Bachelor's Thesis

Bare Fibre Optic Sensors for Strain and Temperature Measurements in Surface-layer Asphalt: An Implementation and Evaluation Case Study

UNIVERSITY OF TWENTE.

ASPARi
Paving the way forward

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Preface

This research was written as a part of my Civil Engineering bachelor study at University of Twente. By the end of this undergraduate cycle, I would have spent 3 years in an international setting, acquiring experience in the professional and social setting of another culture. It was the first time I ever lived anywhere but home, and the period was for sure a life-changing experience. As it nears its end, I would say this was a successful journey for a bachelor's student at the University of Twente. The next steps of my professional career will have been imminently influenced by my time here and I am immensely thankful for all the opportunities I was given. I happened to be here during a complicated time in the world and I would have not been able to successfully finish this adventure without some help. Therefore, I would like to thank Seirgei Miller and Mohammad Sadeghian for supervising and helping me from the very start of this assignment with ASPARi. I would like to thank my family for supporting me throughout these years and reminding me that I was more than capable of finishing whatever I set out to do. Lastly, I would like to thank my fellow students and dear friends Rahadian Rukmana and Daniel Vernhout, without who my student experience at UT would have not been the same. I am grateful for all the amazing professors I had, for the institution as a whole and for every student that has ever contributed to it.

Dankjulliewel!
Stefan Pozinarea
October 5th 2021

Summary

Demands are increasing in the field of road vehicle transportation and with them there is an increasing need for improvements in road infrastructure maintenance and health monitoring. Structural health monitoring takes charge of this issue by, among other methods, making use of sensors for continuous monitoring and assessment. Fibre optical sensors are on the cusp of becoming the go-to alternative among such sensors, due to their many technological advantages. However, they pose just as many if not additional issues and the decision-making behind their appropriate implementation is far more complex. We can identify two instances of usage. One instance is meant for high-performance measurements, case in which the optical fibre is not coated, and the second instance where the optical fibre cables are used in harsher environments, generally while coated, and provide less accurate measurements.

In the field of road maintenance and structural health monitoring, the second instance is far more common and other more traditional sensors are used. This study thus tackles two issues. Firstly, could or should the older sensors be replaced with the new fibre optical technologies, considering the benefits of the more advanced technology. Secondly, regarding the discussion of coating usage and accuracy, the study aims to give some new perspectives on the decision-making and challenge the unspoken consensus about the use of coatings.

In order to achieve this, the study involves the observation of a paving project on the University of Twente campus in Enschede, Overijssel. During this study, fibre optic sensors are used for measuring temperature and strain in the asphalt layer. The results are then evaluated with data from traditional sensors and theoretical values. The evaluation process is meant to establish whether or not the measurements are reliable and accurate. The difference is that the project team aims to test the high-performance uncoated sensors in what would generally be considered a harsh environment. Lastly, a comprehensive discussion of the results and research questions is presented alongside a research conclusion and a proposal for future inquiries in this field.

Although the project’s on-site implementation has led to some failure by various mechanisms, one significant conclusion was derived, alongside a few more insights into fibre optic installation and usage. Moreover, the hinderances in data collection have prevented part of the data evaluation process from allowing a concrete assessment. However, the study has been concluded and is to be used in preparation of future renditions of the paving project and fibre optic sensor research.

The main objective of the study was to generate a calibration and evaluation framework for strain and temperature, offering the opportunity to replace other types of sensors in the future. Although, the data is not optimal, the regression results over all 5 data sets point towards a possibly valid procedure for the evaluation of strain measurements. This could suggest that the FOS can indeed be a functional replacement for the traditional strain gauge. As for the other research questions, it is rather clear that the data retrieved from bare FOS is not satisfactory. Because of that, for the moment, the bare FOS cables cannot be recommended as a functional replacement for both strain and temperature measurements.

Lastly, there is high emphasis on the downfalls of bare FOS and the usage of coating, suggesting that adequate coatings can indeed improve the quality of the study were it to be reiterated.

