Integrated Monitoring of Seasonal Variations and Structural Responses to Enable Intelligent Asset Management of Road Infrastructures

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Abstract. 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 a 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 softer subgrade soil. Commissioned by FTIA the structural instrumentation of Aurora monitoring sections was accomplished jointly by Tampere University (TAU) and Roadscanners Ltd (RS).

This paper exemplifies the integrated analysis of continuous monitoring results regarding both structural condition and structural responses at the Aurora test sites during the first year of monitoring. Special attention is devoted to five follow-up periods lasting one week each. These weeks represent different seasons typical for the Nordic conditions: early and late spring thaw, dry summer period, early phase of seasonal frost and further advanced freezing period.

The results presented in this paper have two unique features: 1) both of the monitoring sites operate fully remote-controlled i.e., all the presented data has been acquired without anyone attending on the monitoring sites and 2) all the data to be collected during a period of almost three years from 2018 to 2020 will be made publicly available via the FTIA website as open data.

Keywords: Aurora, Monitoring, Structural response, Seasonal variation, Intelligent, Asset management, Open data.

1 Introduction

Continuous shortage of resources allocated to road maintenance is urging the need for development of more intelligent practices in the management of road infrastructures that are facing a number of challenges caused by different on-going trends and developments. These include:

- Progress of climate change that results in increasing amounts of rainfall, more frequently appearing extreme heat waves and in the Northern area an increasing number of freeze-thaw cycles per year [1].

- Introduction of super heavy trucks due to the increasing pressure of reducing CO_2 emissions caused by heavy road transports.
- Transition from dual wheels to super single tires that are known to be much more harmful to road infrastructure [e.g., 2, 3].
- Forthcoming introduction of autonomous cars and trucks that can in the worst case result in dramatic reduction of wheel path wander in between different vehicles and further increase of annual paving costs due to accelerated road deterioration [4, 5].

In long run, the only thinkable solution in tackling these challenges is a transition from reactive maintenance to proactive maintenance. In practical terms it means that instead of letting the structures to be severely broken down we must be able to recognize the initiating damages and repair them at an early stage before the required renovation actions are not very extensive and expensive [6].

An essential prerequisite for this transition is that more advanced technologies are applied in surveying the condition of existing roads [7]. Equally important is a better understanding of the mechanical behavior of actual road structures and their deterioration mechanisms in the prevailing conditions is developed. One indispensable tool in accumulation of this understanding is long-term in-situ monitoring of existing road structures while they are exposed to real traffic loading and variable weather conditions. This paper presents an example of this type of monitoring arrangement accomplished jointly by Tampere University and Roadscanners Ltd in the village of Muonio in the Western part of Finnish Lapland.

2 Installed instrumentation

2.1 Description of the monitoring sites

The installed structural monitoring systems 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 and a Weigh-in-Motion (WIM) station installed in a concrete slab bridge in the North side of the village. All of these three monitoring sites belong to the Aurora area, a testing ecosystem of intelligent transport and infrastructure solutions in Nordic conditions launched by the Finnish Transport Infrastructure Agency, FTIA [8].

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 overlain by 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 a sandy subgrade it constitutes a substructure with clearly 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 loading plate, the determined values after the installation of measuring instruments were about 20 for the Aurora 1 test site and 35 for the Aurora 2 test site, respectively. 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 Structural instrumentations

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:

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

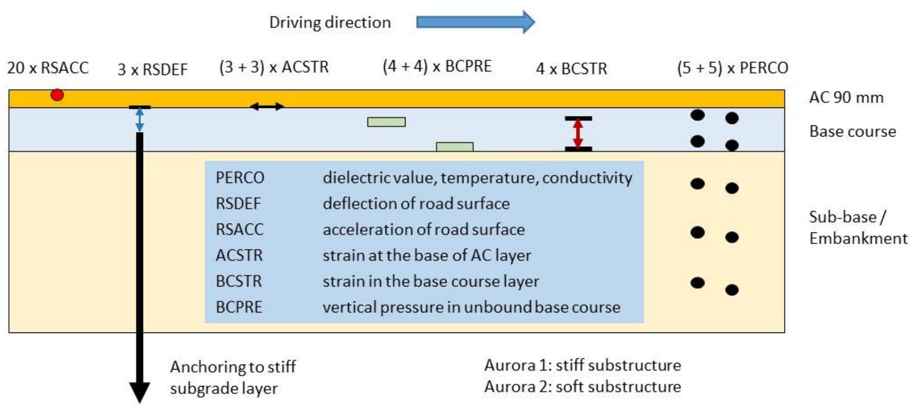

Fig. 1. Schematic picture of structural instrumentations at Aurora 1 and 2 test sites.

