Verification of the structural design parameters for unbound layers of Finnish road structures

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Abstract. Approaches used for the structural design of road pavements are most often combinations of mechanistic and empirical elements, the later ones of which take care of adaptation to the local ambient conditions and available construction materials. In Finland, the standard design approach is to use so called Oedemark's bearing capacity concept, in which the overall stiffness of a road structure is designed to meet a target value set based on the number of ESALs (Equivalent Standard Axle Loads) during an expected service life period. In the meantime, the stiffness value for each structural layer material is estimated based on its granularity and location in road structure, including thus at least to some extent indirectly also the stress conditions under which each material is exposed to during a heavy vehicle loading. However, when the design stiffness values are compared to those determined based on back-calculated response measurement values from two extensively instrumented road sections using a 3D Finite Element model, it is evident that the standard design stiffness values for unbound layer materials are far too low for describing the true mechanical responses of the instrumented road sections. Therefore, they can not be applied as such in any purely mechanistic pavement performance analyses and related service life estimates. More realistic values for structural design parameters are suggested in this paper.

Keywords: Stiffness value, Unbound material, Structural design.

1 Introduction

Due to severe climate conditions prevailing in the Nordic countries like Finland, design against the action of seasonal frost is one of the most decisive aspects in the structural design of roads especially with regard to the overall thickness of road embankments [1]. Because the structural layers must be built fairly thick due to frost action in any case and good quality crushed rock aggregates are abundantly available almost all across the country, it is quite logical that unbound structural layers have an important role in providing the bearing capacity of road structures as well. Correspondingly, the thickness of bound layers is typically rather low, which further emphasizes the importance of unbound aggregate layers and thus, the correctness of their material parameters in the mechanistic design of road structures.

In 2017, Finnish Transport Infrastructure Agency (FTIA) launched an open testing ecosystem of intelligent transport and infrastructure solutions, Aurora. The Aurora test area consists of about 10 km section of main highway E8 South from the village of Muonio in the Western part of Finnish Lapland. Regarding the road infrastructure, a key element of the testing ecosystem consists of two extensively instrumented road sections, one of which is located on stiff subgrade soil area and the other one on a somewhat softer subgrade soil. In this research, results obtained from the Aurora instrumentation sites are utilized in the verification of mechanical modelling parameters describing the true behavior of these two main road sections under the loading effect of a nine-axle heavy truck weighing 740 kN. In the mechanical modelling of road structures, PLAXIS 3D finite element software tool was used.

2 Aurora instrumentation sites

2.1 Description of the monitoring sites

The installed structural monitoring systems utilized in this study include two road sections, Aurora 1 and 2, both located on the main road E8 about four kilometers south from the municipality center of Muonio.

On the Aurora 1 test site, the thickness of structural layers is about 1.1 meters. The substructure of the Aurora 1 site is stiff, and it consists mainly of dense moraine with a number of stones and boulders. Before the structural instrumentations were installed, existing asphalt concrete (AC) layer was removed from the site. After the instrumentation the site was reoverlain using about 120 mm of new AC material that was installed in two layers.

On the Aurora 2 test site, the overall thickness of unbound structural layers resting on top of a sandy embankment is about 1.5 meters. Together with the sandy subgrade it constitutes a substructure with markedly lower stiffness than that of the Aurora 1 test site. In terms of Base Curvature Index, BCI, i.e., the difference in road surface deflections at the distances of 900 mm and 1200 mm from the center of the Falling Weight Deflectometer (FWD) loading plate, the determined values after the installation of measuring instruments were 19 for the Aurora 1 test site and 34 for the Aurora 2 test site, respectively (Table 1). In connection with the renovation works carried out on the Aurora 2 test site area in 2017 the old AC layer of about 70 mm thick was mix-milled with the existing unbound base course layer made of crushed rock. Finally, the road structure was overlain by 90 mm of new AC installed in two layers.