Contents

1. Introduction

1.1. Project framework

ASPARi is a network of organizations involved with research and development of the asphalt construction processes. Recent developments, especially in the case of long-duration projects in the Netherlands, have seen drastic change in terms of process control, quality control, maintenance and risks to contractors. In order to tackle such issues, the construction companies partnered with researchers at the University of Twente to form the ASPARi group in 2006 (https://www.utwente.nl/en/et/aspari/). Since then, ASPARi group and its contractors have gotten involved in up to 80% of the activity in the Dutch asphalt industry. Their ambition is to continuously provide product quality and value for their clients, by focusing on improving the productivity and process control. (https://en.aspari.nl/about).

The population growth and the eagerness for constant economic expansion have greatly contributed to increasing demands for transport accessibility. A very large portion of this demand is served by land vehicle traffic and the interconnected transport infrastructure systems (Robinson, Danielson & Snaith, 1999). As a consequence, roads suffer from intensive surface ware and internal damage more frequently, requiring more frequent diagnosis and better maintenance plans. The field of structural health monitoring (SHM) is heavily involved in the study of these issues and in relationship to the traffic behaviour and other external factors.

Lopez-Higuera et al. (2011) describe SHM as a system that enables the pre-emptive detection of a structural malfunction and allow for an in-time refurbishment intervention, thus involving limited maintenance costs. This could eventually enable the extension of the pavement’s lifespan and a decrease in the direct economic losses involved in repairs, maintenance, and reconstruction. In the course of their lifetime, roads are subject to various threats to their health condition. While there is no way to identify each individual cause and tie it to a possible amount of damage found in a structure, monitoring is an effective way to recognise onset failure and allow for preventive planning.

1.2. Research model

The research model provides a framework of the current thesis report and helps illustrate the process contained therein. Furthermore, the research model helps highlight the guiding process of the research, from the literature study to the research definition, to the implementation and finally to the analysis of results and providing recommendations. The creation of such a research model is described in the work of (Verschuren & Doorewaard, 2011). The research model can be seen in Figure 1. Components that are in the same column indicate confronting aspects of the research and are studied concomitantly. Advancing horizontally to the right, the knowledge and conclusions drawn from a previous column are used as input for the next steps of the research.

