	D_1	D_2
Dense	0.86	0.84	0.52	4.87	0.19
Medium dense	0.55	0.84	0.52	6.04	0.11
Loose	0.29	0.84	0.52	4.64	0.07

RESULTS AND DISCUSSION

A “base” case, for the sake of comparative analyses, is defined as a section with the following parameters: bituminous thickness of 0.2m, bituminous layer elastic modulus of 10^4 MPa, base layer elastic modulus of 10^4 MPa and subgrade elastic modulus of 10^3 MPa. The results of predictions obtained for pavement settlements for the cases with variable parameters (magnitude of loading; thickness of bituminous layer; compaction and elastic properties of subgrade; stiffness of bituminous and base layers; number of applied cycles of loading) are presented below.

The analyses of pavement settlements are performed from the viewpoint of subgrade compaction. Therefore, in the first step, the influence of the variability in the initial subgrade densities is investigated. Varying the values of the subgrade density from dense, through medium dense to loose sand (see Table 3) allows the effect on the pavement settlement to be determined. Typical resultss (obtained for pavement without geosynthetic layer) are presented in Figures 3 and 4. Both of them are plotted for the “base” case (with basic parameters characterized above) and differ only in the magnitude of the acting loading. Figure 3 shows results obtain for the case, when a dual wheel load of magnitude P=20kPa is applied to the pavement surface. Figure 4 shows the results obtained when traffic loading was simulated by pairs of forces of magnitude P=50kN. Both show results obtained for three different numbers of cycles of applied loading. It may be observed that the settlement profiles obtained for different initial density characteristics of pavement subgrade differ greatly. As expected, the greatest deformations are observed for pavements placed on loose sand; the lowest - for those built on dense subgrade.

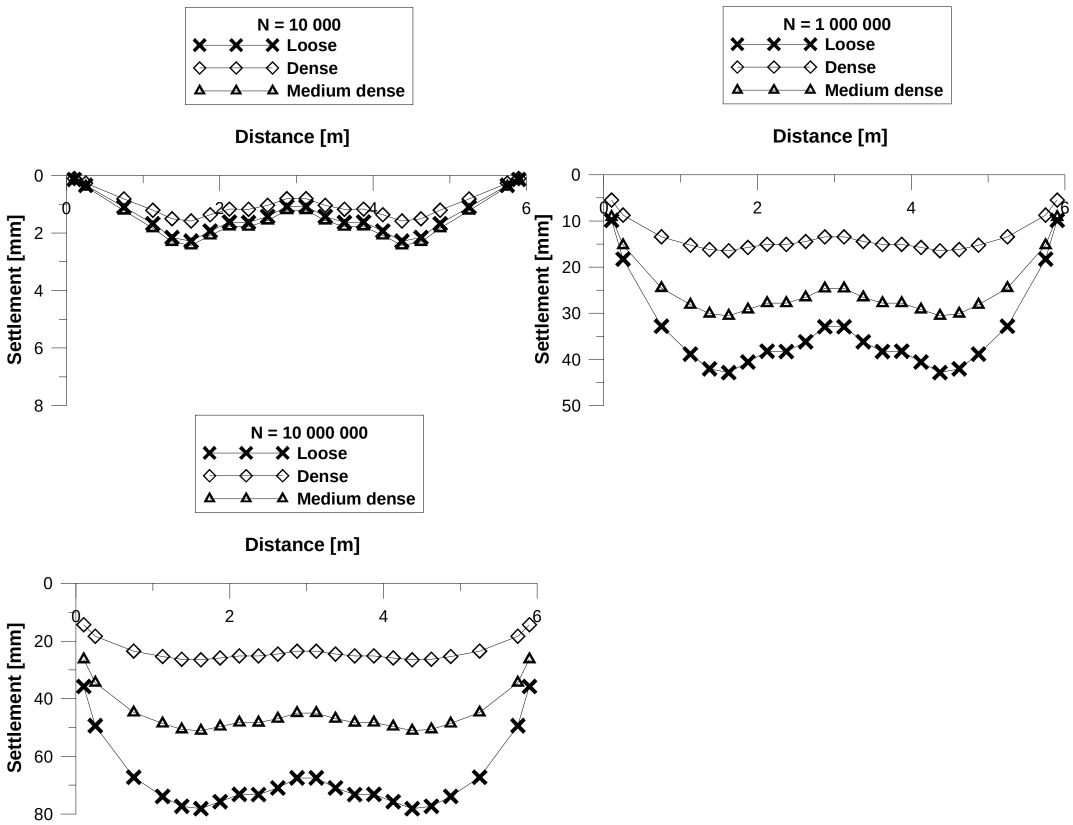

Figure 3. Surface settlement profiles for various initial densities of subgrade sand. Magnitude of loading: P=20kN.

