Optical fiber feasibility study in Accelerated Pavement Testing facility

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ABSTRACT: The presented research has been carried out within the European project Intelligent Roads (INTRO). The major objective followed was to assess the potential of optical fiber for pavement monitoring in comparison with classical strain gauges. Thus, both measurement devices have been tested under the same conditions in a full scale Accelerated Pavement Testing (APT) at LAVOC. This facility allows the user to control different parameters such as loading configuration and temperature and, as a matter of facts, limit the disturbances. A total number of 10 strain gauges and 8 optical fibers have been installed and tested for various conditions. This study showed rather consistent and comparable results for both optical fiber and strain gauges measurements. The comparison with calculated deformation also highlighted the consistency of the measurements results. The sensitivity of the measurement system has also been highlighted and permitted to conclude with some recommendations for further developments.

1 INTRODUCTION

Intelligent Roads (INTRO) is a FERHL project supported by the European Commission under the sixth framework programme. Part of the project aimed at improving the pavement deterioration detection in order to use it further for safety monitoring and communication with ITS. In order to achieve this, it has been decided to assess selected high potential innovative technologies for the measurement of pavement's behavior.

One of the chosen measurement technique was optical fiber. Indeed, optical fiber has an important background in civil engineering, as for instance bridges maintenance and survey, dams monitoring, tunnel convergence, or concrete structures monitoring. However, the experience in pavement area is rather limited even if the potential is obvious. For this study, fibers from the market have been used and some recommendations provided for further developments in road domain.

The expected output of the tests performed in LAVOC's Accelerated Pavement Testing Facility (APT) was an assessment of the feasibility of a continuously-measuring system for monitoring permanent structural conditions on the one hand, as well as the usability of new sensor technologies. Thus, it has been first determined if it is possible to perform measurements with the selected device. Secondly, the measurements have been assessed separately from a qualitative point of view in a first step, before making some comparisons between deformation measurements using the innovative technology i.e. optical fiber and commonly used strain gauges.

Finally, the feasibility of such measurements for in situ conditions has been assessed considering the measurements reliability but also other parameters like installation complexity, data acquisition and economical aspects as well.

2 OPTICAL FIBER USED FOR TESTING

2.1 *Background*

As already explained, optical fibers have been tested in LAVOC's APT facility. This represents a common technology widely used in some civil engineering fields with accurate and reliable results. However, experience in the pavement area is relatively limited because of certain difficulties, e.g. behavior under high temperature (laying phase), mechanical resistance to loading, adhesion to the pavement. Some previous projects highlighted a few key points that need to be controlled as much as possible, in order to achieve reliable measurements. Hence, it has been decided to work with a specialized company that already had important experience, and could help finding the right sensor fitting the road pavement and loads requirements. Thus, the Swiss society SMARTEC [Smartec] was approached and they provided the measurement and data acquisition material. This society is indeed specialized in structural monitoring and they also have already performed few job sites on road and airfield pavements.

2.2 *Optical fiber MuST technology*

MuST (Multiplexed Strain and Temperature) technology has been found to be the most suitable to the requirements of the APT facility and the expected objectives.

The MuST technology is a deformation sensor allowing strain and temperature to be recorded, based on Fiber Bragg Gratings (FBG), which is a type of distributed Bragg reflector (DBR), reflecting a particular wavelength and transmitting all others. Indeed, a Bragg reflector is a high quality reflector used for optical fibers. It is in fact a structure formed from multiple layers of different materials with varying refractive index, or by periodic variation of some characteristics. Hence, each layer boundary causes a partial reflection of an optical wave.

The MuST sensors used are transducers that transform a static or dynamic distance variation into a change in reflected wavelength of a pre-stressed Fiber Bragg Grating that can be measured with an appropriate reading unit. The MuST deformation sensors present the particularity to allow both static and dynamic measurements and the possibility to have a temperature compensation system. Moreover, the utilization of this technology guaranties a constant tension along the fiber during the whole testing.