2.2 Instrumentation for structural response measurements

Both the Aurora 1 and 2 test sites are furnished with almost identical structural instrumentation systems, a schematic picture of which is shown in Fig. 1. The instrumentations consist of the following instrument types and the numbers of installed instruments given in parentheses for the Aurora 1 and Aurora 2 test sites, respectively, e.g. no displacement transducers were installed at Aurora 1 and three of them at Aurora 2:

- Displacement transducers monitoring the road surface deflection, RSDEF (0 + 3)
- Acceleration transducers monitoring the road surface deflection, RSACC (20 + 20)
- Horizontal strain transducers at the base of lower AC layer, ACSTR (5 + 6)
- Vertical pressure cells at two levels in unbound base course layer, BCPRE (8 + 8)
- Vertical strain transducers in the unbound base course layer, BCSTR (4 + 4)
- Percostation measurement probes monitoring dielectric value, electrical conductivity and temperature, PERCO (10 + 10)

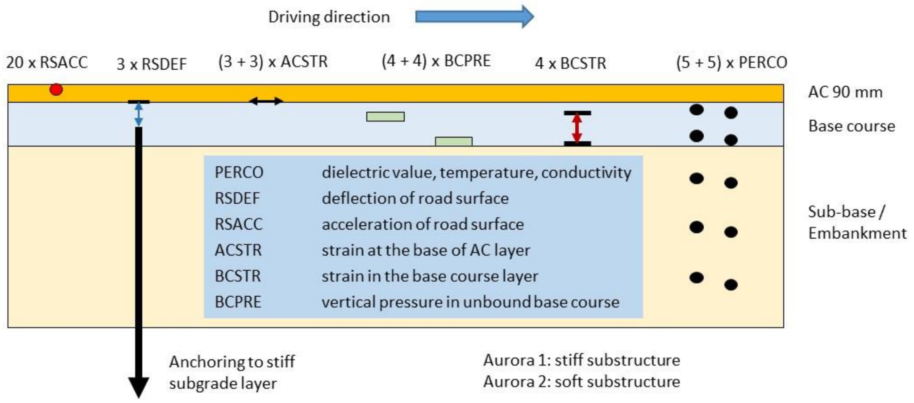

Fig. 1. Schematic picture of structural instrumentations at the Aurora 1 and 2 test sites.

All the structural monitoring instruments on both of the sites have been installed under the outer wheel path of the lane from North to South. Parallel instruments are installed at a spacing of 150 to 200 mm in cross-sectional direction of road to enable a more complete picture of the 3D distribution of structural responses caused by vehicle overpasses to be obtained. The only exception is acceleration transducers that have been installed in two rows with an instrument to instrument spacing of only 100 mm.

2.3 Other installed instruments

In addition to the instrumentation for structural response measurements both Aurora 1 and 2 sites have altogether 10 Percostation® probes monitoring changes in dielectric value, electrical conductivity and temperature at different depths varying from 0.15 m to 1.10 m below the road surface. Meantime, on top of the road vehicle speed, dimensions and wheel path are monitored using a laser scanner and at Aurora 2 site the temperature of road surface is recorded using a thermal camera. A more detail description of these instrumentations as well as data acquisition systems used on the sites have been given earlier together with examples of the acquired monitoring results [2, 3].

3 Bearing capacity analysis

After the installation of measuring instruments and the completion of road rehabilitation works the first step in the structural analysis of Aurora test sites was to perform a series of FWD measurements. The measurements were done on five parallel lines as follows:

- the outer wheel paths in both travel directions
- the centerline of traffic lanes in both travel directions
- the centerline of the road

Altogether 75 FWD tests, 15 on each measurement line, were carried out on both of the Aurora test sites with a measurement point spacing of two meters. The averaged results of all these measurements are summarized in Table 1.

Table 1. Averaged FWD results on Aurora test sites after the installation of measurement instruments and the completion of rehabilitation works.