It is clear that the initial density characteristics of pavement subgrade strongly influence pavement settlements. The results confirm the well-known fact that pavements should be built on well compacted subgrades. The results also show that poor subgrade compaction can cause significant increases in pavement deformation during the service life of roads. As can be seen, from Figures 3 and 4, depending on the dense ground used as subgrade, pavement settlements can be reduced by up to two times to those appear in pavements placed on the loose soil.

The qualitative character of the settlement profiles obtained for different values of loading is the same in both cases. The quantitative character of the curves depends on the magnitude of loading. It is clear that the predicted settlements increase with increasing values of applied load. The magnitude of applied loading can be considered to be an important factor that influences the calculated results.

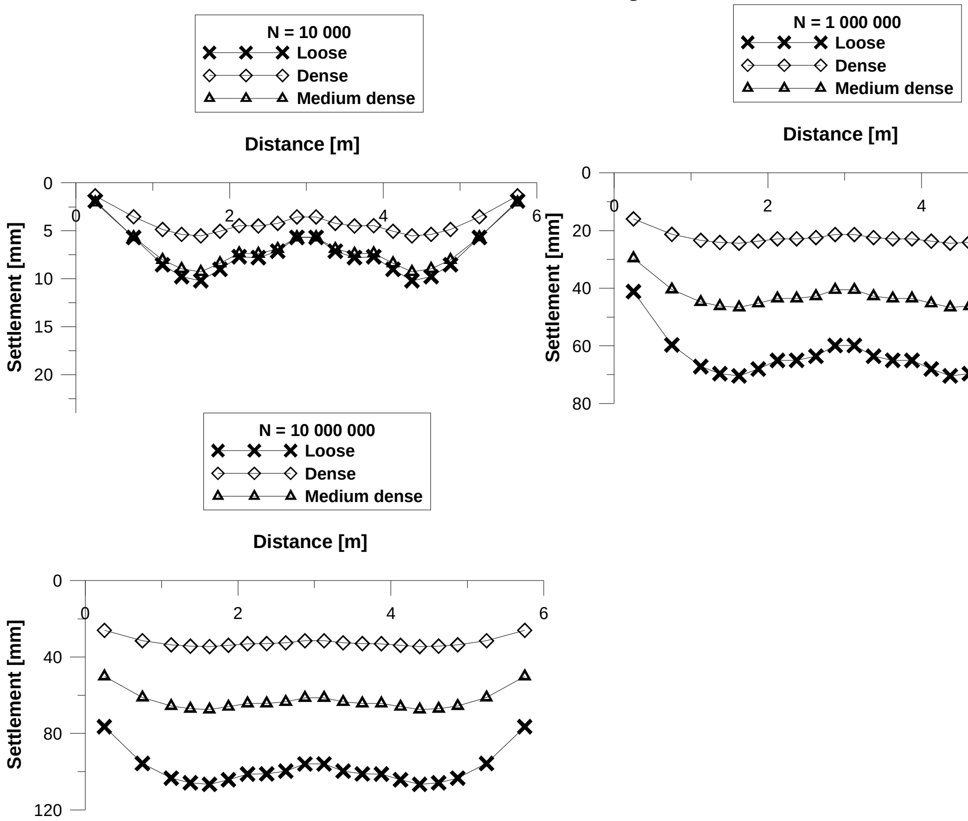

Figure 4. Surface settlement profiles for various initial densities of subgrade sand. Magnitude of loading: P=50kN.

In the next step, the effect of the inclusion of the reinforcement layer on subgrade settlements due to traffic is studied. Figures 5 and 6 present comparative pavement settlement profiles for cases with and without the reinforcement layer. For these analyses all other parameters of the investigated pavement-subgrade system were kept constant. The figures are plotted for the "base" case pavement-subgrade system, the basic parameters of which have been defined above. They show results of comparison obtained for different initial densities of subgrade soil and for a selected number of load applications: 1 000 000 and 10 000 000, respectively. A dual wheel load of magnitude P=50kPa is applied to the pavement surface.

