Future roads and mobility

Fiber Bragg grating monitoring system for heavy-duty pavements

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Abstract

Heavy-duty pavements have met new challenges over the past decades. Many pavements were not designed for servicing today's traffic frequency and axle loads, which impose loads much greater than those initially considered. Both factors result in an accelerated deterioration of the pavement structure. The accurate measurement of the strain and stress distributions in pavement is critical for understanding pavement behavior and modeling failures of pavements. With the development of information technology and digitization, traditional pavement monitoring systems have been integrated with other monitoring systems, including bridge monitoring, Weigh-in-Motion (WIM), traffic classification etc. In the present study, a fiber Bragg grating monitoring system for heavy-duty pavement health monitoring is introduced. The concept was designed by University of Antwerp and first installed together with Com&Sens in a test track demonstration project CyPaTs (Cycle Pavement Technologies) in September 2017. The same advanced system is installed in a larger scale project in a test track in the Port of Antwerp in June 2019. Numerous sensors (strain and temperature) installed between four asphalt layers allow better descriptions of the behavior of asphalt layers under heavy loading during real-time monitoring. This technology can provide strain data for the service life of the asphalt layers during a subsequent monitoring campaign under actual moving vehicular load. Since the accuracy is very high, this technology is appropriate for monitoring the deformation of the asphalt layers over time, considering aging, fatigue and rutting. The real-time monitoring data from the FBG sensors embedded in geogrid and three asphalt layers will be discussed in this study.

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1. INTRODUCTION

Monitoring the mechanistic response of the pavement structure could be an indirect measure to evaluate the overall pavement performance. Is a stepwise long-term pavement performance criterion a new goal in road engineering?

In the last 50 years, pavement research and related pavement techniques have grown. These theories, principles, and/or procedures which were based on the knowledge and research achievements at that time, have helped the pavement professionals to make specific analysis, design, construction and maintenance on pavements. On the other hand, during the same period, a lot of new pavement materials were invented and widely used. The properties of these new materials are considerably different compared to conventional materials. Neither traditional pavement analysis methods nor existing design principles can provide a direct way to consider these differences in all conditions and considering increased traffic loading. This leads to the necessity and the difficulty of modifying the pavement design methods used so far. Currently, there are several important challenges to pavement research related to asphalt pavement analysis and design that include: how to deal with more and more common heavy traffic loads (the allowed max. weight for a 5 axles truck is 44 tons in Belgium and France and 50 tons in The Netherlands) [1], overloads and with increasing traffic volumes; how to consider emerging pavement materials; how to incorporate new materials, new techniques and new design concepts into pavement analysis and design; and how to consider ageing and healing effects.

For instance, heavy-duty pavements got heavily overloaded over the past decades. A relatively large number of infringements is related to the weights of heavy goods vehicles and today's traffic frequency. On average, one in three heavy vehicles checked is overloaded [2]. In a recent internal study in the Antwerp port area (Belgium), on one particular road, the data shows that excess loads often exceed the maximum authorized weight (12% above 44 ton, 3.8% above 52.8 ton (+20%) and 1.8% above 57.2 ton (+30%)). Overweight vehicles lead to all sorts of negative issues, e.g. related to road safety, driver's safety, pavement structures accelerated deterioration. In fact, overloaded trucks increase pavement wear and thus contribute to premature pavement failure. It is important to understand that the rate at which a vehicle destroys a road is proportional not to its weight but to the fourth power of its weight. The effect of 5% overload would result in a 22% increase in damage and 18% reduction in pavement life. The effect of 10% overload would result in a 46% increase in damage and 32% reduction in pavement life [2].

The assessment of pavement mechanical state and service life is very important for design evaluation and road maintenance. On the other hand, it is rather difficult to learn how exactly a pavement works inside the structure and not many research items on the long-term continuous monitoring of the pavements in Europe can be found. Considering that understanding of pavement behavior and modeling failures of pavements are crucial factors in the pavement design, long-term continuous monitoring of the pavements is on high demand.

For a given design traffic, the thickness of the asphalt layer is selected such that two critical pavement responses — tensile strain at the bottom of the lower asphalt layer and vertical strain at the top of subgrade — are controlled within acceptable limits to limit the amount of cracking and deformation in the embankment and subgrade layers. For a given mixture type and a number of load applications, the horizontal tensile strain is used to control fatigue cracking (cracking starting at the bottom of asphalt layer); whereas, excess deformation in the subgrade is controlled by the vertical compressive strain at the top of the subgrade soils. The location of the critical horizontal and vertical strains is shown in Figure 1. For heavy-duty pavements, the values of these strains can be calculated with a reasonable degree of accuracy, assuming the mixture property of stiffness is accurately estimated [3].