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. The parallel instruments are installed at a spacing of 150 to 200 mm in cross-sectional direction of road to enable obtaining of a more complete picture of the 3D distribution of structural responses caused by vehicle overpasses. The only exception is acceleration transducers that have been installed in two rows with an instrument to instrument spacing of only 100 mm.

Five Percostation® probes monitoring long term changes in dielectric value, electrical conductivity and temperature were installed at different depths varying from 0.15 m to 1.10 m below the road surface. Five Digipercostation® probes that enable also monitoring of short term changes in the dielectric value during vehicle overpasses were installed parallel to the traditional type of probes up to the depth of 1.1 m.

2.3 On-surface instrumentation

In addition to the structural instrumentations, there are also on-surface monitoring instruments that enable recognition of passing by vehicles and their loading effects. These include:

- Laser scanners that are recognizing both the speed, dimensions and shape of a passing by vehicle as well as the position of vehicle's outer wheel path in terms of distance to the outer surface of vehicle's tires.
- On the Aurora 2 test site, a thermal camera that records the road surface temperature especially with the aim of recognizing the possible pumping of water from the embankment and subgrade soil into the road structure during spring thaw conditions.

2.4 Weigh-in-Motion system

As mentioned above, a Weigh-in-Motion (WIM) system delivered by Slovenian company Cestel has been installed in a concrete slab bridge a few kilometers North from Aurora 1 and 2 sites. It enables the monitoring of:

- Number and type of heavy vehicles
- Vehicle speed
- Number of axles and distances between axles in each heavy vehicle
- Axle and axle group weights as well as the total weight of a passing over vehicle

2.5 Data acquisition systems

All of the data acquisition systems recording the results from the monitoring instruments described above have been designed to operate fully stand-alone i.e., data acquisition is triggered automatically for a certain time by each passing by heavy vehicle and, therefore, no operating personal are needed on site.

The sampling rate used in connection with structural response measurements is 1 kHz i.e., thousand samples per second and per channel. The only exception is Digipercostation® probes in which the sampling rate is 60 readings per second per channel.

The monitoring data from all of the structural response measurements is transferred daily into a server of the Finnish Transport Infrastructure Agency from where it can be uploaded as open access data [9]. However, in the case of WIM and laser scanner measurements, only the processed data is available at the FTIA server.

3 Monitoring of structural condition and responses

3.1 Selection of monitoring periods using Percostation data

The research contract between FTIA and the service providers, Tampere University and Roadscanners Ltd, included detailed follow up of structural responses under heavy traffic loads on both Aurora monitoring sites during five seasonal periods each one of which was lasting for one week. The selection of these follow-up weeks was made based on the structural condition monitoring of the Aurora test sites accomplished by Percostations providing continuous information on dielectric values, electrical conductivities and temperatures at different depths below the road surface (Fig. 2). The following descriptions were given for the monitoring periods that were selected:

- Week 1: early spring thaw (from 19th to 25th of April 2018)
- Week 2: late/end of spring thaw (from 8th to 14th of June 2018)
- Week 3: dry summer period (from 20th to 26th of August 2018)
- Week 4: early stage of seasonal frost (from 22nd to 29th of October 2018)
- Week 5: frost has penetrated through the upper structural layers (from 11th to 18th of December 2018)