In the cases presented the maximum pavement settlements remain almost constant for pavements with and without a reinforcement layer. The difference is insignificant (see Figures 5 and 6) being only a few percent. However, inclusion of a geosynthetic layer provides more regular settlement profile of pavement. Less difference between the minimum and maximum pavement settlements are observed. The comparison of maximum pavement settlements obtained for different subgrade parameters and different magnitudes of loading for reinforced roads is presented in Figure 7. The calculations have been performed for the subgrade Young's modulus varied in range between 50 and 1200 MPa. It is clear that the maximum pavement settlements decrease with increasing subgrade modulus. The results show a very sharp increase in pavement settlements as the subgrade Young's modulus decreases to below around 300 MPa. Similar correlation is observed for unreinforced and reinforced pavements. For example, the average difference between settlements predicted for pavements with subgrades characterized by the values of the modulus of elasticity: 100 and 1000MPa is below 40% (after 10 000 cycles of loading) and decreases to below 20% (after 1 000 000 cycles of loading).

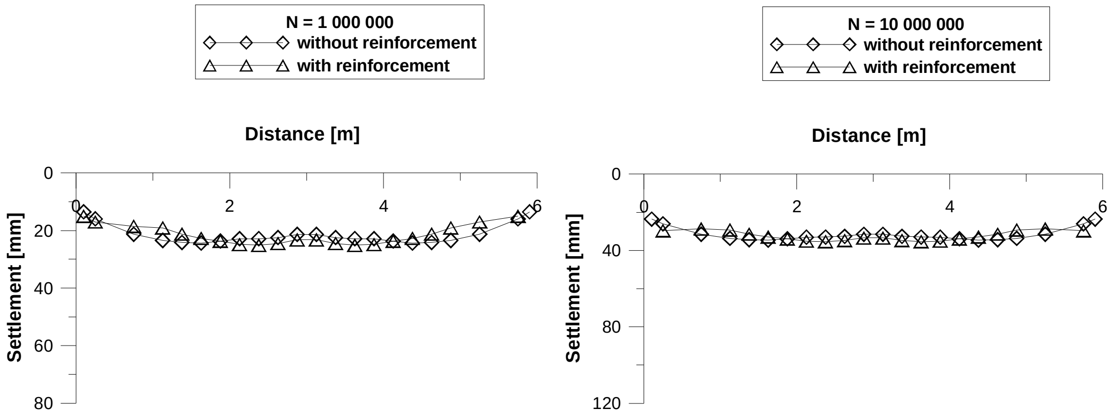

Figure 5. Comparison of reinforced and unreinforced pavements settlements. Dense sand used as subgrade.

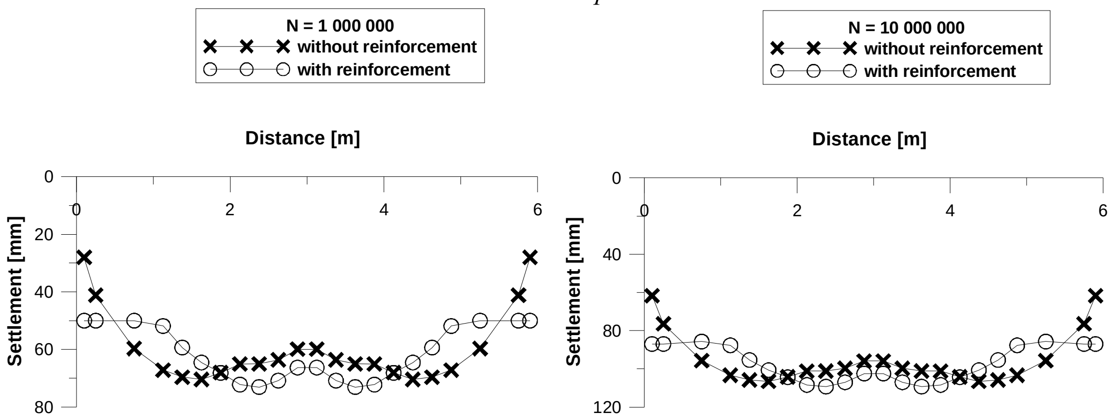

Figure 6. Comparison of reinforced and unreinforced pavements settlements. Loose sand used as subgrade.

