Case Study on the Technique of Installation of Fiber Bragg Grating Sensors in Three Asphalt Layers

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ABSTRACT

The scope of the present case study was to test fiber Bragg grating sensors (FBG) installation in three asphalt layers: the surface layer and both base layers. FBG is a diagnostic tool to monitor accurately and efficiently *in-situ* structure behavior. However, this technology is not commonly used in asphalt due to its application restrictions under installation and service conditions. FBG sensors are fragile and break easily under loading. Therefore, there is a need for a suitable protection of FBG sensors if they are to be installed during the rough construction process and exposed for heavy-duty loading afterwards. Two approaches to FBG installation in three asphalt layers *(at the bottom of each layer)* were tested in the present case study: installation of FBG in prefabricated asphalt specimens in base layer directly on the base and installation of FBG in the previously constructed asphalt layer by implementing fibers without sawing the whole layer in two parts. Obtained results proved a survival rate of the FBG sensors for 100%.

Keywords: fiber Bragg grating sensors, asphalt, cross-section configuration

1. INTRODUCTION

A considerable number of researchers have put emphasis on understanding of the ageing process of road pavements: on developing solutions to decrease or eliminate cracks and structural deformations due to traffic and climatic fatigue [1], on rutting performance analysis and predicting road behavior to ensure highway and urban roads have a longer service life. In the last three decades, traffic volume has dramatically increased, especially the overloaded truck traffic. With the increasing traffic on flexible road, rutting has become one of the most significant problems for road pavements, especially in urban areas due to the channelized traffic and overload, and on heavy-loaded asphalt pavement.

The pavement design is a rather complicated process because layered elastic theory just offers calculation results incongruent with the real state of pavements, ignoring the uneven, anisotropy and nonlinear stress-strain relationship of paving materials. It is divided into two distinct parts: an understanding of characterization of the materials used and assessment of vehicular loading; and the application of these to a design method.

Many researches have been focusing on the pavement performances of asphalt mixes, which show unique physical properties. Asphalt material is often considered – to make simple calculations – to behave in a linearly viscoelastic-plastic manner; thus, its mechanical response is a continuous function of time and temperature. Considering the stiffness of the material, its behavior at lower temperatures is equivalent to a higher strain rate, such as the strain on pavement due to moving traffic. In the case of high stiffness, the strain on asphalt should ideally be measured directly for the greatest accuracy; however, instruments capable of making such measurements are not generally available. In fact, a higher temperature or a lower strain rate, such as the strain caused by the subsidence of the foundation, results in an extremely low elastic modulus of asphalt; hence, rigid instruments, such as electrical foil strain gauges, are often assumed to have negligible stiffness. In such cases, the stress transferred from the asphalt to an embedded sensor decreases drastically, thereby reducing the sensitivity of the sensor reading [2].

It is very hard to devise an efficient method to determine realistic mechanical properties of the pavement [3]. For this reason, there has been interest in improving all kinds of sensors to exhibit strain, stress and displacement with a much higher precision starting already from early nineties [4]. A number of different technologies have been developed over the last years, and among them are - fiber Bragg grating based sensors technique. A fiber Bragg grating (FBG) is a distributed mirror in a short segment of the optical fiber, reflecting a limited wavelength range and transmitting all others. The working principle is based on a periodic variation of the refractive index of the fiber core, which is acts as a wavelength-selective filter with a central reflecting wavelength. The sensing information is encoded in the optical spectrum, which is reflected by the fiber Bragg grating. An external perturbation (temperature, strain) causes the central Bragg wavelength to shift [5]. FBG is one of the most used technologies in commercial applications in the field of optical communication and composite materials [6], temperature sensors and strain sensors due to several inherent advantages over other technologies: accuracy and range, lightweight, small size, self-referencing, multiplexing, immunity to electromagnetic interference and environmental ruggedness [7]. The tensility or compression of grating can lead to period change when the FBG sensor is deformed caused by outside temperature change or loading up. While FBGs can be used to immediately replace electrical strain gauges and thermocouples for strain measurement and temperature measurement, respectively, the use of unpackaged FBGs is not practical when field measurements are required. Consequently, a number of different designs have been developed to allow an easier installation of FBGs. Sensors aimed at measurements different from strain and temperature have also been developed. In this case, the sensor packaging includes mechanisms capable of converting the measurement to the strain on the FBG.