A scheme of a MuST sensor is presented in Figure 1. The sensor is composed of two main parts, the active and passive part. The active zone contains the measurement fiber and measures the deformation (average value) between its two ends, transforming it into a wavelength shift of the Fiber Bragg Grating. Thus, the data file obtained contains wavelength shifts that need to be converted in deformation. The passive part is insensitive to deformation and is used to connect the sensor to the reading unit. A loose Fiber Bragg Grating for temperature sensing and compensation has not been installed in the passive part for this research.

The main technical characteristics of the sensors used are:

- Static and dynamic measurements
- Length of active zone: 0.1 m
- Length of passive zone: 10 m
- Measurement range: 0.5% in shortening, 0.75% in elongation
- Strain accuracy: 0.2 με
- Operating temperature: -50 °C to 170 °C for special active zone
- Calibration is necessary

Note that the length of the active zone was chosen to 10 cm. Thus, the deformation measured is an average value over the 10 cm length that is comparable to the Kyowa strain gauges used.

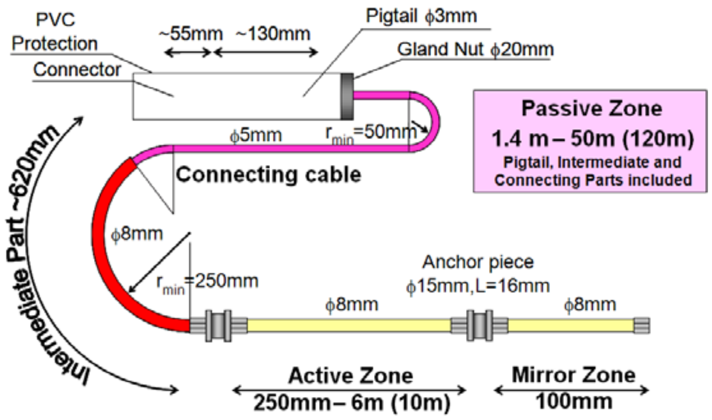

Figure 1. Scheme of a MuST sensor [Smartec].

As mentioned, it was chosen not to measure temperature by using optical fibers. Indeed, the precision for such measurements is currently not very high (±0.5 °C) and fibers measuring temperature are very expensive in comparison with other temperature sensors such as Pt100 that are more suitable. The indicative price of the fiber used is about € 600 per unit (in 2007), depending on the active and passive length. Note that the most expensive part usually consists of the data acquisition unit.

Some other optical fiber measurements techniques have also been assessed (e.g. SOFO technique) in order to select the more convenient for the tests to be done. However, MuSt technology seems to be more accurate for this type of measurements on a short distance using both static and dynamic measurements, this despite a slightly larger sensor size in comparison with some other alternatives.

3 FEASIBILITY STUDY IN ACCELERATED PAVEMENT TESTING FACILITY

3.1 *Description of the Accelerated Pavement Testing Facility and pavement tested*

Fiber optics technologies have been tested in LAVOC's APT facility. This facility has an accelerated loading facility (ALF) that is used to test full scale pavement structures. Thus, the facility allows the passage of a truck axle reproducing the dynamic loading induced by heavy traffic as accurately as possible.

Here are the main features of the ALF:

- Tire: single, super single or dual wheel
- Five different speeds; maximum speed (central area): 2.7 m/s ≈ 10 km/h
- Pass-by frequency up to 2000/hour (fifth speed)
- Maximum axle load: 140 kN
- Tire pressure: depending on tire type
- Constant speed rolling length: 2 m
- Side wandering: +/- 0.4 m

In addition to the ALF, a heating/cooling system providing an air flow to the pavement surface in the temperature range of -15 °C to 40 °C has been applied for this project. For this purpose, an insulated hall covering the tested field is used to control the air and asphalt temperature conditions.