Aurora 1 test site	**D0**	**D200**	**D300**	**D450**	**D600**	**D900**	**D1200**	**SCI**	**BCI**
FWD averaged	378	265	210	149	111	65	46	113	19
Aurora 2 test site	**D0**	**D200**	**D300**	**D450**	**D600**	**D900**	**D1200**	**SCI**	**BCI**
FWD averaged	543	418	355	279	229	158	124	125	34

The averaged deflection bowls of both Aurora test sites were used as a reference to back calculate the material parameters for unbound structural layers. The back calculation was performed with two different methods and softwares. The first software used in determining the stiffnesses of road structural layer materials was BISAR-PC provided by the oil company Shell [4]. BISAR uses a multi-layer linear elastic modeling approach. The program assumes the layers to be infinite in horizontal direction and to have a constant stiffness. In order to improve the analysis, the layer thicknesses were limited to a maximum of 0.3 meters in the calculations performed in this study.

The size of loading plate (300 mm diameter) and loading intensity (707 kPa) of FWD measurements were replicated on top of the model. The stiffnesses of unbound structural layers were iterated to match the measured deflection bowls. In the last phase of analysis, the resilient moduli of unbound structural layers were calculated based on the simulated stress state in the middle of each unbound layer using the so called kθ [5] Uzan models [6] as shown in Equations 1 and 2, respectively.

$$M_r = K_1 \theta_0 \left(\frac{\theta}{\theta_0} \right)^{K_2} \qquad (1)$$

where M_r is resilient modulus; K_1 is modulus number; K_2 is stress exponent; θ is sum of principal stresses and θ_0 is a reference stress, 100 kPa.

$$M_r = k_1\theta_0\left(\frac{\theta}{\theta_0}\right)^{k_2}\left(\frac{q}{\theta_0}\right)^{k_3} \qquad (2)$$

where q is deviatoric stress; k_1, k_2 and k_3 are model parameters.

Similar determination of unbound structural layer stiffnesses was also performed using Finite Element Method and PLAXIS 3D software. FWD loading was applied on top of 3D structural model presented in Chapter 4. The results of parameter determination for the Aurora 1 test site are shown in Table 2. The k-values used in the analysis represent typical values obtained for Finnish unbound road construction materials, when they have been tested in large-scale repeated loading triaxial test facility as reported by Kolisoja [7].

Table 2. Resilient modulus values determined for the Aurora 1 test site.

Layer	**FEM analysis**				**BISAR analysis**			
	Kθ-model							
	K_1	K_2	θ	$\mathbf{M_r}$	K_1	K_2	θ	$\mathbf{M_r}$
Base course	2500	0,5	296,1	**430**	2500	0,5	273,3	**413**
Subbase	2500	0,5	101,8	**252**	2500	0,5	103,1	**254**
Road structure	2500	0,5	66,3	**204**	2500	0,5	54,6	**185**
	Uzan model							
	k_1	k_2	k_3	$\mathbf{M_r}$	k_1	k_2	k_3	$\mathbf{M_r}$
Base course	2500	0,7	-0,2	**545**	2500	0,7	-0,2	**504**
Subbase	2500	0,7	-0,2	**336**	2500	0,7	-0,2	**334**
Road structure	2500	0,7	-0,2	**272**	2500	0,7	-0,2	**228**

4 Structural model

4.1 Finite Element Model features

Fig 2 illustrates the basic idea of the Finite Element Model used in this study. A 35-metre long section with identical cross-section was used for both of the instrumented test sites. The tire contact areas of a nine axle, 740 kN vehicle were modeled as area loads having a constant intensity. The intensity of tire load was equal to the assumed tire inflation pressure (850 kPa) and the contact area for each tire was back calculated from the tire widths and measured axle loads. All single wheels of the loading vehicle were of the type 385/60 R22.5 and all the dual wheels of the type 315/80 R22.5.