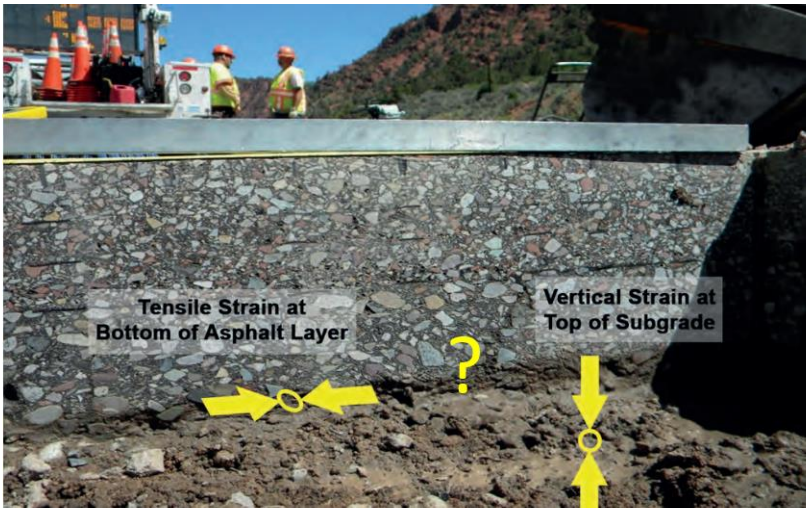


Figure 1: Location of critical strains in a full-depth asphalt pavement [3]

The initial mechanistic-empirical (ME) based procedures focused more on determining the layer thickness using standard dense-graded asphalt mixtures. Most of those procedures simply assumed that the difference in the asphalt elasticity or dynamic moduli could explain any difference in resistance to cracking and rutting. This assumption is reasonable but inappropriate for the non-conventional or specialized asphalt mixtures specified for heavy-duty asphalt pavements [3]. The road load-carrying capacity of pavements is influenced not only by the thickness of the layers but also their mechanical properties such as flexural strength and plastic deformation resistance.

With the development of information technology and digitization, traditional pavement monitoring systems have been integrated with monitoring systems, including bridge monitoring, Weigh-in-Motion (WIM), traffic classification etc. FBG, as one of the optical fiber components, have been widely applied in sensing fields, such as strain sensors and temperature sensors. Compared with conventional sensors, FBG sensors are the most promising candidates to effectively replace conventional strain gauges for long-term monitoring applications in a harsh environment [4]. Until now, FBG sensors are not commonly used in asphalt technology due to their application restrictions during rough construction processes, in case of roads, which require the sensors to endure high temperatures (up to 160°C), moisture, high compaction force, repeated heavy loading, etc. [5]. The accurate measurement of the pavement responses (strain and stress) distributions in the pavement structure, combined with temperature, is critical for the understanding of pavement behavior and the modeling of pavement failure [6].

In the present study, a fiber Bragg grating (FBG) monitoring system for heavy-duty pavement health monitoring is introduced. The initial concept of FBG monitoring system was designed by University of Antwerp (UAntwerp) and first installed together with Com&Sens (Belgium) in a test track demonstration project CyPaTs (Cycle Pavement Technologies) in September 2017 [4,7]. The same advanced system, as a unique concept for monitoring heavy-duty asphalt pavement layers, is installed in a larger scale project together with Com&Sens in a test track in the Port of Antwerp in June 2019. Numerous sensors (strain and temperature) installed between four asphalt layers allow better descriptions of the behavior of asphalt layers under heavy loading during real-time monitoring. This technology can provide strain data for the mechanical response and service life of the asphalt layers during a subsequent monitoring campaign under actual moving vehicular load. Since the accuracy is very high, this technology is appropriate for monitoring the deformation of the asphalt layers over time, e.g. rutting. The real-time monitoring data from the FBG sensors embedded in a geogrid and in between the three asphalt layers will be discussed in this study.