The dimensions of the test field are 5.4 meters (circulation direction) by 13 meters that allow testing of different types of structure. The total rolling length is 4.5 meters, and 1.5 meters are necessary for braking and acceleration. The tested structure is as follows:

- Layer 1: High stiffness modulus asphalt (8cm)
- Layer 2: Soil foundation composed by gravel 0/60 (40 cm) and fine sand (145 cm)
- Layer 3: Concrete box

More details concerning the tested structure and properties of the various layers can be found in [NR2C, 2007]. For this research, it has been chosen to use an existing pavement already loaded. Indeed, the type of pavement has no major incidence on the test and the utilization of this pavement permitted to have a complete set of information about the pavement's behavior under loading. Nevertheless, it is important to mention that the various optical fibers have been installed in an existing pavement and compared with strain gauges installed during the laying phase. The optical fiber can be installed during the laying phase, as for normal sensors, but unlike strain gauges, also on an already aged pavement. Furthermore this allows better comparisons with a well known technique used for strain gauges. Some consideration for the installation of fibers in new pavements has also been made.
In order to be as close as possible to real conditions, the facility allows the utilization of classical materials and machines used for in situ pavement laying as for instance finisher and compactor.

Figure 2 illustrates the APT facility used for this full scale pavement test.

Figure 2. APT facility at LAVOC (EPFL) and machine detail.

3.2 *Optical fiber installation*

As previously mentioned, fibers have been installed in an existing pavement. The aim of the installation was to induce as less as possible disturbance in the pavement, i.e. obtain a similar behavior under loading of the various layers. For the installation of the various fibers, a special emphasis has been put on following items that will be further detailed:

- Choice of the position of the fibers
- Filling material

Considering the existing pavement and its configuration, the position of the different optical fibers has been fixed. For fatigue tests, the measurement of the solicitations at the bottom of the asphalt layer is of greatest interest and that is why the different strain gauges have been laid at the interface between HMA and gravel foundation, i.e. at 8 cm depth. Indeed, the measurement of the micro-deformation at this level is very important as it will allow us to assess the fatigue behavior of the pavement. It is currently well known that the highest traction deformation will occur at the bottom of the asphalt layer. Hence, fatigue cracking should first occur at that point before propagating to the surface of the pavement. Thus, the top of the asphalt layer is in compression, and the neutral axis is within the asphalt layer [Perret, 2003]. In conclusion, the ideal case is to install the different optical fibers at the bottom of the HMA as well, this in order to make direct comparison with strain gauge measurements. In addition to the fibers laid at the bottom of the asphalt layers, it was chosen to place some sensors at the middle of the high modulus asphalt layer, i.e. at 3 cm depth. Considering the position of the different cables used for data acquisition, the position of the various optical fibers has been finally chosen. This is indicated in Figure 3 for the various depths. Note that in this figure the optical fibers are indicated in green and the Kyowa strain gauges in red. The various strain gauges have been installed during the laying phase at 8 cm depth while the optical fibers have been installed in the middle and at the bottom of the asphalt layer. Besides, both types of sensors have been laid in the longitudinal and transversal direction. A total number of 10 strain gauges and 8 optical fibers have been installed and measured under loading.