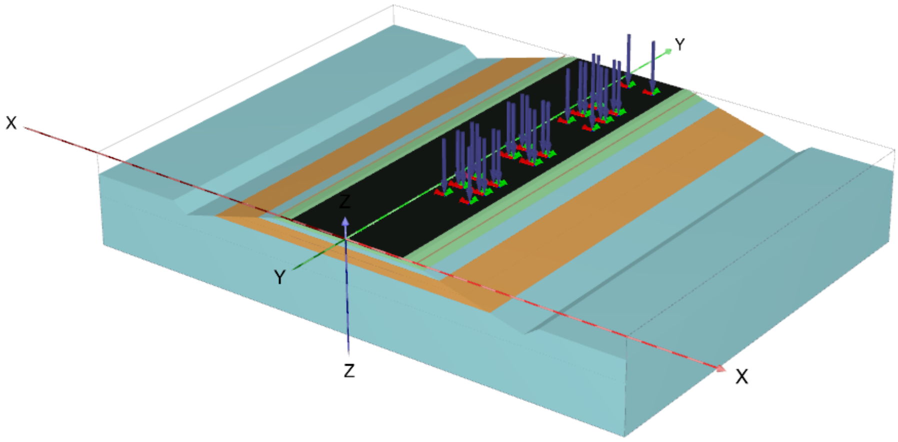

Fig 2. Structural model used for 3D FEM simulations in this study.

PLAXIS 3D uses 10-node tetrahedral elements for volume elements (e.g. soil layers) and 6-node plate elements. User can define the refinement for elements and the program calculates a target element size based on outer model geometry dimensions. In addition, user can influence meshing procedure by defining a relative element size factor, polyline angle tolerance and surface angle tolerance [8]. In this project, the finest mesh of automatic meshing procedure was used, i.e. target element size was 0.5, polyline tolerance angle was 30° and surface angle tolerance 15°, respectively.

4.2 Material models used

Several different material models are included in PLAXIS 3D software. The material models used in this study are shortly described hereafter. The Hardening-Soil Model (HS) is an advanced model for the simulation of soil behavior. Limiting states of stresses are described by means of the friction angle, φ, the cohesion, c, and the dilatancy angle, ψ. Soil stiffness is described by using three different input stiffnesses: the triaxial loading stiffness, E_{50}, the triaxial unloading stiffness, E_{ur}, and the oedometer loading stiffness, E_{oed}. All these stiffnesses relate to a reference stress, 100 kPa in this study.

The HS model was chosen for unbound structural layers since the yield surface is not fixed but can expand due to plastic straining. The material parameters used in simulations are summarized in Table 3. They have been derived based on a number of laboratory tests carried out with similar materials and the back-calculation of site specific FWD results obtained from Aurora test sites.

The hardening rules can be divided into two main types of hardening, namely shear and compression hardening. Shear hardening is used to model plastic strains due to primary deviatoric loading. Compression hardening is used to model irreversible strains in oedometric and isotropic loading. Therefore, the stiffnesses of aggregate layers are more appropriate on both sides of the yield surface i.e. when subjected to deviatoric loading, the soil stiffness decreases simultaneously with the development of irreversible strains.

The Linear Elastic model (LE) was chosen for asphalt concrete (AC) and subgrade. Linear elasticity for subgrade was considered suitable since the modelled loading scheme is momentary and the stiffness of subgrade determines the amount of deflection. The AC layer was also assumed to behave in linear range during a short-term loading. The moduli values used for LE layers are shown in Table 4.

Table 3. HS-model parameters used in simulations.

Sr構ctural layer	**E_{50} (MPa)**	**E_{oed} (MPa)**	**E_{ur} (MPa)**	**m (-)**	**c (kPa)**	**phi (°)**	**psi (°)**	**K_0 (-)**	**v_{ur} (-)**
Base course	500	500	1000	0.5	20	50	20	0.33	0.2
Subbase	350	350	700	0.5	10	45	15	0.33	0.2
Road structure	250	250	500	0.5	5	45	15	0.33	0.2

Table 4. LE-model parameters used in simulations.