FBGs have been applied to the measurement of strain at multiple points on a line and have been studied for application in asphalt layer monitoring [8]. Lu et al. [9] studied the strain change at the gap opening by wheel loading, whereas Iten et al. [10] successfully detected settlement by installation of sensors in a trench on the surface of an asphalt road pavement. Imai et al. [2] have experimentally proved that embedded FBGs, coated with an adhesive polyethylene composite to 5 mm in diameter, have the potential to detect asphalt behavior directly even if the asphalt exhibits a low modulus of elasticity, because the flexible FBGs have negligible reinforcement effects on the strain field. Tan et al. [11] proved that FBGs could identify weak, compacted areas based on different FBG sensor response values and could serve as a long-term monitoring system of pavement structural behavior. Liu et al. [12] made co-line and integration designs of FBG sensors and BOTDR (Brillouin Optical Time Domain Reflectometry) sensors, which could provide real-time subgrade settlement and rutting information. The potential and feasibility of the practical application were proved in lab tests. FBG sensors could also be applied to, and worked well in severe environments, like high temperature or moisture conditions. But it must be noted, that in the most cases of the practical engineering, the test methods in the laboratory are not suitable to measure the stress and strain of pavement structures under different loading conditions. FBG is a diagnostic tool to monitor accurately and efficiently *in-situ* structure behavior. Although, FBG is not commonly used in asphalt technology due to its application restrictions during rough construction processes. FBG sensors are fragile and break easily under loading. The harsh working environment require the sensors to endure high temperature (up to 160°C), moisture, high compaction force, repeated heavy loading, etc. and have a large coverage. It must be noted that most of the traditional sensors for other civil structures cannot be used for pavement structure directly [13].

In this paper, suggested two novel approaches to FBGs installation in three asphalt layers were elaborated in a bicycle path structure at the University of Antwerp (Belgium) for testing innovative technologies for the asphalt industry.

2. INSTALLATION OF FBG SENSORS IN ASPHALT LAYERS

FBGs are fragile and break easily under loading; therefore, there is a need for suitable protection of sensors if they are going to be installed during rough construction process. For appropriate protection, which guarantees the accuracy of both strain and temperature measurements, commercially available organic modulated ceramic-coated Draw Tower Gratings (DTG®) embedded in a Glass Fiber Reinforced Plastic (GFRP) round profile with outer diameter of 1 mm and protected with an additional High-Density Polyethylene (HDPE) coating with outer diameter of 0.5 mm (see Figure 1). These DTGs can measure very high strain levels (>10000 μm/m) and supposed to show an excellent long-term stability under mechanical fatigue conditions.

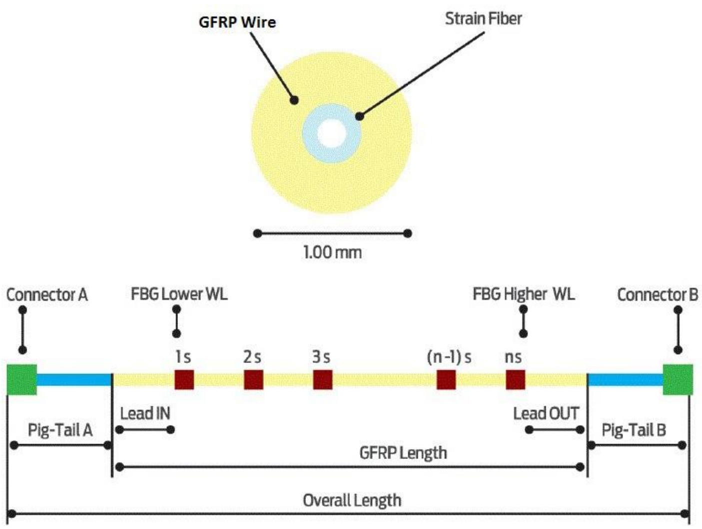

FIGURE 1 Draw Tower Gratings (DTG®) [www.fbgs.com]

Draw Tower Gratings (DTG®s) are produced during the drawing process of the fiber itself, before the primary coating is applied. This is a cost-effective production process for high quality fiber Bragg gratings and offers unique characteristics such as extremely high breaking strength, insensitivity to bending, spliceless array configurations and uniform coating coverage.