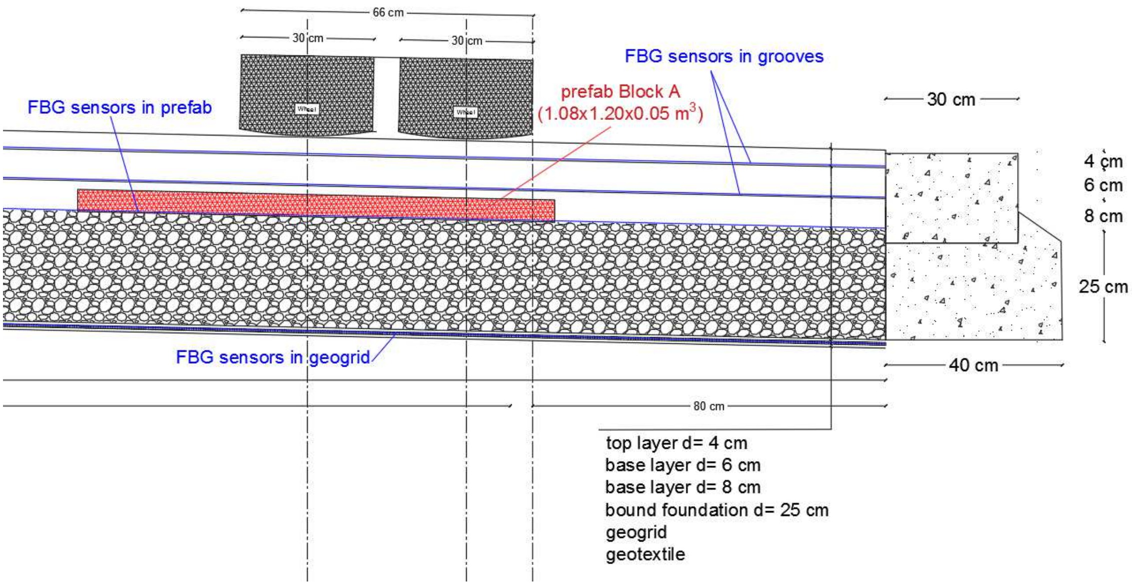
2. FIBER BRAGG GRATING MONITORING SYSTEM

2.1. Concept for CyPaTs project

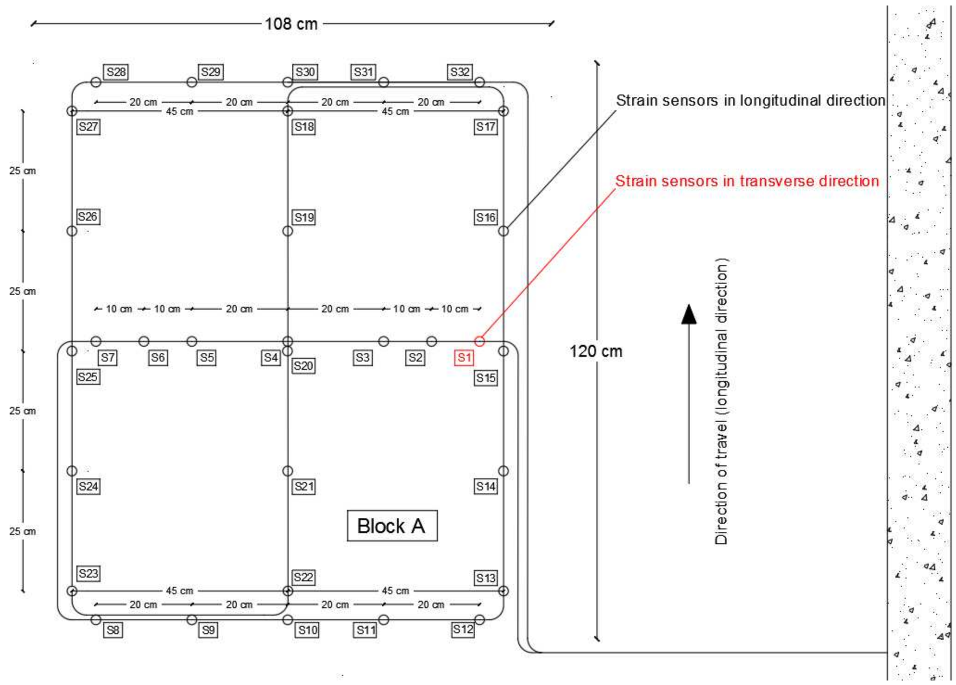
The installation of the FBG monitoring system prototype was a part of the CyPaTs project, in which a bicycle path (96 m long and 4 m wide) was accomplished at UAntwerp in 2017. The installed FBG sensors were commercially available, organic modulated, ceramic-coated Draw Tower Gratings (DTG®) with an outer diameter of 0.2 mm, embedded in a glass fiber reinforced plastic (GFRP) round profile with an outer diameter of 1 mm and protected with an additional high-density polyethylene (HDPE) coating with outer diameter of 0.5 mm. The installed FBG monitoring system prototype consisted of several FBG chains: 2 fibers with 30 DTG® (spacing between sensors 10 cm) and 4 fibers with 5 DTG® (spacing between sensors 80 cm) and two temperature sensors (FBG based ~40 mm SS housing and ~1 mm diameter) embedded in three asphalt layers with a cross-section configuration (width of 4 m and length of 3.2 m). The strain and temperature data were obtained using an interrogator FBG-SCAN 808D with 8 channels (1507–1593 nm wavelength range, 250 Hz measurement frequency for all channels). The FBG sensors configuration was embedded in the three asphalt layers in both transverse and longitudinal directions at the bottom of each layer. All FBG sensors in all three asphalt layers survived during pavement construction. It was possible to learn how exactly the pavement behaves inside during the pavement construction. Fiber egress points were designed as such to come out at the side of the pavement. Redundancy was built-in by the option to measure the strain wires from both sides. The monitoring of the FBG system was performed since the construction of the pavement. All sensing fibers were connected to a single-mode multifiber (SMF) backbone cable to enable continuous monitoring from inside the building. This FBG system's application as a long-term monitoring system is possible and it can be installed, for example, in heavy-duty roads during their construction. The detailed description of the system is given in references [4,7].