Layer	**E (MPa)**	**v (-)**
AC layer, + 40 °C	1500	0.35
AC layer, 0 °C	10 000	0.35
Subgrade, Aurora 1 test site	125	0.35
Subgrade, Aurora 2 test site	100	0.35

5 Comparison of modelled and measured responses

In order to obtain reliable data under heavy truck loading, two specific loading test series were performed at Aurora test sites. The first loading test was carried out in July (test I) when pavement temperature varied between +37 and +45 °C. During the second loading test pavement temperature was practically 0°C (test II). Fig 3 indicates the measured and modelled values of road surface deflection at the Aurora 2 test site during loading test I. In all of the figures from Fig 3 to Fig 8 the charts have been arranged as follows:

- Modelled results are indicated using a blue or red dotted line
- Peak values measured with different parallel transducers are shown using separate dots with different transducer specific colors
- Upper left chart corresponds to a 85 kN single wheel axle
- Upper right chart corresponds to a 74 kN single wheel axle
- Lower left chart corresponds to a 113 kN dual wheel axle
- Lower right chart corresponds to a 78 kN dual wheel axle

In general, the modelling results correspond well with the measured results under a dual wheel axle. In the case of single wheels, however, the measured peak values are somewhat higher. This might be due to the lack of exact tire inflation pressure information. Since the simulation series carried out in this study was a preliminary one, the effect of tire inflation pressure was not studied in detail.

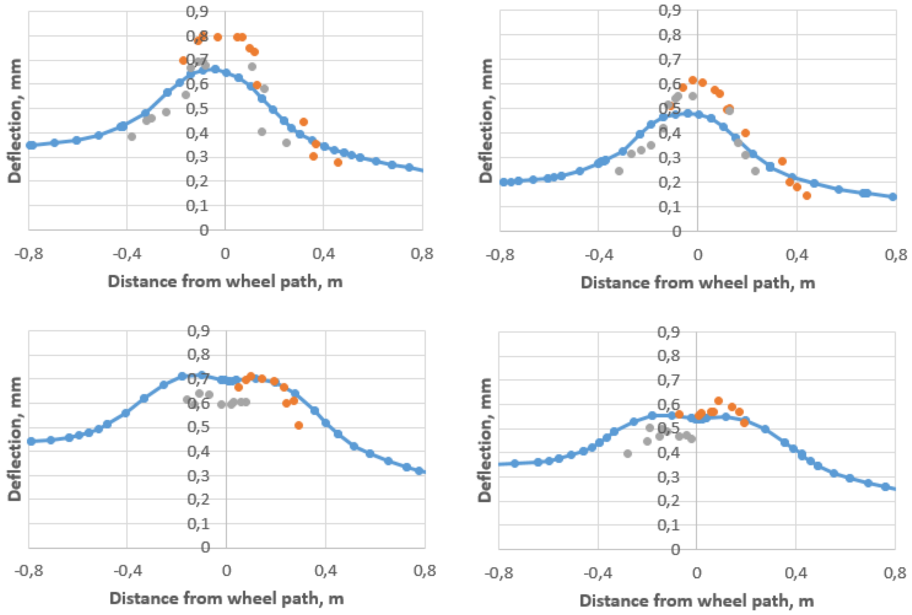

Fig 3. Measured and modelled road surface deflections at the Aurora 2 test site in loading test I.

Similar results were obtained when analyzing the vertical pressures in the upper part of base course layer. During loading test I, the measured peak values under single wheel loads were again higher than the modelled ones at both Aurora test sites. The respective results of vertical pressures are illustrated in Fig 4 and Fig 5.