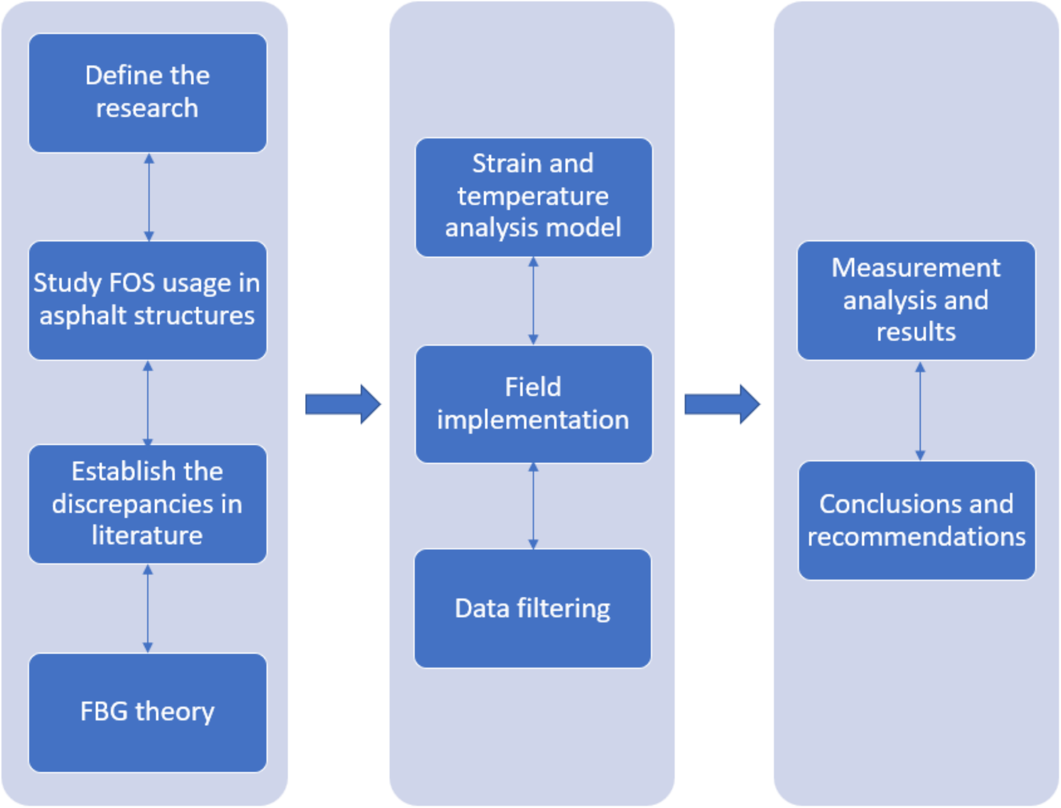

Figure 1: Research model

The left column revolves around knowledge acquisition and research definition. It features a review of the literature on the state of the art of fibre optic sensors (FOS) usage in pavement SHM. Alongside that, the theoretical basis for usage of fibre Bragg-gratings (FBG) is acquired and the research is defined around the gaps in current field literature, the research scope, aim and questions that drive this project. In the middle column, a framework for the measurement analysis is given, alongside data filtering practices involved in reaching the final results. At the same stage in the report, an overview of the project's implementation is given. In right column, the strain and temperature measurements are presented, analysed validated and the results are discussed. Right after that, conclusions are drawn based on the degree to which the results provide satisfactory answers to the research questions. And finally, a set of recommendations is given for future iterations of the project and for future research.

1.3. Thesis structure

This thesis report has the following structure. Section 1 is representative of the first column in the research model. It features a state-of-the-art review and the definition of the overall research. Section 2 will describe the project site and setup, the tools and analysis methods used during this study. Section 3 presents a preview of the raw data and some pre-emptive data filtering practices. Next, in section 4 results will be presented and assessed relative to the research questions, followed by a discussion of the research methods, questions and other observations. Lastly, in section 5 conclusions for the research will be drawn alongside some recommendations for future research.

1.4. Literature review

To this day, devising an efficient method to determine realistic mechanical properties of pavement proves challenging. Since the early 1990s, there has been interest for developing new technology around structural behaviour with the possibility of obtaining higher precision measurements. Older technologies helped identify failure through rather invasive and infrequent inspection procedures that would themselves damage the road and require partial reparations in the aftermath. Ideally, the health inspection and monitoring processes should be continuous and non-invasive. Several developments have been done in that sense ever since the introduction of road sensor data collection paradigms. Traditional sensors, such as strain gauges and thermocouples, are commonly used for their reliability and direct output, while only providing localized point measurements from a single signal.

A number of different technologies have emerged over the last 3 decades, and, among them are sensors with fibre Bragg gratings. An FBG is a short mirroring component of an optical fibre, which can reflect within a limited wavelength range and transmitting all signal components form outside that range. The working principle is based on the variation of the refractive index of the fibre, which filters signals with respect to the central reflecting wavelength (Kara De Maeijer et al., 2019). The sensing information is then read from an optical encoder, which catches the signal portion the reflected by the fibre Bragg grating. External perturbations, such as temperature or strain, cause the central Bragg wavelength to shift (Van Hoe et al., 2012), thus allowing for measuring of the perturbation.

As part of the current state of the art in monitoring technologies, the usage of fibre optic sensors with embedded FBGs is a continuous development. They have quickly proven to be one of the most promising tools currently available (Imai, Igarashi, Shibata, & Miura, 2014) for SHM. Besides being non-invasive, FOSs provide a lot of advantages such as high sensitivity and precision for absolute measurements, being of small volume and geometrically versatile and convenient for network integration and multiplexing.

In their collaborative work, (Kara De Maeijer, Van den Bergh & Vuye, 2018) have themselves comprised a state-of-the-art analysis on the usage of FBG-based sensors in pavement structures. The paper is focused on some significant experimental attempts of using FOS, over the previous 2 decades. Their work brings forth the following conclusions, with regards to the current common practices:

a) Very few studies provide technical details on the installation procedure;

b) Only a few cases could be referred to as long-term monitoring;

c) Most of the literature covers experimental settings extensively, rather than monitoring of the pavement itself.

d) FOSs have proved they could still be useful and promising when monitoring in-situ strain measurements, but systems with varied designs and installation approaches contribute to differences in both the recorded and expected measurement outcomes;

e) There is no consensus on calibration, and there are also no combined efforts towards one.