2.2. Concept for Port of Antwerp project "Antwerpsebaan - Bevrijdingsdok"

The same advanced FBG monitoring system — in collaboration with Port of Antwerp and Com&Sens — was installed in June 2019 in the Port of Antwerp to monitor a heavy-duty pavement in real-time and over the long-term. The installed FBG sensors were commercially available, organic modulated, ceramic-coated Draw Tower Gratings (DTG®) with an outer diameter of 0.2 mm, embedded in a glass fiber reinforced plastic (GFRP) round profile with an outer diameter of 1 mm (1512-1586 nm wavelength range). The installed FBG monitoring system prototype consisted of 8 FBG chains with 32 DTG® (spacing between sensors varied from 10 cm to 25 cm) and temperature sensors (FBG based ~40 mm SS housing and ~1 mm diameter). Two FBG chains and one temperature sensor were embedded in each layer of the road structure: attached to the geogrid under the bound base material and between each of the three asphalt layers with a configuration shown in Figure 2a. The following configuration was chosen with the same number of sensors as in CyPaTs project but with a different allocation of the sensors in the asphalt pavement to cover a bigger area to monitor. The aim of this configuration is to track the passage of the truck wheels in such a way that all sensors are allocated in a mesh and not in a line (like in CyPaTs project) (see Figure 2b).



(a)



(b)

Figure 2: FBG sensors configuration (a) in geogrid and three asphalt pavement layers and (b) FBG sensors configuration at each layer (Block A)

The test track (*Antwerpsebaan - Bevrijdingsdok, Port of Antwerp*) consists of two sections with different types of base asphalt mixtures: (1) APO section - asphalt mixtures with performance characteristics for base courses and (2) AVS section - high modulus asphalt, known as EME (*in French: Enrobés à Module Elevé).* It must be mentioned that both sections have the same thickness of all layers. An FBG monitoring system prototype was installed in each section. The FGB sensors were placed at the bottom of each layer (see Figure 1a):

- attached to the geogrid below the bound base layer;

- embedded in prefabricated blocks between the bound base layer and first asphalt layer;
- embedded in grooves on site at the bottom of the second and third asphalt layers.

The FBG sensors were directly attached to the geogrid and allocated underneath when placed on the construction site. The FBG chains at the bottom of the first asphalt layer were embedded in prefabricated asphalt blocks (block A and block B) with dimensions 1.08 × 1.20 × 0.05 m^3 in a 2 mm deep groove at the bottom of the block, directed towards the base. The four prefabricated blocks (two blocks per FBG monitoring system) consisted of 30 slabs with dimensions 0.6 × 0.4× 0.05 m^3. The slabs were casted by the Belgian contractor Stadsbader and assembled in four large blocks at the UAntwerp EMIB lab, where the FBG chains were embedded. Next, those ready-to place blocks with embedded FBG chains were transported to the test site. The FBG chains at the bottom of the second and third layers were installed in 2 mm deep grooves which were grooved on site. The installation of the FBG monitoring systems is shown in Figure 3.

The advantages of the present FBG monitoring prototype are:
- ✓ System proved to be successfully installed in a heavy-duty pavement under heavy loading during the construction of the road structure;
- ✓ System can be easily installed if FBG sensors are placed only in grooves on the asphalt pavement (installation in geogrid and prefab blocks requires more time for preparation in advance in lab facilities);
- ✓ System can be continuously monitored for a long time period all year round in all types of weather;
- ✓ System can be monitored (strains and temperatures) at each layer of the road structure;
- ✓ The thickness of each asphalt layer in the multi-layered pavement is used for evaluation of the deformations and not the total thickness of all asphalt layers (like for example in falling weight deflectometer measurements);
- ✓ System can be remotely monitored.