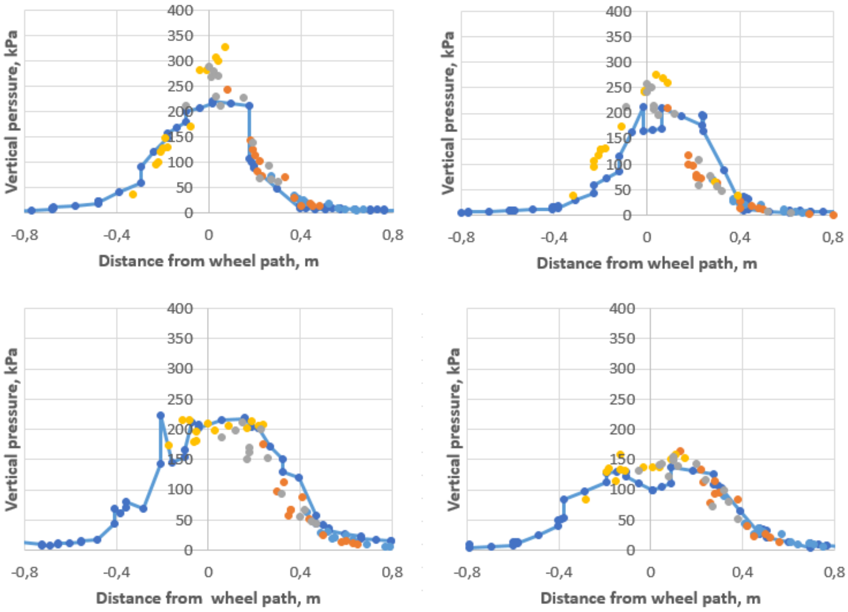

Fig 4. Measured and modelled vertical pressures in the upper part of base course (180 mm depth) at the Aurora 1 test site in loading test I.

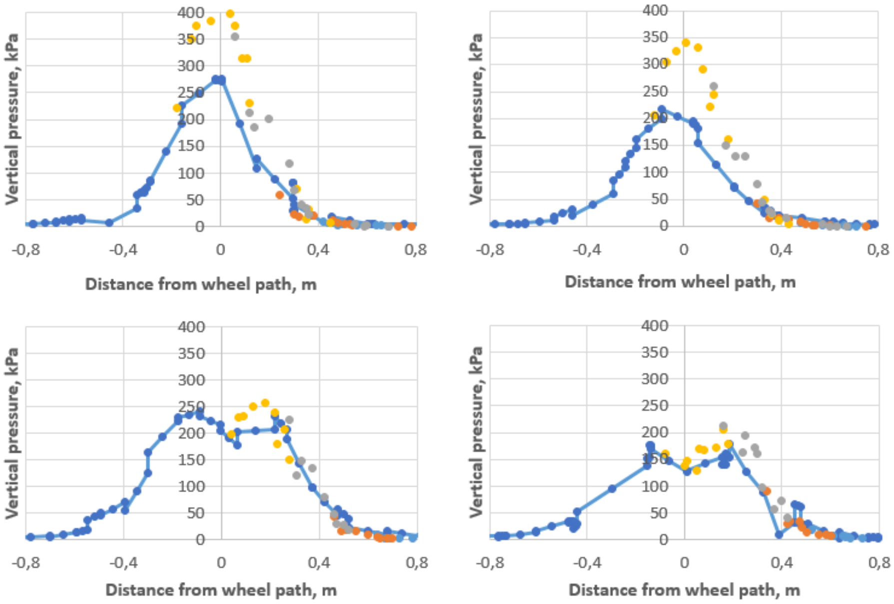

Fig 5. Measured and modelled vertical pressures in the upper part of base course (220 mm depth) at th Aurora 2 test site in loading test I.

One more interesting example of modelling results in shown in Fig 6. The only distinction in the FEM simulations between test I (Fig 4) and test II (Fig 6) was the modulus value of AC layer. The temperature correction of AC layer stiffness appears to explain nicely the changes in the measured and modelled stress states.