With the previously mentioned state-of-the-art study as a starting point, the rest of this section presents a literature review of the field. The review begins with a study of some of the cases mentioned by (Kara De Maeijer et al., 2018) and includes multiple others, presenting the various practices, revolving around asphalt structure FOS measurements, that are employed throughout the world. This section aims to highlight the various methods and equipment used in every particular study, and the perceived effects the different implementations have on the overall outcome of the experiments. The study of these journals and conference papers is aimed at identifying a clear gap in the current research and suggesting a clear aim for this particular research piece and others to come.

In China, (Yiqiu, Haipeng, Shaojun & Huining, 2014) proposed a quality control paradigm for asphalt pavement compaction. This process would focus on compaction behaviour of a prefabricated asphalt plate under controlled rolling cycles. This behaviour would be derived from strain measurements recorded with FBG optical sensors. There have been numerous more traditional quality control methods before, but they came with some known issues such as: destructive invasive testing, unreliable compaction measurements (due to heterogeneous asphalt mixtures), and, most importantly, the compaction control methods can only be used after the rollers have been used. One of the main goals of compaction control tests would be to indicate when the compaction operations should be stopped. Therefore, these methods are deemed unsuitable for real-time quality control in situ. This is where the implementation of FOS helped avoid making invasive tests and helped obtain direct strain measurements. Most importantly, once installed, the optical fibre cables could help guide the compaction process in real time. For this study, no particularly complex equipment is mentioned, and only basic FBG wavelength theory is used ($\frac{\Delta\lambda}{\lambda} = k_{\varepsilon} \cdot \Delta\varepsilon + k_{T} \cdot \Delta T$). The implementation is not very descriptive (besides a set of photographs) and there is no mention of any coatings being used, even though some can be seen in the implementation pictures. Overall, the research was mostly a success with the conclusions indicating that the FOSs are quite competent at measuring independent strain behaviour.

Also in China, (Xie, Li, Gao & Liu, 2017) proposed a study for rutting prediction with the use of FBG-based sensors. They used the FOSs to study cumulative deformation, through repeated strain measurements, but mention in the introduction that, at the time, the FOS technology was “still in practice” and sometimes only functional in a laboratory setting. Compared to the paper of (Yiqiu, Haipeng, Shaojun & Huining, 2014), this study includes the consideration for temperature in the viscoelastic behaviour of the asphalt and is a more ample study overall. It includes a more elaborate calibration procedure and a linear regression validation model, both based on the adaptation to temperature change. This study is also executed on a rutting plate that is later mounted onto a road, but there are more intricate study cases, and the analysis is also broader. The results of their calibration tests showed that the linearity condition could reliably meet the requirements of pavement monitoring. Unlike the previous piece of research, this implementation does mention the usage of Acrylate coating for the FOS cables, but does not elaborate any further.

Another study of (Liu, Liu, Wang & Zhou, 2019), does involve the plastic deformation behaviour of an unconventional asphalt mixture with volcanic ash. For all intents and purposes, this does not significantly affect the usage of FOSs in the structure. Similar to the last study, the FOS strain recordings are calibrated for changes in both strain and temperature. The difference here lies in the experimental setting. The tests presented in this study are entirely done in a laboratory setting with a chamber that cam ensure constant temperature and much smaller samples. Probably the most notable aspect of this paper is the strife for very high sampling frequency and very high measurement accuracy. This was made possible by, multiple developments in the field over the last 5 years. However, these experiments are done in the much more predictable setting of a laboratory, where significantly fewer things can go wrong. This ensures the calibration is properly done and remains valid throughout any test. The handling and implementation of the FOS cables are also much easier and safer, thus improving the survival rate of the otherwise fragile optical fibres. As mentioned previously, this particular piece of research aims to obtain very high measurement accuracy and its conclusions suggest that it succeeds in doing so. One key aspect of this laboratory study is the deliberate usage of bare FOS cables. In order to obtain accuracy of up to $1\mu\varepsilon$ any hinderance to the measurement capabilities of the sensor should be avoided. This includes removing any coating, leaving the sensor cable far more susceptible to breaking. This is in general the trade-off between reliability/survival-rate and accuracy and precision. The study of (Liu, Liu, Wang & Zhou, 2019) is likely only possible in a laboratory setting.