In the present case study, FBG chains of 30 DTG® and 5 DTG® were selected for installation in three asphalt layers: the surface layer and both base layers with a cross section configuration to carry out measurements in two directions (in width of bicycle path of 4 m and in length over 3.2 m). The asphalt was applied at a temperature between 120-160 °C. Two novel approaches to FBGs installation in three asphalt layers were tested: installation of FBGs in prefabricated asphalt in the bottom of base layer (see Figure 2a) and installation of FBGs in the previously constructed asphalt layer by implementing fibers without sawing the whole layer in two parts (see Figure 2b). The FBGs configuration is shown in the Figure 3.

FIGURE 2 Installation of FBGs in prefabricated asphalt in base layer (a) and installation of FBGs in the previously constructed asphalt layer (b)

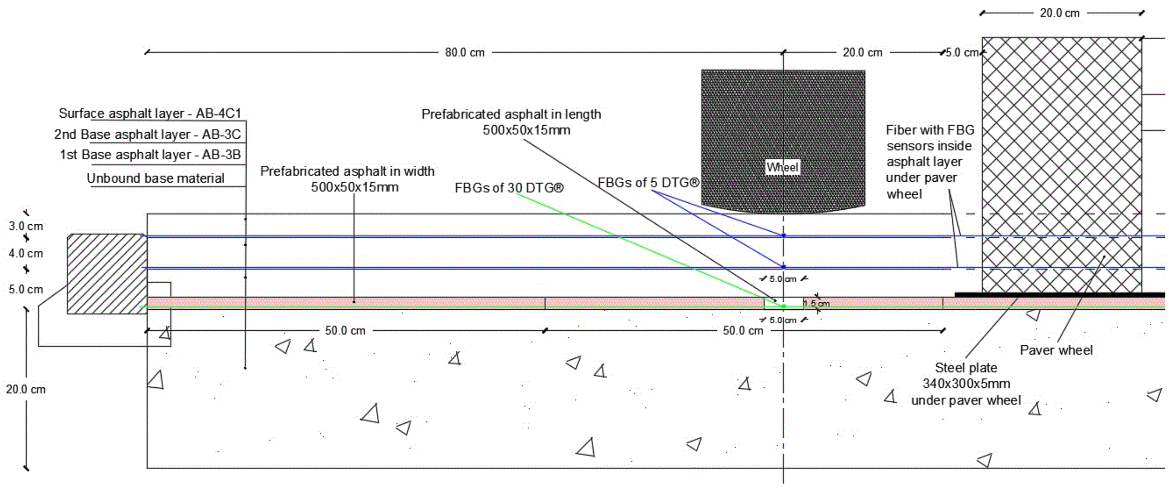

FIGURE 3 FBGs configuration in 3 asphalt layers

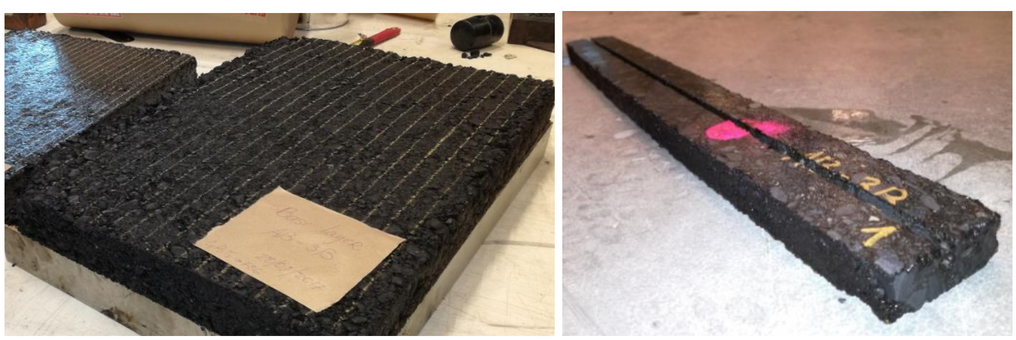

FIGURE 4 Prefabricated asphalt specimens with groove for FBGs embedment preparation

After an extensive literature review, the protection of sensors is a challenging issue to deal with, especially, the protection of FBG sensors installed at a very high asphalt temperatures and during heavy compaction loading. Several protection measures including Fiber Reinforced Polymer (FRP), steel tubing and carbon fiber reinforced epoxy resin coatings, have been shown to be able to provide adequate protection. However, in order to guarantee the survival rate of FBGs during the installation process in base asphalt layer in this case study, it was suggested to embed them in prefabricated asphalt specimens and adjust on site during the construction process.