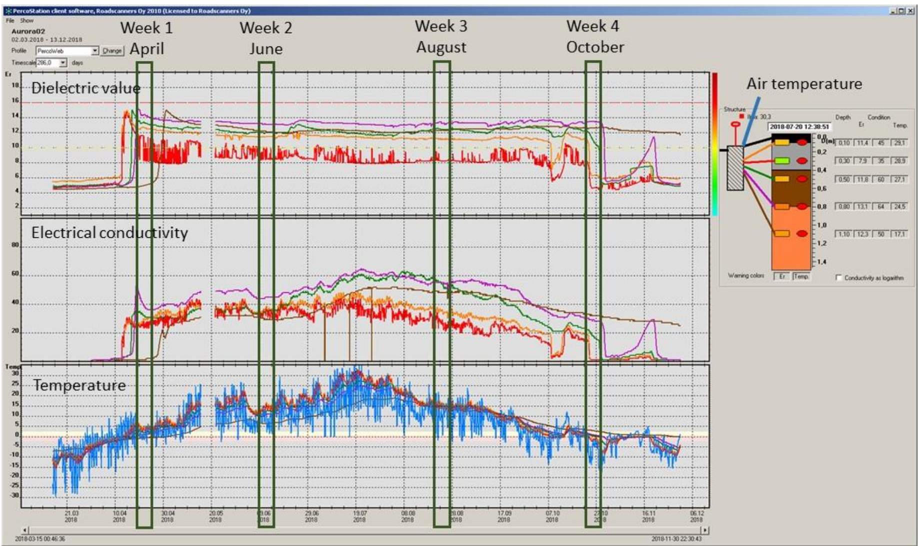

Fig. 2. Aurora 2 Percostation monitoring data in between the mid of March and the end of November 2018. The first four follow-up weeks are indicated by green rectangles, while the fifth follow-up week is outside of the shown time window.

As Fig. 2 indicates, the first follow-up week took place in the end of April when the upper part of road structure had already thawed; however, the Percosation probe at the depth of 1.1 meters was still clearly surrounded by frozen soil, in which dielectric value is of the order of five. During the second follow-up week close to the mid of June thawing had already progressed below the lowest Percostation probe and no more frozen soil was assumed to exist below the road embankment since temperature had already remained above +5 degrees throughout the structure for some time.

Summer 2018 was exceptionally warm even in the Northern Finnish Lapland and as a result of that temperature values exceeding +15 degrees were monitored at the depth of 1.1 meters below the road surface. The third follow-up week was selected towards the end this warm summer season in the last half of August.

A temporary freezing of the upper part of road structure took place in early October after which the structure thawed again in the mid of October. The fourth follow-up week was selected to the end of October when the structure started to freeze again. After that, air temperature remained mostly below 0 degree and frost continued to penetrate deeper into the road structure. Around the mid of December there was a short milder period during which partial thawing took place especially at the depth of 0.8 meters below the road surface, but by the beginning of December the structure was again frozen at that level. During the fifth follow-up week in the mid of December (not shown in Fig. 2) the frost penetration depth was already more than 1.1 meters i.e., below the deepest Percostation measurement probe.

3.2 Examples of structural response measurement results

Since the monitoring systems are built to operate fully stand-alone, it is very easy to record the structural responses caused by a large number of heavy vehicle overpassing the instrumentation sites. On the other hand, a drawback of the autonomous data recording is that the passing by vehicle types must be recognized based on the monitored data and, then, connected to the information on vehicle and axle weights available from the WIM-station. An example of the utilization of this type of massively collected monitoring data is given hereafter.

One frequent type of heavy vehicles traveling from North to South via highway E8 is a semitrailer truck transporting fish from Norway to Finland. These trucks typically weigh about 40 to 50 tons and have a 1 + 2 axle truck pulling a trailer with three axles. The left side of Fig. 3 presents a summary of the measured road surface deflections at Aurora 2 test site caused by the steering axles of these “fish trucks” during the first follow-up week from the 19th of April to the 25th of April 2018. Correspondingly, on the right side of Fig. 3 there is a summary of the measured values of compressive strain in the base course layer of Aurora 2 test site. At the time of these measurements, the road structure had thawed up to the depth of about one meter (Fig. 2).

When the recorded results are plotted as a function of the distance between the transducer in question and the location of outer wheel path of the vehicle (Fig. 3), it is easy to see that all the parallel instruments have been producing quite nicely identical results. When analyzing the results shown in Fig. 3, it is important to note that the actual weights of the steering axles of these trucks recorded at the WIM-station varied from 65 kN to 93 kN. Therefore, a certain amount of scatter in the results is inherent.

Corresponding results recorded during the overpasses of the same set of vehicles as in Fig. 3 is given for vertical pressure at the depth of 180 mm below the road surface on the left side of Fig. 4 and vertical pressure at the depth of 280 mm on the right side of Fig. 4. Furthermore, the left side of Fig. 5 indicates horizontal strain at the base of AC layer in the longitudinal direction of road and the right side of Fig. 5 horizontal strain in the transversal direction of road.

In addition to the actual recorded values of structural responses, Fig. 3 to 5 indicate by dotted lines also the respective curve fittings that have been made in each data set. In chapter 3.3 these curve fittings are used in comparing the response measurement results obtained during different follow-up weeks representing different seasonal conditions prevailing at the monitoring site.