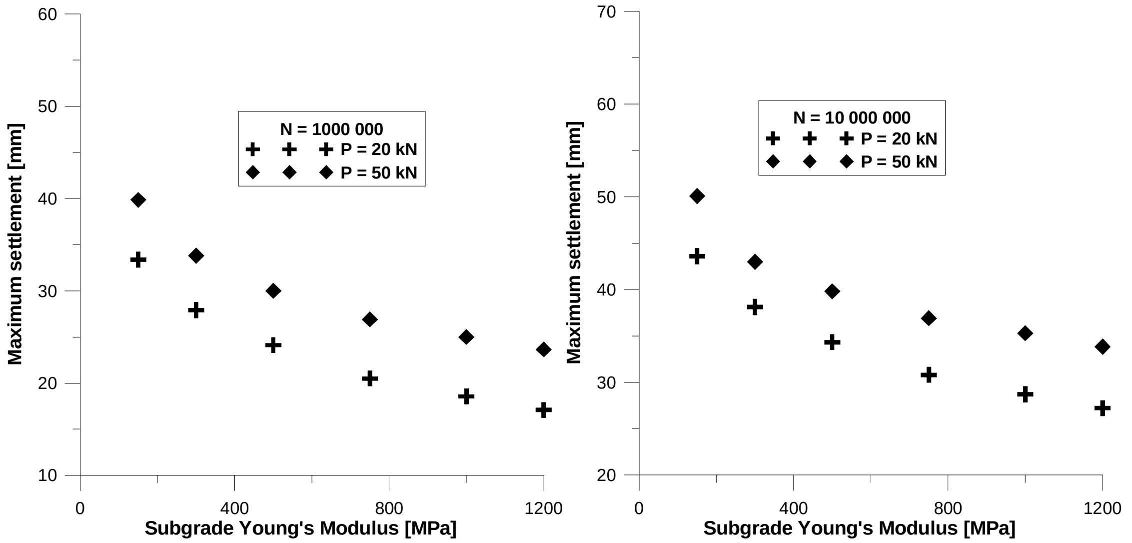

Figure 7. Effect of changing subgrade Young’s Modulus on maximum pavement settlements. Pavement with geosynthetic layer.

The calculated results (Figure 7) also show that average pavement settlements can be reduced by up to two times when the subgrade is characterized by a Young modulus of 500 MPa (compared to a more typical value of E=100 MPa), providing a stiffer support below the road structure.

The results show that the value of the subgrade Young’s Modulus should be considered an important factor that affects the results of pavement settlements. They confirm the well-known fact that pavements placed on stronger subgrades are more resistant to settlements.

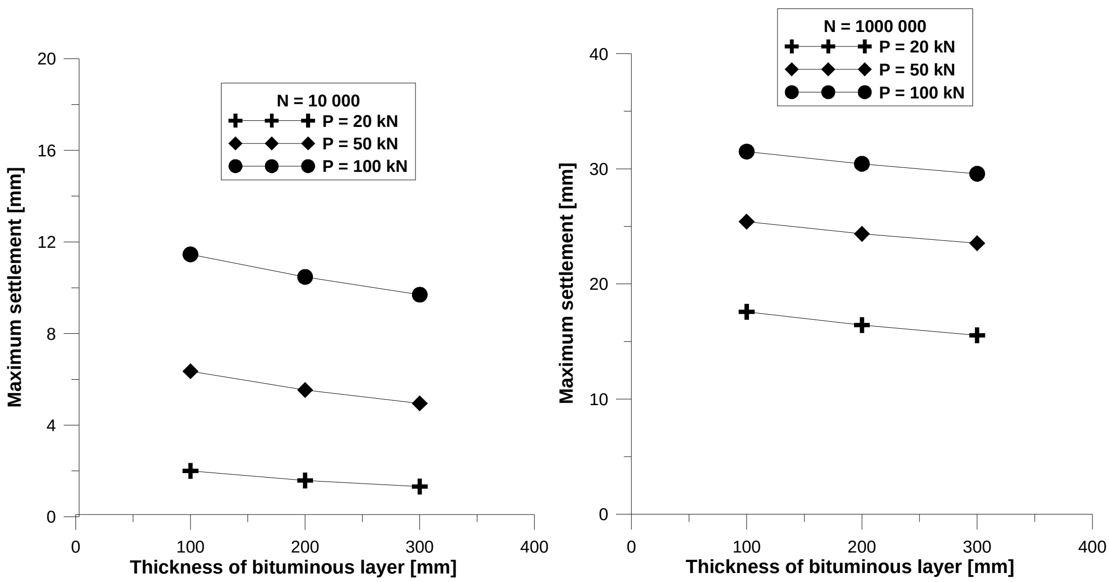

Figure 8. Influence of bituminous thickness on maximum pavement settlement.