In a study in Greece (Loizos, Plati & Papavasiliou, 2013), the FOSs are used in assessing the performance of cold-recycled asphalt pavements. They use a slightly older variation of the technology, opting for a Fabry –Pérot sensor type instead of the FGBs. This variation was once frequently used, being known as a potent tool for strain measurement. This fits the use case since the asphalt is cold-recycled and the tests are executed after the asphalt layers are set, so temperature has a significantly smaller impact on the visco-elastic behaviour. One particularity of these tests, being run after the asphalt layers have finished setting, is that the FOS cables are not laid in between the layers and paved over. Instead, the researchers bored through the pavement structure and the FOS cables are then fed through the resulting channels. Because of that, the handling of the cables in situ becomes much safer and the optical fibres are less likely to break. To add to that, although not mentioned in the paper, the research team shows photos of the installation process where the FOS cables have some sort of rubber coating, which further helps prevent contact or strain failure.

A study in France (Chapeleau, Blanc, Hornych, Gautier & Carroget, 2017) proposes the usage of a “Rayleigh sensing technique” that can be applied to standard fibre optic cables. However, for monitoring pavements, special fibre optic cables for sensing measurement should be used. Such cables must have somewhat mechanical resistance for easy handling and to be able to withstand the stress of the pavement compaction process. For their experiment, the optical fibre cable was protected by an epoxy overcoat and a steel bar jacket. The cable does not need the FBG technology and has a longer, continuous sensing range. The downside of that is, that the measurements, although more complete, are much slower, possibly taking up to 10 seconds for one entire measurement, compared to the microsecond-order response time of the FBGs. Despite that, the method is present in the literature and deemed successful at monitoring strain curves. One selling point of the Rayleigh distribution would be the capacity to measure both strain and temperature with the same sensor cable. This is unfortunately not presented in this study.

A very extensive study was also executed in Japan. In their paper (Imai, Igarashi, Shibata, & Miura, 2014), include tests that account for many variables, when measuring strain propagation through various asphalt structures. The most significant variables are temperature range, stiffness and incline. The method of choice for measuring strain is in this case is Brillouin scattering with FBG-based optical fibres. This method revolves around lowering the scope of the measurement, so that the impact is only studied in the immediate vicinity of the FBGs. This method is not yet very common in the literature. The supposed benefits are the ability to introduce material stiffness as input strain measurement calibration. This would in turn allow the usage of the sensors in both stiffer and softer materials. The main current drawback is that, despite the narrower measurement scope, the error tends to be higher, compared to the classic FBG central wavelength method. The study concludes that the Brillouin scattering method yields results comparable to direct FBG measurements. However, the implementation is significantly more demanding and costly, and the large number of experiments executed can lead to contradictory findings. Another particularity of the study is the usage of adhesive polyethylene as coating of the sensor cables. This proved to be suitable for every single one of the numerous tests the researchers have run, while measuring pavement strain.

Last but not least, two interesting studies have been done in Belgium. In the first one (Luyckx, Voet, Lammens & Degrieck, 2010), the authors put present a great comparison between the usage of coated and bare FOS cables. There are clear benefits to using coated fibres, mainly with respects handling and survival rate. On the on the other hand, bare fibres have niche use cases they excel in. To name the main ones, bare FOSs have better accuracy at temperatures lower than 180°C, give much clearer spectral response and allow for linear analysis of the wavelength output (which is usually unreliable when using coatings). Various use cases are mentioned in an attempt to underline the differences between the two choices, but no experiments or validation methods are presented and the yet again only strain measurements are part of the analysis.

The second study from Belgium (Geernaert et al., 2014) proposes the usage of butterfly-designed birefringent FBGs in the optical fibres. Unlike any of the other studies we mentioned, this study suggests the possibility of multiplexing the signal. In our case, it allows for the measurement of both strain and temperature simultaneously, with the same FBG-based sensor, by splitting the signal into separate strain and temperature relative-wavelength components. This method is later elaborated upon in our project, but for this section it is important to mention that concomitant measurements like these are very rarely explored in the literature. Most of the study cases, including the one previously mentioned, usually focus on a proof of concept rather than on thorough experimental results. The sensor cables in case are introduced in an epoxy buffer plate which is also not accurately representative of the asphalt structure.

1.5. Research Gap

A few very important ideas have been pointed out over the course of this literature review section. The next paragraphs represent a summary of these findings and points towards a gap in the current research literature. The purpose of the project described later in this report is to attempt to fill this research gap.