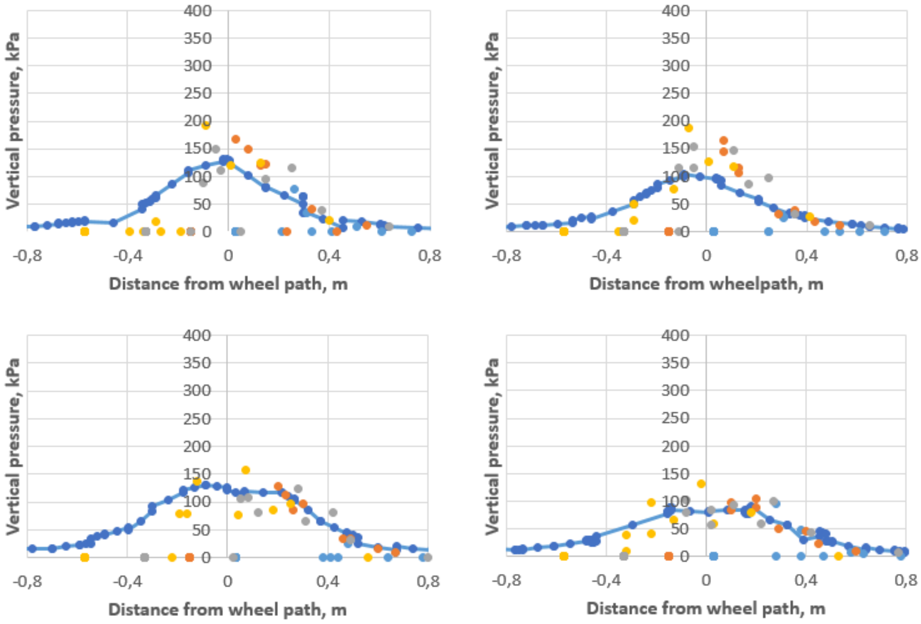

Fig 6. Measured and modelled vertical pressures in the upper part of base course (180 mm depth) at the Aurora 1 test site in loading test II.

Fig 7 and Fig 8 illustrate the effect of pavement temperature on horizontal strains at the base of AC layer. The modelling results are somewhat scattered in comparison to the measured peak values, but the magnitude of modelled AC strains also appears to be correct, roughly from 300 to 500 microstrains, when AC temperature is close to + 40°C. During loading test II temperature was so low that the measured responses may have been disturbed by partial freezing of the underlying base-course layer (Fig 8). In any case, the results indicate that more research would be needed to properly take into account the effects of pavement temperature and tire inflation pressure in the structural design of road structures. In Fig 7 and 8 blue and yellow dots stand for the peak values of compressive AC strain preceding the approaching wheel load and are therefore not meaningful to compare with modelled strain values.

Altogether, the results obtained in this study strongly suggest that the design parameters for unbound structural layers in the current Finnish guidelines should be updated. Compared to the present design values, from 200 MPa to 280 MPa depending on the base course aggregate grading [1], the modelling results suggest that the design stiffness values for unbound aggregates should be clearly higher.