For the first approach to FBGs installation, asphalt slabs with dimensions 600x400x50 mm were produced under laboratory conditions with the same asphalt mix composition as the base layer used during the bicycle path construction process. The slabs were sawn into specimens with dimensions 500x50x15 mm, and a groove with a depth of 2 mm was made in each specimen (see Figure 4). During the construction process the FBGs were imbedded in the prefabricated asphalt specimens and covered with a thin layer of mastic to keep FBGs in the position inside the groove. Specimens were connected to each other on-site by gluing them together with layer of mastic. Prefabricated asphalt specimens were placed with groove facing down on the unbound material base layer. In order to avoid collapse of prefabricated asphalt specimens steel plates with dimensions of 340x300x5 mm were placed on top of specimens during construction process when the asphalt truck and the paver were driving over them (see Figure 5).

FIGURE 5 Installation of FBGs in base asphalt layer directly on the base

FIGURE 6 Installation of FBGs in two asphalt base layers

During the construction process, it was observed that the new method, with prefabricated asphalt specimens as part of the asphalt base layer, is quite reliable and all FBGs have proved a survival rate of 100%. However, for the high-volume applications, this method had to be adjusted for an easy application on-site. Considering that stiffness and homogeneity of asphalt base layer is higher than those of unbound base material layer, for the second approach of FBGs installation, it was decided to groove the layer to a depth of 2 mm on top and embed the FBGs by covering them with a thin layer of mastic on top. It has shown the ease of the process on-site for the installation of FBGs in the base layers, however, it is not applicable in the case of the lowest base layer. The preparation of grooves in the next 2 asphalt layers on-site was possible two hours after the compaction of the respective asphalt layer (see Figure 6). The monitoring of survival rate of FBGs showed positive results: all embedded sensors worked during and after construction. There were no differences in measurement quality observed between two approaches of FBGs installation. The response of the sensors during loading with the four-axle truck and the paver during paving process of the second base layer is shown in Figure 7. It can be seen that the sensors show a positive shift (tension) or negative shift (compression) during loading. This clearly indicates that the asphalt is deforming during paving and that each time the wheel has passed the sensors zone, there is a new 'steady' state until the next loading event.

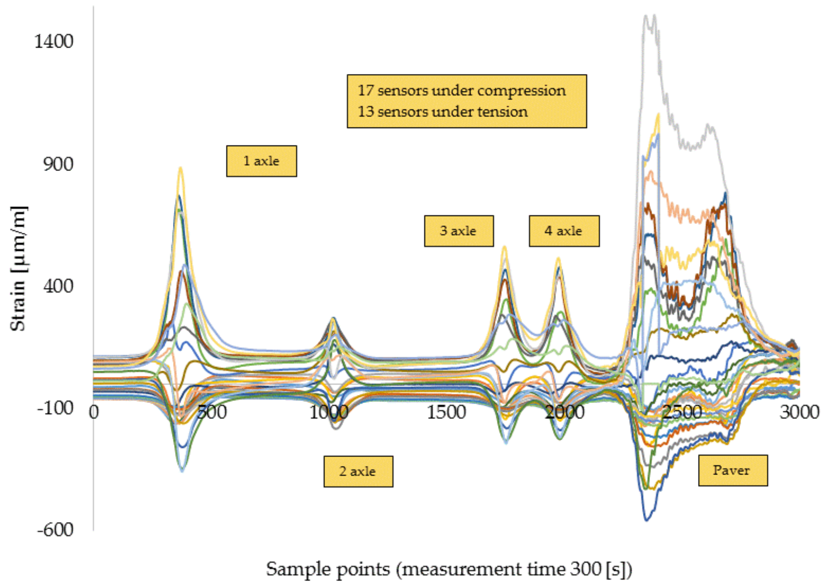

FIGURE 7 Monitoring during the paving process of the second base layer when four-axle asphalt truck and the paver cross the FBG chain of 30 DTG® embedded under the first base asphalt layer

3. CONCLUSIONS

This case study results showed that the FBG sensors are a feasible technology to monitor strain progression during asphalt construction. The technology is able to provide strain data during the service life of the asphalt layers. Two approaches to FBGs installation in three asphalt layers are feasible to install FBGs properly on-site. Obtained results proved a survival rate of 100% for the FBG sensors. The further investigation will be focused on the quality of monitoring of bicycle path asphalt structural changes under loading of the asphalt during service life.

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