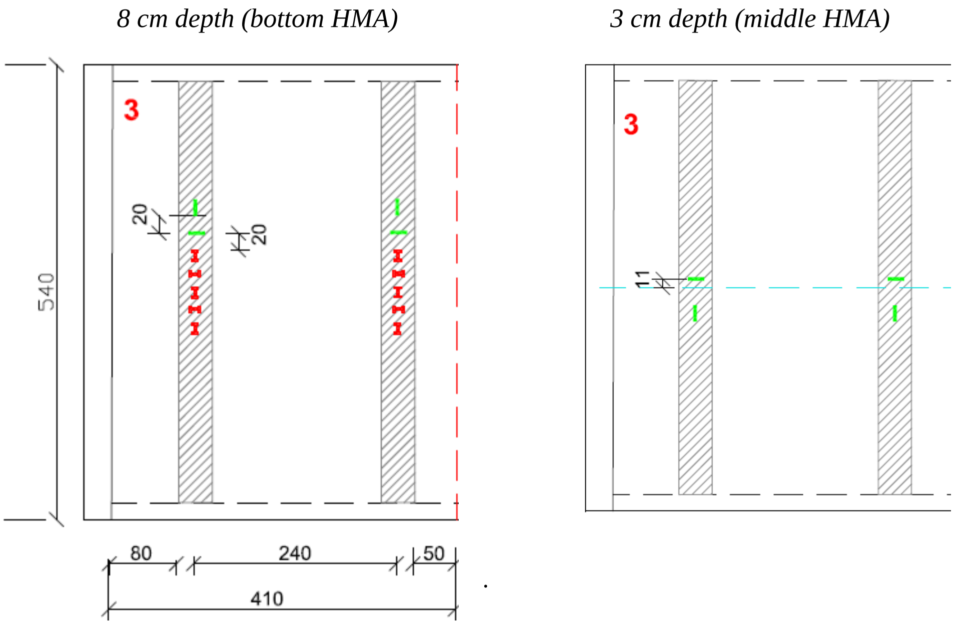

Figure 3. Optical fibers and strain gauges at the bottom of the asphalt layer (left) and in the middle of the asphalt layer (right).

For strain gauges, classical Kyowa strain gauges using the Wheatstone bridge principle have been used. We can also mention that in addition to these measurement devices, some temperature sensors (Pt100) have been installed at the bottom of the asphalt layer and at the top of the pavement as well.

The installation of the optical fibers was a crucial point of the study. Indeed, it is necessary to have a very good adhesion between sensors and asphalt mixture, this in order to measure the "real" behavior of the structure. Thus, the two extremities of the 10 cm active length needed to be glued on the pavement using an epoxy resin, this in order to ensure a total adhesion.

Finally, after installing the various optical sensors, the different trenches have then been filled. The choice of the filling material was a crucial point as well. Indeed, it is important to have a filling material that has a good adhesion with the measurement system, but also a mechanical behavior, i.e. an elastic modulus as close as possible to the modulus of the existing pavement. Indeed, the creation of any important discontinuity would have a significant impact on the further measurements. As the trenches are 2.5 cm wide, they cannot be filled with a classical bituminous mixture because of the aggregate size and the compaction rate needed. Hence, it has been chosen to use a binder-sand mix, with very rich binder content.

3.3 *Data acquisition and test procedure*

For the data acquisition process of optical fiber, SOFO DB software has been used with the MuST reading unit that could be rent for short measurement periods. For Kyowa strain gauges, data acquisition has been carried out using classical National Instruments hardware and Labview software. The measurement frequency for both sensors was 1 kHz. This could be easily changed but it was found that such a frequency was sufficient enough in order to get an exploitable and accurate signal.

Concerning the test site, LAVOC's APT facility was chosen, since it is possible to control a lot of parameters, e.g. temperature, water in the foundation, load, tire pressure and speed.

Hence, some specific variations have been performed on selected parameters, always keeping the other parameters constant.

One important effect on stress and strain measurements is the temperature. As both, strain gauges and optical fiber sensors, were not temperature compensated, the measurements have been performed at a constant temperature during the whole testing campaign. During the tests, it has been chosen to also vary the load between 0 (only wheel weight) and 12 tons and rutting tester speed between 0 (static measurement) and 4 km/h.

Table 1 contains the different tests performed. Note that the indicated temperatures correspond to air temperature measured with a Pt100 sensor while the pavement temperatures were also registered.