(a)

(b)

(c)

(d)

Figure 3: Installation of FBG monitoring system in Port of Antwerp (a) installation of geogrid with FBG sensors, (b) installation of prefabricated asphalt blocks with FBG sensors, (c) installation of FBG sensors in grooves on the surface of the asphalt layer, (d) placing of asphalt top layer above the FBG sensors

The monitoring campaign started in August 2019 with calibration of two FBG monitoring systems (one for APO section and one for AVS section). The calibration was performed with a test truck with known axles weight and at a constant speed of 30 km/h. The distances between six axles were 3.9 m, 1.35 m, 1.35 m, 3.95 m and 5.43 m. The maximum actual speed at this part of the road is estimated to 40 km/h. Both systems are located on the same side of the road separated by 40 m from each other. They are connected with a single-mode multi-fiber (SMF) backbone cable and can be simultaneously monitored.

3. ANALYSIS OF STRAIN AND TEMPERATURE

The current/applied FBG system can be monitored at a certain sample rate, which can be selected depending on the monitoring purpose. For example, a high sampling rate for instantaneous effects; seconds, minutes or even hours for long term effects. This type of measurement can provide information on seasonal effects on the pavement condition. During pavement monitoring, FBG sensors can perform the function of axle counter as well, since each peak represents the presence of each axle, and counting the number of peaks generated from each sensor. Thus, it is possible to use FBG sensors also as a good alternative to the conventional axle counter.

The monitoring system in Port of Antwerp has been recently installed and the first calibration measurements were performed in the beginning of August 2019. At this moment, the measurement data derived from the calibration tests showed that both systems are functioning. Even though damage has occurred during the construction of pavement and there is a certain loss of sensors in geogrid, prefabs and asphalt layers. That mostly has happened due to non-controlled and traffic loaded construction process of a heavy-duty pavement in the port. For example, it was a controlled construction environment for FBG installation in the bicycle path pavement and no traffic during construction, therefore, all sensors survived the construction process at that test track. Considering that it was the first experience of such type of installation for a heavy-duty pavement, it can be concluded that it was successful.

In the following Figures 4-9 some strain and temperature effects are summarized. According to the design, each monitoring system consists of 64 sensors per road structure layer; at this moment, it was decided to show only the initial results of one sensor (S1) (see Figure 2b) through all layers (this sensor is located under the passing wheel load point). In Figures 4 & 5, it is possible to see the response of S1 through all the pavement layers during the test when the truck was passing above the systems 12 times. Accordingly, it is possible to see 12 peaks. In Figures 6 & 7, two peaks are zoomed in and it is possible to observe the response of S1 more in detail under the passing truck. The measurement is taken at the same time for both FBG monitoring systems. In Figures 4 & 5, there is a difference in time for the first peak in X-axis but that is due to FBG monitoring system in AVS section is connected first and then second system is connected in APO section. The test starts only when both monitoring systems are online. Figures 4 & 5 show a thermal expansion behavior when one layer causes thermal tension and compression in the different layers/directions (it can be clearly observed in Figure 5).

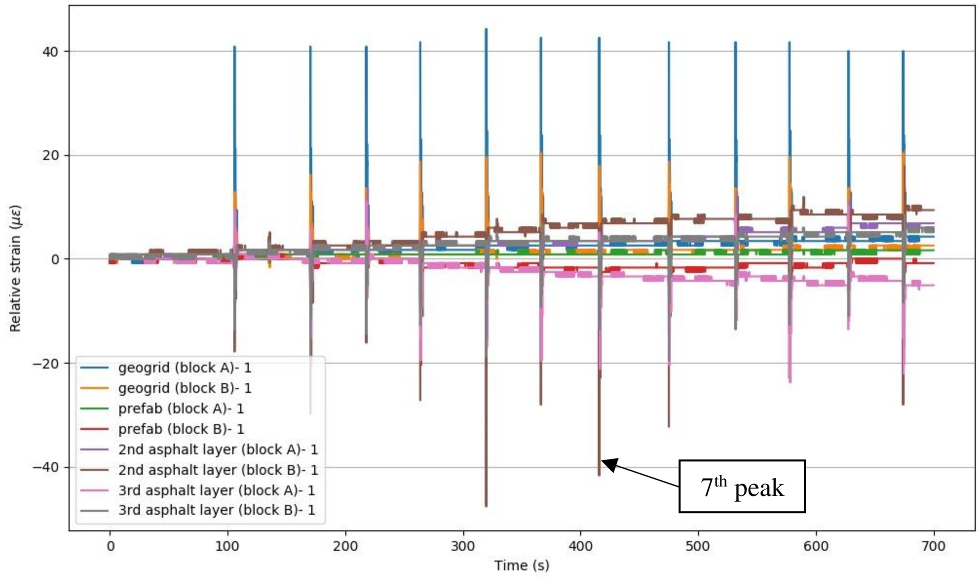


Figure 4: Response of APO sensor 1 - through all the pavement layers (12 peaks)