Additionally, the influence of such parameters as: bituminous layer thickness and Young's modulus of this layer on pavement settlements due to traffic is presented. The bituminous layer thickness is generally recommended to be in the 50 to 500mm range. Therefore, calculations have been performed for three different bituminous layer thicknesses: 100mm, 200mm and 300mm and for three different magnitudes of loading (20, 50 and 100kN). Figure 8 shows the relation of maximum pavement settlement to the thickness of the bituminous layer. Calculations have been performed for two different numbers of load applications. It may generally be concluded that increasing of bituminous layer thickness caused decrease of pavement settlements, although the differences are relatively insignificant – around a few percent.

The effect of changing the Young's modulus of the bituminous layer on maximum pavement settlements is shown in Figure 9. Calculations have been performed for decreasing values of bituminous layer Young's modulus in the range between 10 000MPa and 1000 MPa. As shown in Figure 9, the calculated pavement settlements are nearly constant, reducing only very slightly less for the stiffer bituminous layer.

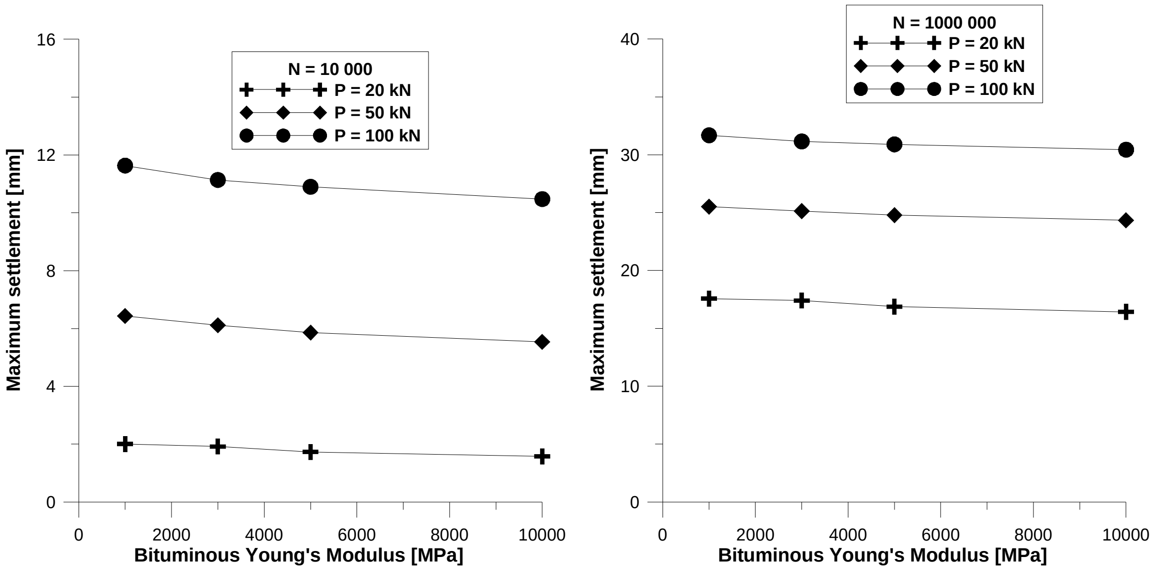

Figure 9. Effect of changing bituminous layer Young's Modulus on maximum pavement settlement.