First of all, we can take into consideration the conclusions on the state of the art given by (Kara De Maeijer, Van den Bergh & Vuye, 2018). All 5 points are completely valid and accurately descriptive of the current state of FOS research in asphalt structures. On top of those findings, the following statements can be added.

Literature findings	**Context**
Almost all studies, revolve around a constant temperature abstraction and only study the continuous strain behaviour.	It is generally agreed that both strain and temperature are key factors in pavement monitoring. FBGs are also commonly known for allowing the recording and parsing multiple signals simultaneously. Despite these agreements, almost no studies attempt concomitant measuring of the variables.
There is no consensus on implementation, installation, or calibration practices in the literature.	Despite trying to reach a common goal, no two pieces of research emphasize any desire for a commonly validated approach. This is in part due to the extremely varied use cases and experimental settings, but also the complexity and array of possibilities that the technology poses.
The decision to use or not use coatings is almost never treated as a specific design choice in these FOS measurement systems.	These sensor cables are very light, sensitive, and easy to brake which becomes the main challenge when using such technologies (Lopez-Higuera et al., 2011). When used in laboratory settings the bare sensor can be more carefully handled and is not prone to suffer from unexpected failure. When used in an actual construction setting, the sensor cables have a very high rate of failure due unexpected external influences. Despite this choice being very influential, no paper focuses on giving a decision framework with regards to coating usage.

Very few studies discuss failure to acquire desired results. There are plenty failure mechanisms, but they are seldom given significant consideration within the published work.

Each piece of research presents the author's own attempt at ensuring the survival of the sensor cables, based on their isolated experience. Moreover, no consideration is given to proposing frameworks for better handling and implementation of the FOS systems, but the failure mechanisms are plenty and unexpected (Jülich et al., 2013) There is space in the literature for a framework of protective practices, that help mitigate sensor breakage.

As a summary, the main ideas that I see constituting the research gap are as follows:

- Very few studies consider using the same FOS for measuring both strain and temperature.
- Bare optical fibres are only studied in a laboratory setting and lack in situ representation, despite being able to provide better measurement accuracy.
- Because all implementations differ, there is no consensus on what the common failure mechanisms are and how to avoid them.

1.6. Research aim and questions

In an attempt to contribute to the research gaps mentioned at the end of the previous section, this thesis project will focus on providing pertinent additions to those sections of the literature.

In the following project study, we will observe the installation and usage of FOSs in situ and assess whether or not this is a viable method of measuring both strain and temperature, rather than employing more generic sensors (thermocouple and strain gauge) for one or the other. These traditional sensors will only be used to validate our findings.

On top of that, this iteration of the project will feature the usage of bare/uncoated FOS in situ. When making this decision, we have to consider the following line of reasoning. On one hand, there has been an increasing demand for the use of optical fibres in harsher environments, where the fibre must withstand high strain and temperature on top of resisting fatigue over long periods of time. Sometimes, the reliability of such FOS cables decreases with time, in the presence of moisture or other corroding agents and is being even further degraded with elevated temperature. The use of coatings undoubtedly helps mitigate these issues.

On the other hand, high performance measurements are desired for this project, as they could facilitate the evaluation framework. More precise measurements can better inform on the reliability of the FOS measurements, allowing for these sensors to potentially become better alternatives to the classic alternatives. The coatings in this case are undesirable, but a healthy compromise needs to be reached for the sake of practicality.

It is clear that most users predominantly use and recommend coated FOS and bare FOS for largely different purposes. Despite that, in the case of both strain and temperature measurements, the literature almost always omits to justify why such choices are made.

Thus, during project the focus is put on trying to justify the use of bare FOS as one sensor over the use of both thermocouples and strain gauges, while retrieving relevant strain and temperature data and evaluating the accuracy of the process. Additionally, the crucial question that need to be answered revolves around the reliability of bare FOS in such a setting.

Lastly, any possible issues that are observed at any moment during project's implementation process will be addressed and a set of guiding recommendations will be presented. This is done in order to help identify and prevent failure mechanisms and create a framework for decision-making in implementation.

In order to touch on these three points, the following research questions need to be answered.

1. To what degree are the bare FOSs a reliable alternative for a traditional strain gauge or other strain sensors.
2. To what degree are the bare FOSs a reliable alternative for a thermocouple?
3. How did the bare FOS behave in situ? Is this behaviour adequate?
4. What failure mechanisms can be observed? How could they be avoided?