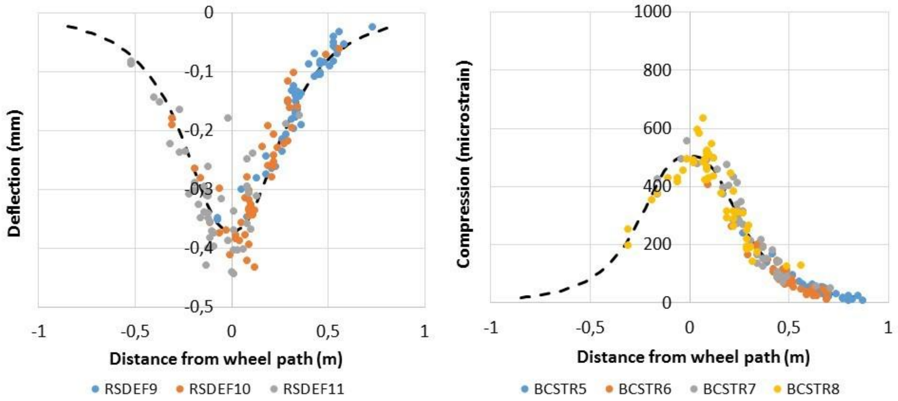

Fig. 3. Vertical deflections of road surface measured with three parallel displacement transducers (left side) and compressive strains of unbound base course layer measured with four parallel strain transducers (right side) at Aurora 2 test site during Week 1.

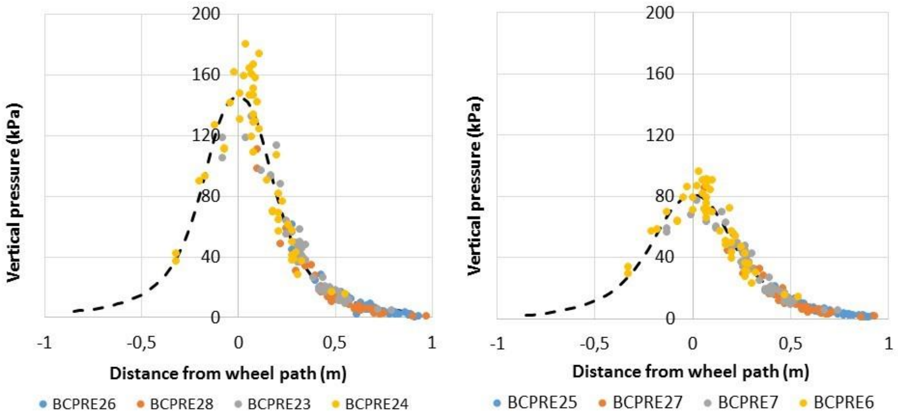

Fig. 4. Vertical pressures measured with four parallel pressure cells at the depth of 180 mm (left side) and at the depth of 280 mm (right side) at Aurora 2 test site during Week 1.

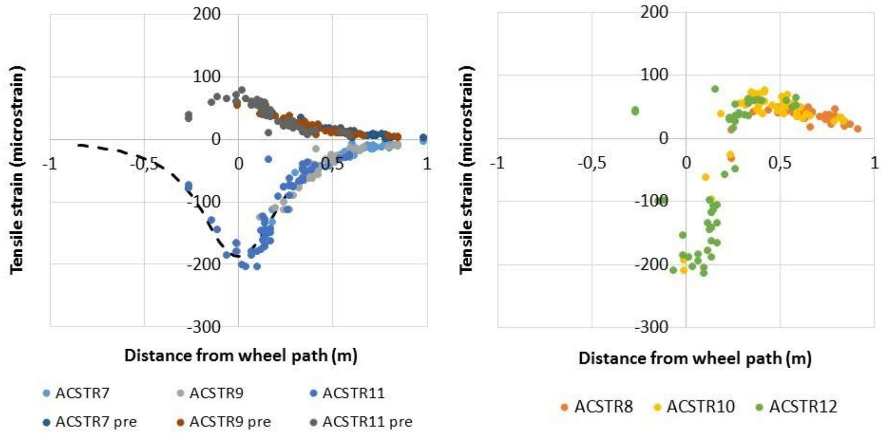

Fig. 5. Horizontal strain at the base of AC layer in the longitudinal direction of road measured with three parallel strain transducers (left side) and horizontal strain at the base of AC layer in the transversal direction of road measured with three parallel strain transducers (right side) at Aurora 2 test site during Week 1.