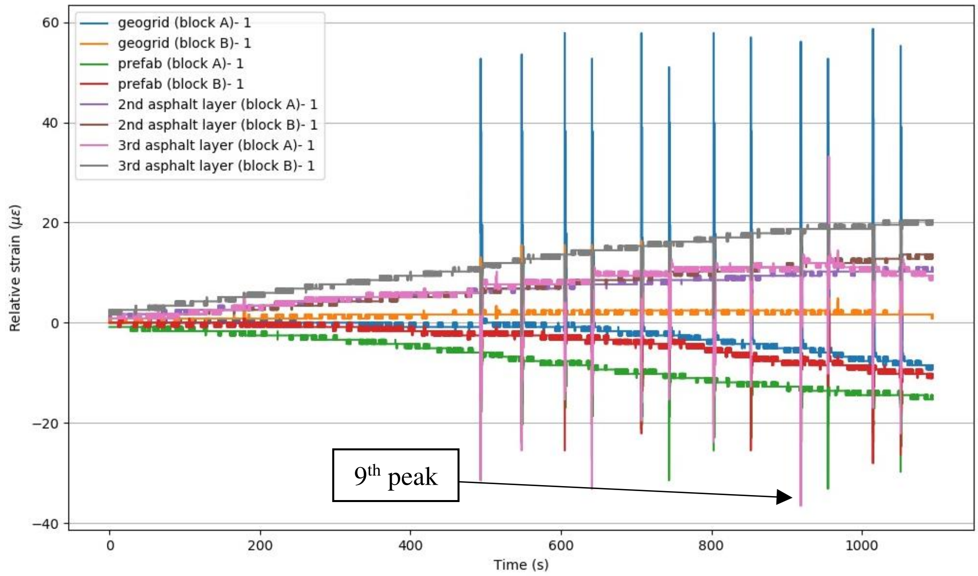


Figure 5: Response of AVS sensor 1 - through all the pavement layers (12 peaks)

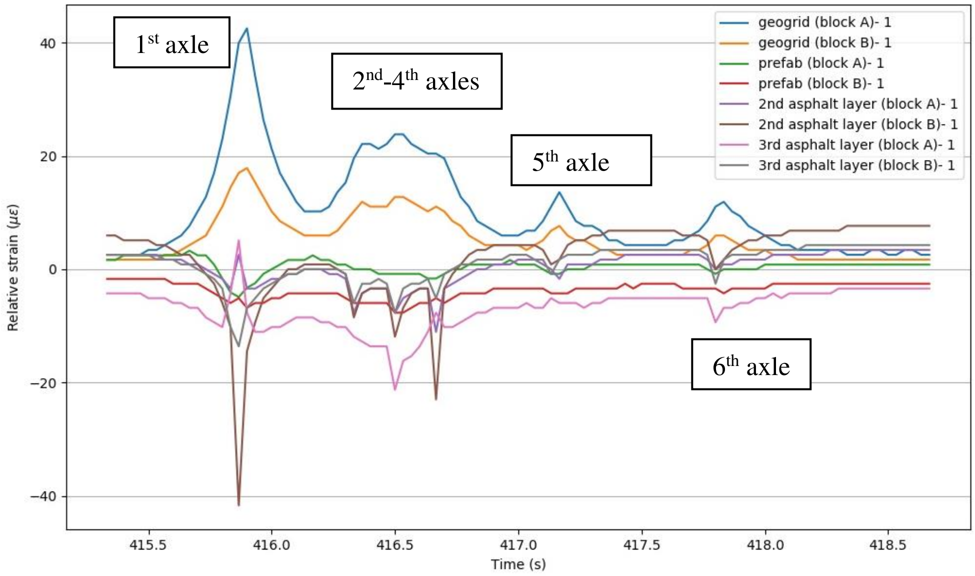


Figure 6: Response of APO sensor 1 - through all the pavement layers (zoomed in 7th peak from Figure 4)