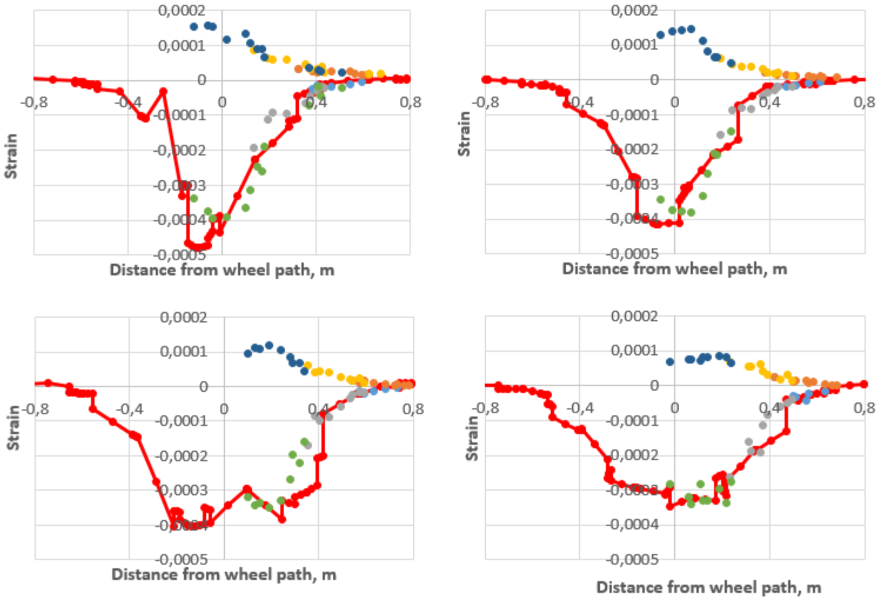

Fig 7. Measured and modelled horizontal strains at the bottom of pavement layer in longitudinal direction at the Aurora 2 test site in loading test I.

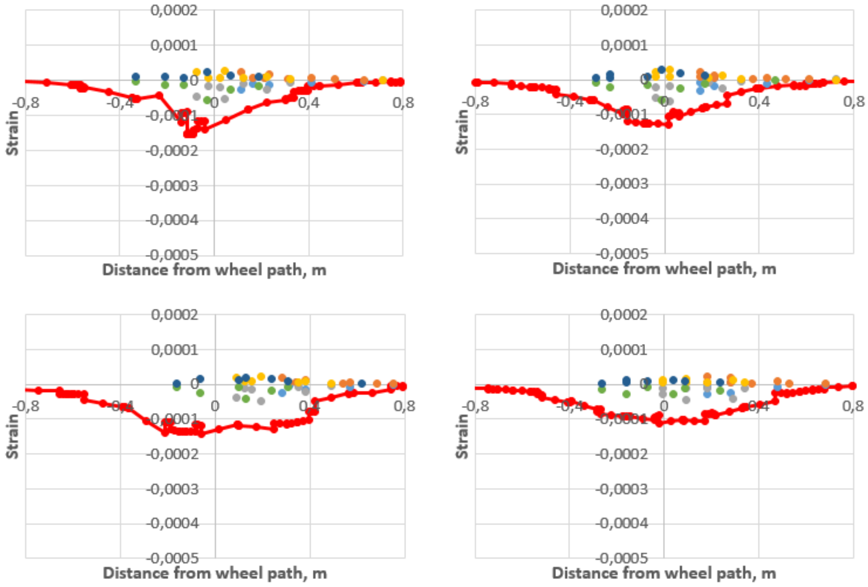

Fig 8. Measured and modelled horizontal strains at the bottom of pavement layer in longitudinal direction at the Aurora 2 test site in loading test II.

6 Conclusions

The data obtained from the Aurora test sites is very valuable in enhancing the overall understanding on the load carrying capacity of road structures. Especially this concerns road structures with relatively thin AC layer in which the role of unbound layers is pronounced.

The results obtained from these first modelling exercises clearly indicate that there is an obvious need to improve the current Finnish road dimensioning guidelines and to update respective design parameters. Two separate conclusions can be pointed out:

- The stiffness values of unbound layers should be increased in order to represent the actual responses under vehicle loading.
- The true behavior of AC layer should be included into the dimensioning procedure. At a high temperature both measured and modelled horizontal tensile strains at the bottom of AC layer clearly indicate that a life-cycle cost efficient design would require a more detailed dimensioning procedure for AC layers, especially in Finland, where AC layer thicknesses in general are rather thin.

Acknowledgements

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