Especially regarding the vertical pressures at the depth of 180 mm (Fig. 4) it seems that the scatter of results around peak value is fairly high and some of the measured values are clearly exceeding the respective peak of curve fitting. The main reasons for this phenomenon are believed to be the scatter in the actual values of axle load, but also the variation in tire inflation pressures different vehicles have been using. Due to load spreading deeper inside of the structure, the effect of tire inflation pressure is not any more as pronounced in vertical pressures measured at the depth of 280 mm.

As Fig. 5 indicates, the typical peak values of tensile strain at the base of AC layer during Week 1 have been of the order of 200 microstrain and the peak values of compressive strain both in longitudinal direction preceding a wheel load and in transversal direction next to a passing by wheel load have been slightly above 50 microstrain. A remarkable observation regarding transversal stains is the very sharp transition from tensile strain to compressive strain at the edge of wheel contact area about 200 mm from the center of wheel contact area. Clearly this is a critical point regarding the service life of AC layer and deserves a special attention in the further analysis of results especially regarding the forthcoming introduction of autonomous trucks which may in the worst case be driving identical wheel paths.

3.3 Comparison of response measurement results between different seasons

Fig. 6 presents a summary of the measured values of surface deflection at Aurora 2 test site during the five follow-up weeks representing different seasons of year 2018 as indicated in Fig. 2. All the responses have again been measured under the steering axles of the six-axle "fish trucks" travelling over the site from North to South and the comparison is made using the results of curve fitting on each week's data set as exemplified in Fig. 3 for Week 1.

Respective comparisons have been made for compressive strains measured in unbound base course layer (Fig. 7), vertical pressures measured at the depth of 180 mm (Fig. 8) and at the depth of 280 mm (Fig. 9) in base course layer, and finally for tensile strains in the longitudinal direction of road at the base of AC layer (Fig. 10).
Since freezing of the structure progressed rapidly during Week 4 (Fig. 2), the measured changes in structural responses during the first half of that week (i.e., from 22nd to 25th of October) have been indicated in Fig. 6, 7, and 10. These results underline the drastic effect that freezing of the upper couple of tens of centimeters has on the mechanical behavior of the whole structure. During Week 5 the structure was already frozen up to a depth exceeding one meter and the measured responses became either very scattered (vertical pressures) or too small to be meaningful any more (base course and AC strains). Therefore, results from Week 5 are not included in Fig. 7 to 9.

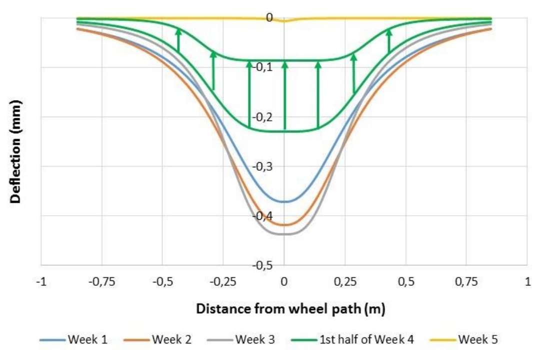

Fig. 6. Comparison of road surface deflections at the Aurora 2 test site during different follow-up weeks of 2018.

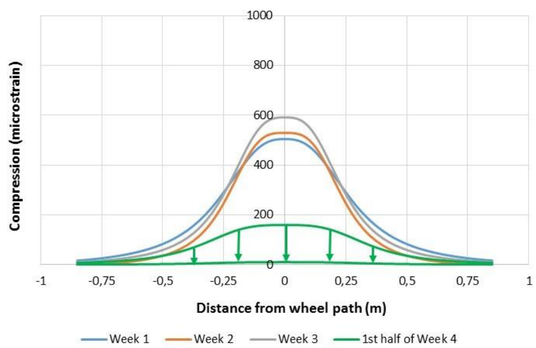

Fig. 7. Comparison of compressive stains in unbound base course layer at the Aurora 2 test site during different follow-up weeks of 2018.

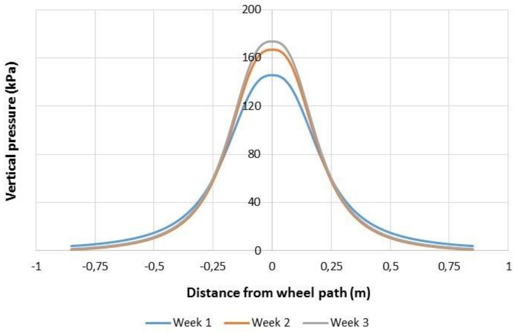

Fig. 8. Comparison of vertical pressures in unbound base course layer at a depth of 180 mm at the Aurora 2 test site during different follow-up weeks of 2018.