Table 1. Test planning performed

Side wandering	Air temperature	Load	Speed
± 40 cm	°C	t.	km/h
First week measurements			
No	15	0, 4, 8, 12	0, 1.6, 4
No	5	0, 4, 8, 12	0, 1.6, 4
No	10	0, 4, 8, 12	0, 1.6, 4
No	-2	0, 4, 8, 12	0, 1.6, 4
No	-10	0, 4, 8, 12	0, 1.6, 4
Yes	-10	4, 8, 12	0, 1.6, 4
Yes	10	4, 8, 12	0, 1.6, 4
Yes	-2	4, 8, 12	0, 1.6, 4
Additional week measurements			
No	42	0, 4, 8, 12	0, 1.6, 4
No	23	0, 4, 8, 12	0, 1.6, 4

Concerning the planning we can mention that for each case indicated in the table (combination of horizontal side wander, temperature, load and speed) three measurements have been carried out. This permitted an assessment of the repeatability and also the reliability of the different measurements. Each measurement session lasted 9 s at1 kHz frequency.

4 TESTS RESULTS AND ANALYSIS

In a first step, separate analysis of the results obtained using optical fibers and Kyowa strain gauges have been carried out, before to make some comparisons and additional calculations.

4.1 *Measurements with strain gauges and optical fibers*

A typical signal of a strain gauge output is represented in Figure 4. This signal corresponds to a loading case of 8 tons and 15 °C air temperature. Each peak corresponds to a passage of the load. Hence, during the 9 s. of data acquisition, 4 loadings have been registered at this speed. We can also notice that each strain gauge is represented by a specific code which first number indicates the depth of the sensor from the top of the pit, i.e. -11 corresponds to the bottom of the HMA asphalt layer.

We can also highlight the order of magnitude measured in this specific case that is between 200 and 400 με, except for one of the gauges. These deformations registered were quite high, but it is important to keep in mind that the pavement had already been deteriorated by previously performed fatigue and low temperature tests. Besides, the total asphalt thickness is very weak (8 cm).

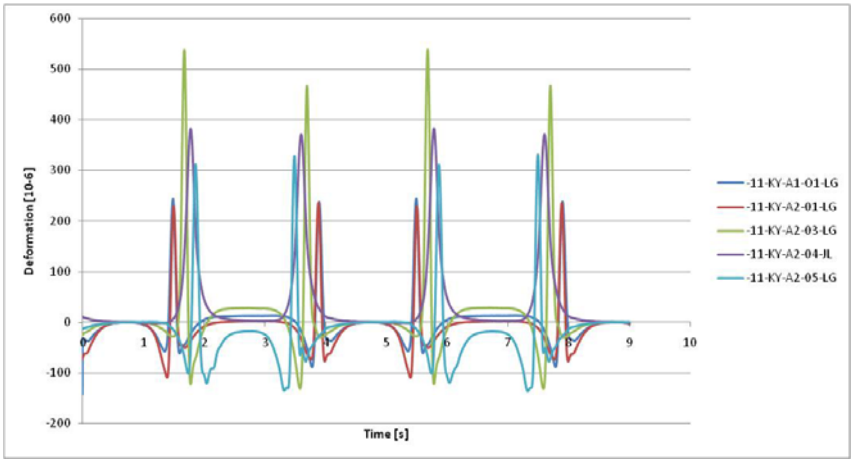

Figure 4. Strain gauges measurements (15 °C, 8 tons).

Figure 5 contains the measurements using optical fiber, for the same testing conditions. For these measurements, a global conversion factor between frequency and deformation has to be applied. In fact, the data acquisition recorded frequency variations for each fiber and these variations have then been converted into micro deformations by applying a ration of 830. Note that for the optical fibers, sensors N° 5991, 5998, 5994 and 5996 were installed at the bottom of the asphalt layer, i.e. at the same depth as the strain gauges. The last four sensors (N° 5995, 5992, 5997 and 5993) were installed at 3 cm depth, in the middle of the asphalt layer.