2. Tools and setup

The proposed FOSs use embedded fiber Bragg gratings (FBG) that have been described and used in numerous experimental settings for micro strain and temperature pavement measurements (Wang et al., 2021). As a wave signal is sent through the grating the sensors are affected by external conditions (such as variations in load and heat) and the outcome is reflected in the optical signal. The FBGs inside the fibre cables are very sensitive to external thermal and mechanical stimuli. The Bragg wavelength changes are proportional to the temperature or micro strain variation. (Chapeleau, Blanc, Hornych, Gautier & Carroget, 2017). General information about the fibre optic cables and further specifications of the FBGs are given in Table 1.

Sensor type	**Fibre Bragg Grating Array**
P/N	FBGA – PI – 8
ID	161205 – 8
Fibre type	Acrylate SMF-28
Recoating	Polyamide
Fibre length	7400mm

Grating No.	**Position (mm)**	**Central/Resonance wavelength (nm)**	**Reflectivity**
1	6734	1518 ± 0.5	95.4%
2	6822	1527 ± 0.5	95.8%
3	6910	1536 ± 0.5	94.7%
4	6998	1545 ± 0.5	95.3%
5	7086	1554 ± 0.5	94.7%
6	7174	1563 ± 0.5	93.7%
7	7262	1572 ± 0.5	94.2%
8	7350	1581 ± 0.5	93.9%

Table 1: Cable and FBG specifications

A ‘Gator’ FBG interrogator is used to record the Bragg wavelengths within the sensors. Each cable contains 8 FBGs and the use of 3 cables was intended during the project. Two of these cables are aligned in parallel along the wheel path for longitudinal micro strain measurements and one is in placed across the wheel path for transversal measurements. Additionally, 4 thermo-loggers are used to record internal temperature of the pavement at different locations. The thermo-loggers are recording data from pairs of thermocouples at two different depths in the asphalt layer. However, considering that the FOS cables are placed underneath the surface asphalt layer (meaning lower that the stands themselves) the data form the bottom thermocouple is predominantly used.

One thermo-logger is connected to 2 pairs of thermocouples placed in the FOS study quadrant. One pair is placed near the longitudinal FOSs and one pair is placed near the transversal FOS. Lastly for eventual interest in temperature interpolation and heat one pair of thermocouples was placed approximately 10m before the FOS quadrant and one pair was placed approximately 5m ahead of the quadrant. These pairs and their data were eventually excluded from this study. The placement of both the FOS and the relevant thermocouples is highlighted in Figure 2.