The effect on the maximum pavement settlements of varying the number of applied loading cycles from 1 to 10 000 000, has been studied. Typical results are presented in Figure 10. It shows the relation of maximum pavement settlement and the number of applied load cycles. It has been plotted for reinforced and unreinforced pavements built on a dense sand subgrade. They are plotted for the "base case" pavement structure (characterized by parameters described above). The same qualitative and very similar quantitative character of curves (which showed variation of maximum pavement settlements with number of load application) is observed in both cases. It can be noted, that the strain rate tends to decrease with the number of applied load cycles.

a)

b)

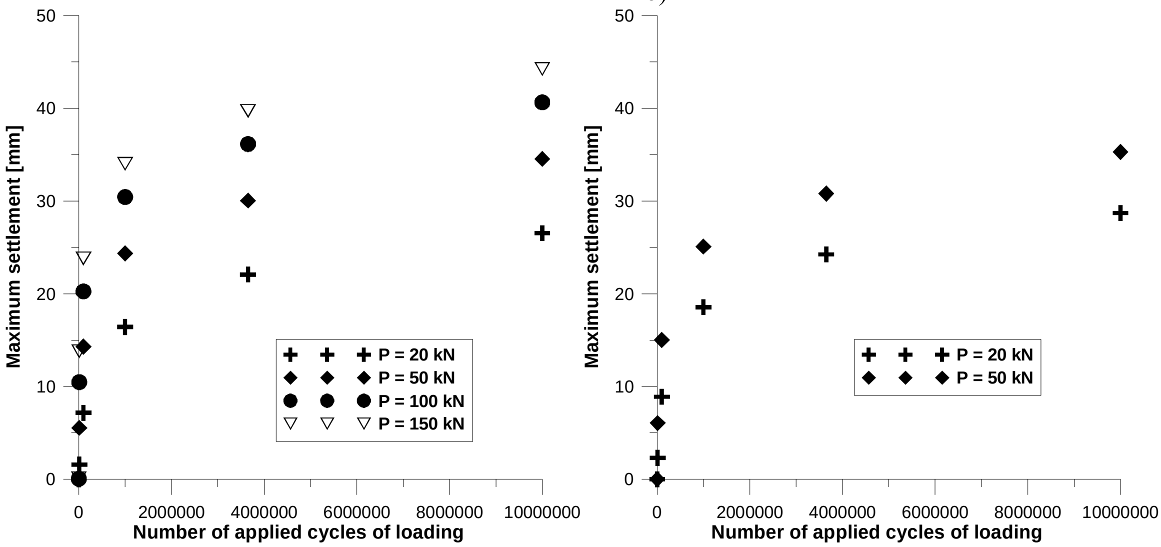

Figure 10. Influence of number of load application on maximum settlements: unreinforced (a) and reinforced (b) pavement.

CONCLUSIONS

A carefully selected model for the compaction of soil has been applied to enable the prediction of pavement settlements due to traffic. The behaviour of the pavement-subgrade system has been analysed from the viewpoint of subgrade compaction. Although, the results obtained from calculations are far from being exhaustive, based on them the following preliminary conclusions can be summarized as follows:

- The stiffness of soil used for pavement subgrade is one of the most important factors controlling the traffic-load-induced permanent deformations of pavements. It can be noted, that settlements increase rapidly when the value of subgrade Young modulus decreases to below 300 MPa.
- The significant influence of initial density characteristics of the pavement subgrade on compaction beneath flexible pavements has been identified. It has been shown that poor subgrade compaction can cause significant increases in pavement deformation during the service life of roads, decreasing the service life of pavement. Pavement settlements can be reduced by up to two times if dense soil is used as subgrade.
- For the cases investigated the benefits accrued from laying a reinforcing layer between the pavement construction and the subgrade are limited to more regular pavement settlement profiles. Maximum settlements calculated for the cases of reinforced and unreinforced pavements are very similar. It is important to note that only one type of pavement subgrade (sand) has been tested. In the next step of investigation, calculations will be performed for different types of pavement subgrade soil.
- Preliminary findings also suggest that the bituminous and base layer parameters play a negligible role on pavement settlements due to traffic. They remain nearly constant, when the parameter values change.
- The magnitude of the applied load and the number of load cycles (passed traffic) also strongly affected pavement settlements. Calculation results show that the magnitude of loading changed the quantitative character of settlements profiles. Their qualitative character is very similar.

Some general remarks may also be made:

- Analyses of pavement settlements have been performed from the viewpoint of subgrade compaction. Obviously, the problem of pavement settlement is more complex and road deformations depend on different parameters, but more extensive discussion on this problem is beyond the scope of the present paper.
- These preliminary calculation results should be verified with reference to a wide experimental campaign in which different pavement constructions are used. A more exhaustive investigation, testing the behaviour of different types of ground used as pavement subgrade and different types of reinforcement, is required to confirm that the above conclusions apply to field-scale construction behaviour.

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