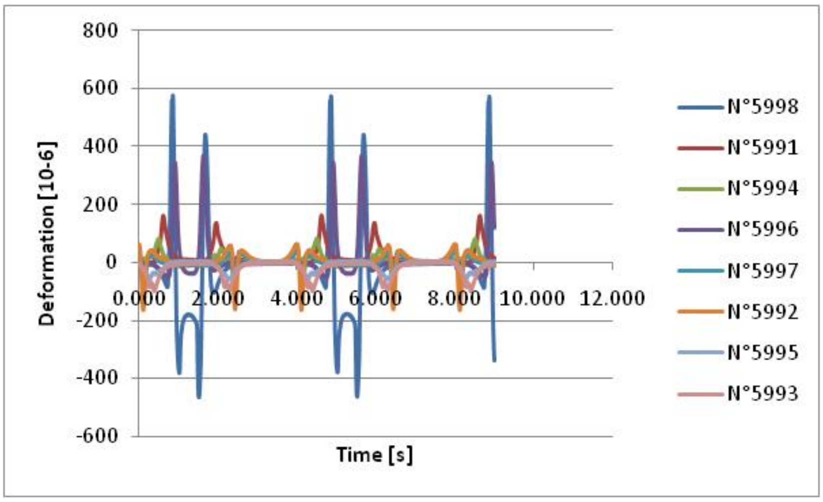

Figure 5. Optical fiber measurements (15 °C, 8 tons).

4.2 *Comparison between strain gauges and optical fiber*

Various cases have been investigated by applying load, speed, temperature and side wandering. For each specific condition, 3 measurements have been carried out in order to assess the repeatability of the measurements and to ensure the quality of the data acquisition. Hence, a very complete set of data has been recorded, with a total amount of 111 different cases.

By comparing the measured values for the various sensors, in the same conditions, following comments raised:

- It was chosen to install optical fibers in the middle of the asphalt layer, at 3 cm depth. The measurements of these sensors have been used to compare to the calculated deformation, since no strain gauge exists at this depth. Hence, no comparison between strain gauges and optical fibers can be achieved for this group of sensors. We can notice that the sensors at 3 cm depth have a negative deformation value, i.e. the sensors are in compression.
- Concerning the measurements performed using Kyowa strain gauges, we can notice that some sensors obtained comparable values that are quite different from other strain gauges. Hence, in some cases Kyowa strain gauge measurements are quite different from the optical fibers, despite being made with exactly the same loading conditions.
- If we consider the comparison between strain gauges and optical fibers, the deformations measured are closer for higher loading and speed than for a weak loading and/or speed. For instance, the measurements performed with an unloaded rutting tester gave more variation in the peak value of the different sensors than with a fully loaded rutting tester.
- A comparison between sensors transverse to loading was relatively difficult as only one strain gauge gave reliable results in that direction. Hence, these transverse sensors were not further analyzed. Besides, we can mention that a previous specific comparison between transverse and longitudinal peak value showed that no significant differences exist; the same order of deformation had been recorded. Moreover, we usually compare sensors longitudinal to loading as they have been found to be more reliable.

Figure 6 illustrates a specific example of comparison between the different peaks values measured with sensors longitudinal to loading, at the bottom of the asphalt layer. Measurements indicated in blue correspond to strain gauges, while the red data correspond to optical fiber measurements. Note that we obtained two groups of maximal amplitude. This trend is confirmed by considering all the measurements carried out: in general strain gauges A2-03 and A2-05 are relatively close to optical fiber 5998 and also sometimes 5996. Very few cases with a high difference between the two measurement techniques have been obtained by comparing the strain gauges A2-03 and A2-05 with the optical fiber laid longitudinal to loading. This conclusion cannot be extended to the other strain gauges A1-01 and A1-02 where some important deviation with optical fiber measurements have been observed that might be linked to a strain gauge problem.