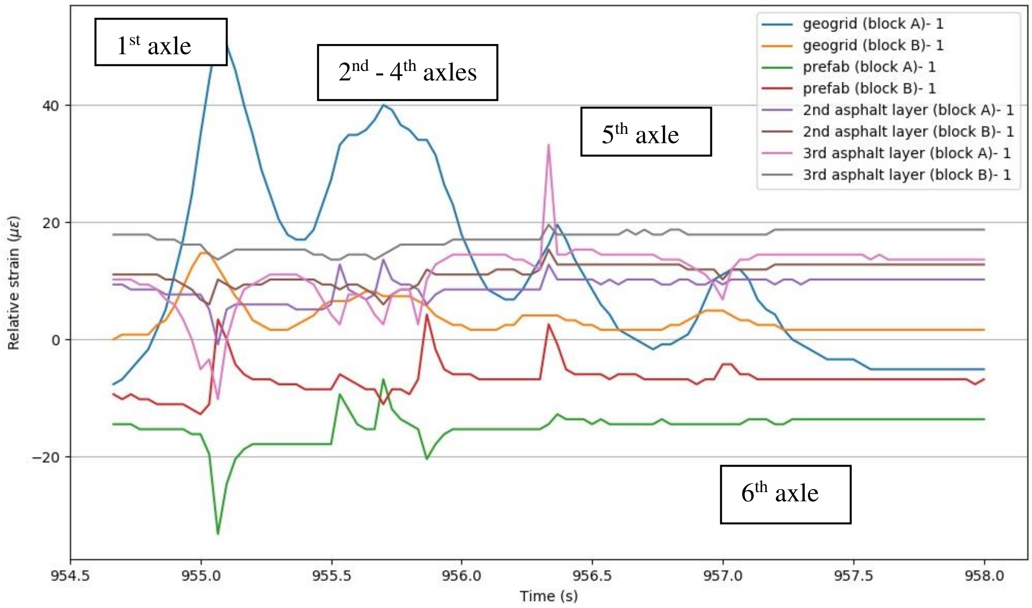


Figure 7: Response of AVS sensor 1 - through all the pavement layers (zoomed in 9th peak from Figure 5)

In Figures 6 & 7, it is possible to observe the response of pavement when the truck drives with speed 30 km/h over the FBG monitoring systems. There is a certain response of layers to the applied load in both sections but with different values. The obtained strain values in AVS section have higher values in tension and lower values in compression. A similar response to the load for the sensors in the geogrid is present in both sections, but AVS shows higher values. The asphalt pavement in APO system mostly shows compression, in AVS system sensors show both compression and tension.

Regarding the temperature measurement values of the sensors installed at each layer (Figures 8 & 9), it can be clearly observed how temperature is different at each layer for the different asphalt base mixtures, although the top layer is the same for the both test tracks. For example, when analyzing these temperature values: (1) in geogrid for APO it is around 24.5 - 25.0 °C and for AVS 25.0 - 26.0 °C; (2) in prefabs under 1st asphalt layer for APO it is around 22.5 °C and for AVS 23.5 °C; (3) under 2nd asphalt layer for APO it is around 26.0 - 26.5 °C and for AVS 23.5 - 25.5 °C; (4) under 3rd asphalt layer for APO it is around 23.5 - 24.0 °C and for AVS 25.5 - 27 °C. These temperature differences need to be investigated further, by comparing the thermal properties of both mixtures APO and AVS, and to eliminate possible calibration differences in the sensors. The top asphalt layer is the same for both systems and it is expected to have the same temperature for the top sensors. But it is possible to see that there are different temperatures for the T probe 3rd layer (Block B). Now, these differences cannot be explained.