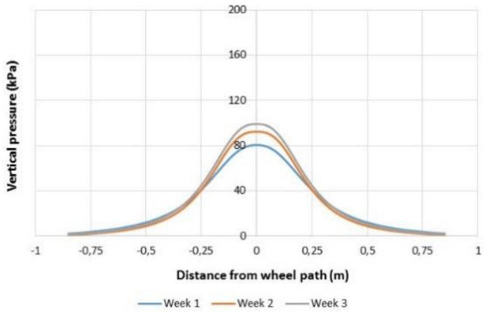

Fig. 9. Comparison of vertical pressures in unbound base course layer at a depth of 280 mm at the Aurora 2 test site during different follow-up weeks of 2018.

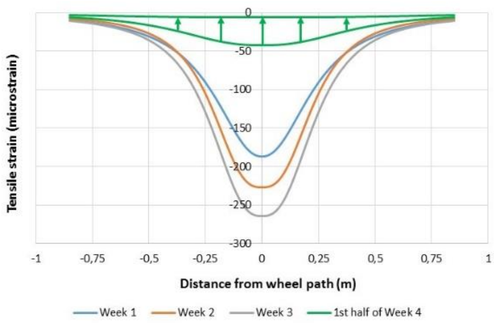

Fig. 10. Comparison of tensile strains in longitudinal direction of road at the base of AC layer at the Aurora 2 test site during different follow-up weeks of 2018.

Overall, it seems that in the conditions of this monitoring site the dominant seasonal effects are the effect of temperature on the stiffness of AC layer and the effect of freezing as soon as temperature in the uppermost couple of tens of centimeters from the top of structure falls below 0 degrees. On the site, there was no direct measurement of AC layer temperature; however, if it is approximated using the uppermost Percosation probe almost right below AC layer, AC layer temperatures have been close to 0 degree during Weeks 1 and 4, while during Weeks 2 and 3 it has been close to +15 degrees. In the daytime, AC temperature may probably have been higher due to solar radiation, but not necessarily very much since the air temperatures during those weeks has mostly remained around +10 degrees (Fig. 2).

On the contrary, the effect of moisture condition in unbound structural layers and embankment has not been very important on the performance of road structure here, because the dielectric values have remained almost constant throughout the whole summer season on each Percostation measurement probe levels. Most likely this can be attributed to the water tightness of new AC layer and the excellent drainage conditions of monitoring site, since the road surface at the Aurora 2 site is more than two meters higher than the surrounding ground surface.

Due to changes in the stiffness of AC layer, the deflection of road surface has been smaller during Week 1 than during Weeks 2 and 3. Correspondingly, both compressive strains in the base course layer and the tensile strains at the base of AC layer as well vertical pressures at the depths of 180 mm and 280 mm in unbound base course have been higher during Weeks 2 and 3 due to the lower stress distribution capability of AC layer. When comparing Weeks 2 and 3, it seems that in terms of all the measured responses AC layer has been slightly stiffer and, thus, spreading loads more efficiently in the mid of June (Week 2) than in the end of August (week 3).

4 Conclusions

The paper presented a monitoring system installed in a road section located in Northern Finnish Lapland. Special features of the instrumentation include:

- Comprehensive instrumentation includes both monitoring of the seasonal variations and the structural responses of the selected road section.
- Monitoring system operates fully stand-alone and, thus, provides continuous information on the mechanical behavior of the instrumented road section all year round, even though in wintertime the results are of little practical value.
- By combining structural monitoring results to those of the nearby Weigh-in-Motion station, normal traffic flow can be used in accumulating continuous response measurement data as exemplified in this paper.
- All the response measurement results automatically triggered by the overpasses of heavy vehicles are available as open data at the server of the Finnish Transport Infrastructure Agency [9]; therefore, anyone can utilize the site for his/her own loading tests just by keeping track of the time labels of vehicle overpasses. By now that has been realized at least in connection with the development of a special type of trailer aimed for heavy timber haulage.

The monitoring results collected during the five one-week-long periods selected to represent different seasons of year 2018 indicate that:

- At this well drained site the most dominant seasonal effects are the effect of temperature on the stiffness of AC layer and the effect of freezing of the overall performance of monitoring section as soon as freezing has penetrated a couple of tens of centimeters below road surface.
- All the structural instrumentations are producing consistent results that are believed to be highly useful when developing the mechanistic design approach and related structural modelling of road embankments under the effects of seasonal variations.

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