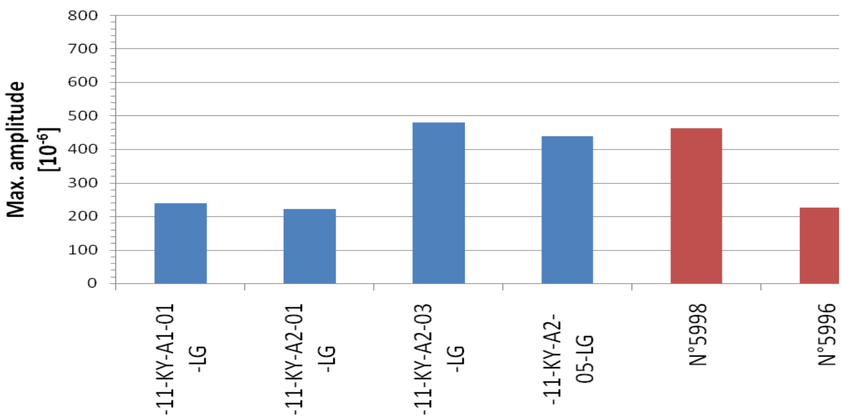

Figure 6. Comparison between strain gauges (blue) and optical fiber (red) measurements (-2 °C, 8 tons).

As explained in introduction, different sensitivity analyses have been conducted. These aimed determining the effect of selected parameters and also compare the general conclusion between the sensor types. Indeed, not only the measured values but also the variations between various conditions need to be assessed with the selected techniques. As an illustration, Figure 7 indicates the deformations measured for various loading conditions. As expected, deformation increased with increasing load. This trend is better represented with the optical fiber measurements while strain gauges showed some deviation. The deformation values are close by comparing 8 to 12 tons measurements.

Concerning these measurements, we can also mention the very good repeatability that has been observed with a standard deviation of maximum 15 με in most cases.

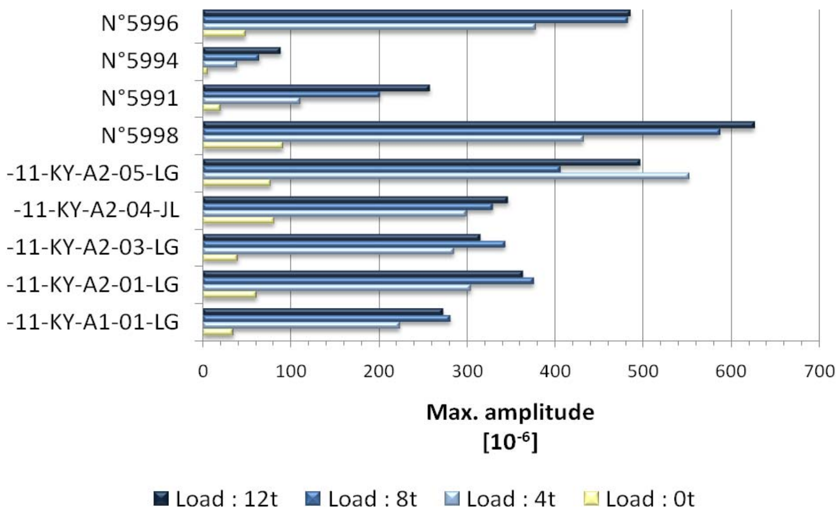

Figure 7. Comparison between different loadings (temperature 42 °C, 4 km/h).

4.3 *Comparison between measured and calculated deformations*

In order to compare the different measurements with theoretical calculated deformation, a modeling of the pavement has been achieved using the multilayer software NOAH. This software is based on the French design method, and strains are calculated using the multilayer theory of Burmister.

For the input parameters, updated material properties have been taken from a complete laboratory study performed within the NR2C project [NR2C, 2007]. Calculations have been performed for three different cases chosen in function of the test temperature. Furthermore, ALF speed was taken in account by modifying the frequency of loading. Indeed, it was demonstrated that the second speed of the rutting tester corresponds to about 2.5 Hz and the fourth to 4.5 Hz loading frequency [Perret, 2003].

Figure 8 represents a comparison between calculated and measured strains for the sensors placed at the bottom of the asphalt layer at 10 °C and 10 tons loading. Data with a black border correspond to sensors transverse to loading. The calculated values are very close to the values measured by strain gauges A1-01 and A2-01 and these results are also consistent with the measurements using optical fiber 5996. On the other hand, the strain gauges A2-03 and A2-05 and optical fiber 5998 have slightly more important deformations measured. These comments can be extended to the other calculated cases as the same results have been obtained, i.e. the calculated deformations are very close to part of the strain gauges and optical fiber while the other sensors have a more important deformation measured.