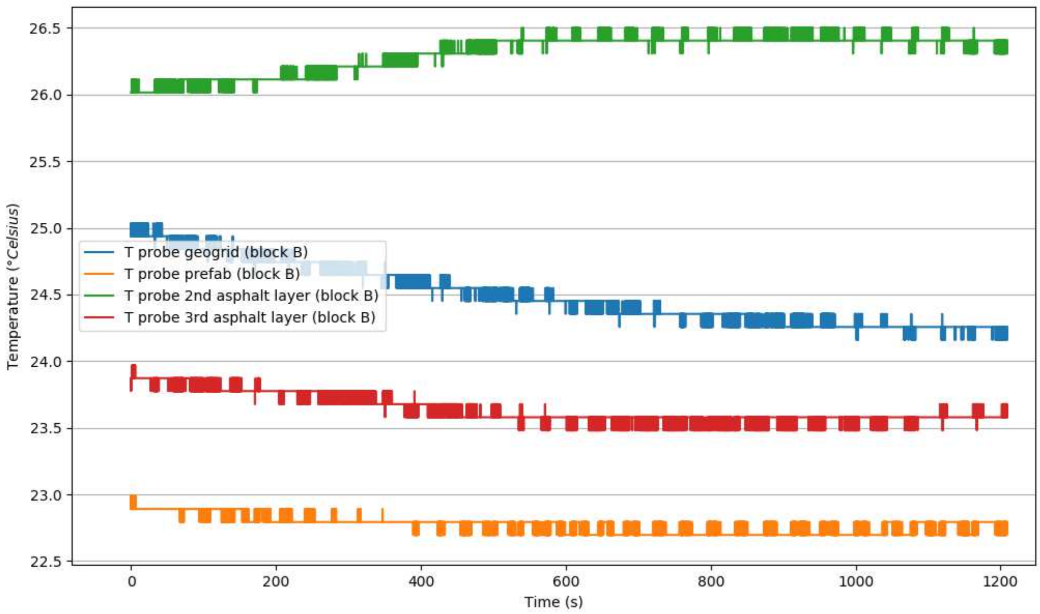


Figure 8: APO temperature variations related to thickness

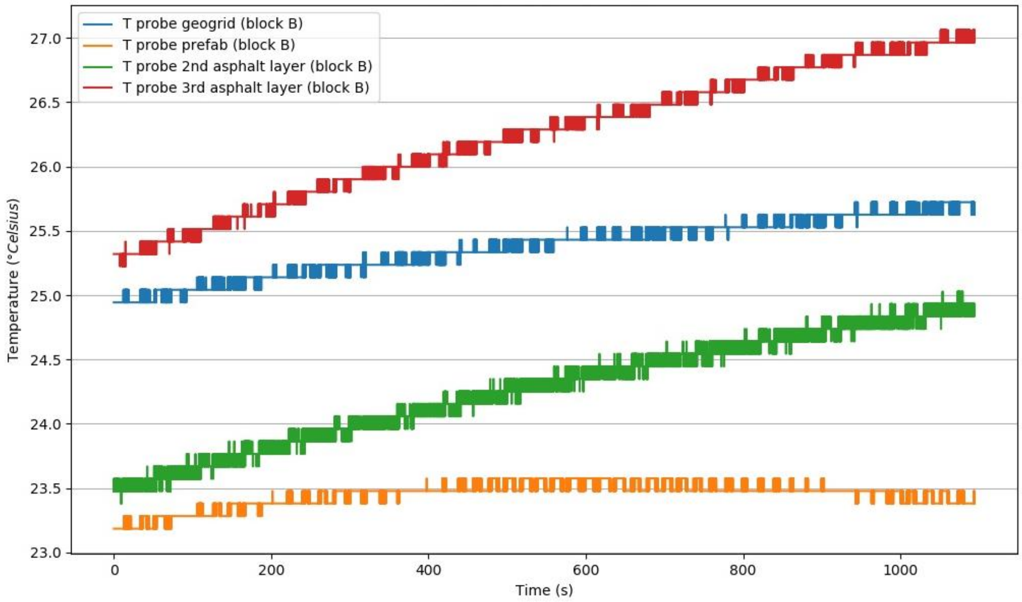


Figure 9: AVS temperature variations related to thickness

4. CONCLUSIONS

Monitoring the mechanistic response of the pavement structure could be an indirect measure to evaluate the overall pavement performance. A long-term pavement performance criterion can be a new goal in road engineering. The performed installation of FBG sensors in 4 layered road structure proved that FBG monitoring system can be successfully installed in a heavy-duty pavement under heavy loading and can be operational after installation for long-term monitoring. During installation, it was concluded that the best way of sensors installation is placing of sensors in grooves since that can be done on site. Installation in geogrid and prefab blocks requires more time and caution for preparation in advance in lab facilities. Based on the current obtained installation experience, improved design of FBG monitoring system may lead to an increase in the survival rate of sensors. Still, in this installation, it is feasible to get significant results from the sensors to monitor the road performance as foreseen. The provided initial results show an interesting potential for the interpretation of asphalt behavior under different conditions in a heavy-duty pavement.

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REFERENCES

[1] Permissible maximum weights of lorries in Europe, International Transport Forum. 2015.

[2] Oehry B., Haas L., van Driel C. Study on heavy vehicle on-board weighing, Final report, Rapp Trans AG, 2013.

[3] Harold L. Von Quintus, Charles S. Hughes. Design and construction of heavy-duty pavements, Quality Improvement Series 123, 2nd Edition, NAPA, 2019, p. 74.

[4] Kara De Maeijer P., Van den bergh W., Vuye C. Fiber Bragg gratings sensors in three asphalt pavement layers. Infrastructures 2018, 3(16), DOI: 10.3390/infrastructures3020016

[5] Dong Z., Li S., Wen J., Chen H. Asphalt pavement structural health monitoring utilizing FBG sensors. Advanced Engineering Forum, 2012, 5, pp. 339-344, DOI: 10.4028/www.scientific.net/AEF.5.339

[6] Xue W., Wang D., Wang L. A review and perspective about pavement monitoring. International Journal of Pavement Research and Technology, 2012, 5, 5, pp. 295-302.

[7] Kara De Maeijer P., Luyckx G., Vuye C., Voet E., Van den bergh W., Vanlanduit S., Braspenninckx J., Stevens N., De Wolf J. Fiber optics sensors in asphalt pavement: state-of-the-art review, Infrastructures, 2019, 4(36), DOI: 10.3390/infrastructures4020036