By comparing calculated deformations with measured deformations at the middle of the asphalt layer (3 cm depth), the same conclusions have been obtained.

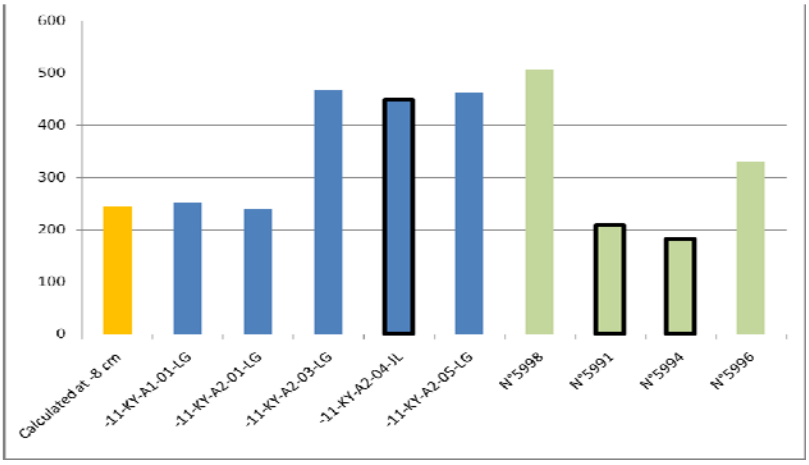

Figure 8. Comparison between calculated (orange) and measured deformations (blue: strain gauges, green: optical fiber).

5 CONCLUSIONS AND RECOMMENDATIONS

As mentioned in introduction, this study aimed at assessing the potential and reliability of optical fiber. During the whole analysis, optical fiber data have been compared with Kyowa strain gauges. In many cases, it has been found that both technologies gave consistent and comparable results. Firstly, the signals and general trends obtained by using optical fibers are correct and the order of magnitude is often quite close to the strain gauge results. Moreover, it is important to keep in mind that strain gauges provide an indicative value of deformation for a specific loading with an order of magnitude. In fact, for most of the pavement design and evaluation, a high accuracy is not required. Deformation measurements of strain gauges are very sensitive to a lot of parameters (adhesion, horizontality, presence of aggregates,…).

Thus, the results obtained with optical fibers are very promising; a further application on a real test site would be advisable. The present study also highlighted a few important points that need to be considered or improved in order to have a good experience on the test site:

- The sensor installation in an existing pavement was quite different from the installation in a new asphalt pavement. In our case, to make a trench and then fill it with a sand-binder mix seemed to work quite well. However, one of the main points is the adhesion between the optical fiber and the pavement; it is crucial that the active length of the fiber is well fixed at its extremities.
- Another possible application on existing pavements could be to install the fiber on cores that are then reintroduced in the pavement. This kind of application is currently developed by some societies.
- For application in a new pavement, it is important to ensure that the fiber is protected from high temperature with a resistance sheath. This could be achieved without great problem as the high temperature is only during a very limited period during the pavement construction. Besides, a special emphasis has to be put on the compaction system during the laying phase, resistance to corrosion and humidity as well.
- In comparison with Kyowa strain gauges, the optical fibers present an important advantage with lengths up to 2 meters for the active zone. Hence, by using a multiple Bragg system in the same optical fiber, it could be possible to measure the whole deflection curve instead of some local points as achieved with classical sensors.

Finally, for a good measurement of the pavement deformation, it is important to have as little disturbance of the pavement homogeneity as possible. Hence, it would be advisable to have a smaller sensor, for instance by reducing the sheath dimensions. This can be achieved by developing optical fiber for specific road applications that certainly have an important potential.

6 REFERENCES

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