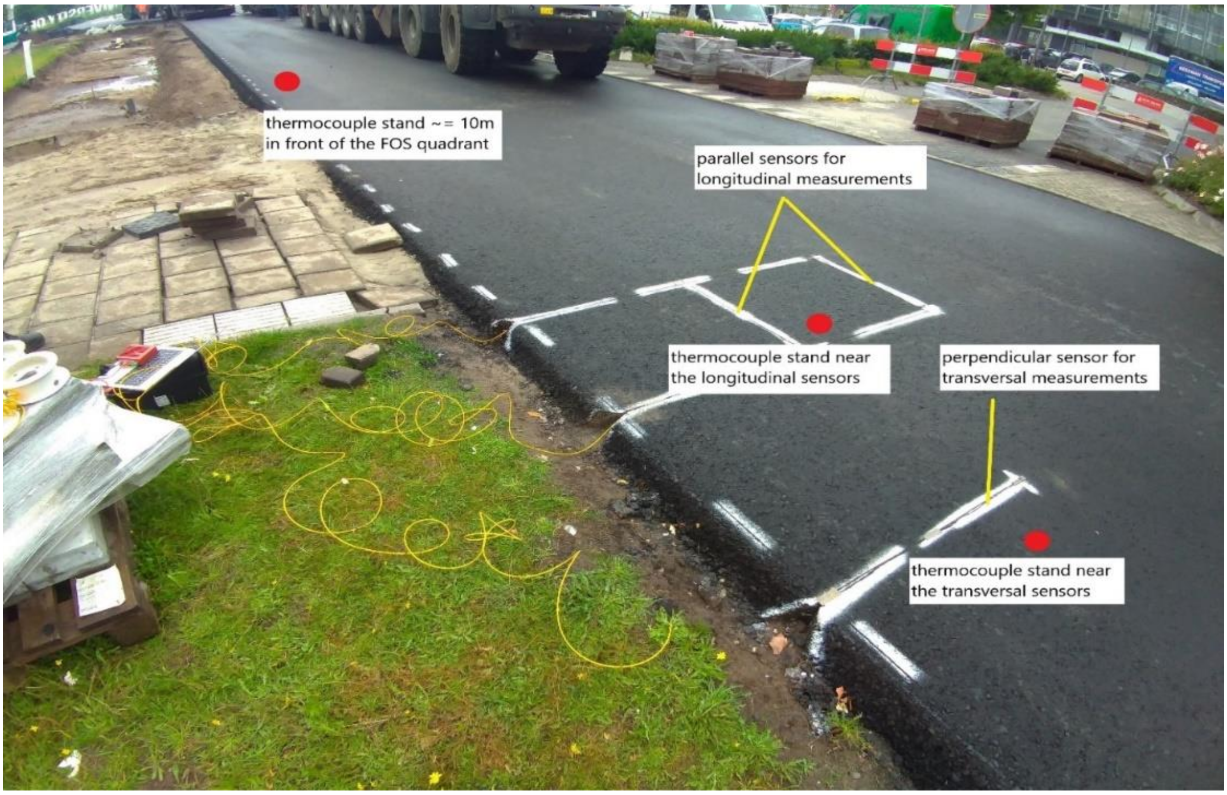

Figure 2: Installation quadrant and road setup

2.1. Analysis models

As mentioned previously, the FBG interrogator is used to record wavelength measurements that reflect changes in micro strain and temperature. However, the output of the of the interrogator is not directly descriptive of these measurements. It outputs a Centre of Gravity signal series that can be translated to wavelength measurements. Subsequently, the wavelength measurements need to be translated to the two study components of micro strain and temperature. The manufacturer of the interrogator describes a method for achieving this in the user manual (Gator FBG Interrogator, User Manual, Original Version, 2020).

$\lambda = 1514 + \frac{output * (1586 - 1514)}{2^{18}}$	Where, • λ is the required wavelength in nanometres. • $output$ is the Centre of Gravity signal value
$\mu\varepsilon = \frac{\lambda - \lambda_0}{\lambda_0} \cdot \frac{1}{k_{\mu\varepsilon}} \cdot 10^6$	Where, • $\mu\varepsilon$ is the requested micro strain value • λ_0 is the central wavelength according to the FBG manufacturer (the value can be found Table 1 for every FBG on the cable) • $k_{\mu\varepsilon}$ is the manufacturer's conversion coefficient for micro strain (0.78 for silica strain gauges)
$T = \mu\varepsilon * T_{conversion} + \Delta T$ $\Delta T = \frac{\lambda - \lambda_0}{\lambda_0} \cdot \frac{1}{k_T}$	Where, • T is the requested temperature value • $T_{conversion}$ is the default temperature projection factor for finding the measurement baseline ($\cong 8.8\ K/\mu\varepsilon$ for silica) • k_T is the manufacturer's conversion coefficient for temperature (7.429 for silica strain cables)

Table 2: Conversion Theory

Alternatively, in a study of FBG properties (Oh, Han, Paek & Chung, 2004) describe a different relationship between the changes in signal wavelength behaviour and the concomitant changes in micro strain and temperature.

$$\frac{\lambda - \lambda_0}{\lambda_0} = s_T \cdot T + s_{\mu\varepsilon} \cdot \mu\varepsilon$$

Where s_T and $s_{\mu\varepsilon}$ are coefficients of micro strain and temperature sensitivity relative to the cable properties and the asphalt mixture.

It is immediately apparent that the Gator manufacturer method is based on a single linear conversion with multiplicative coefficient components for both micro strain and temperature. By comparison to the (Oh, Han, Paek & Chung, 2004) method is based on a multilinear conversion with two additive components. For the second method a double linear regression is used to find the appropriate coefficients. A comparative study of these methods will be presented, followed up by an evaluation based on the thermocouple temperature measurements.

2.2. FOS installation and paving processes

The process of installing all sensors and taking measurements has been documented and is described in the Table 4 alongside particular circumstances that may hinder the study. Based on the events that are deemed significant to the measuring and evaluation process the data chosen for later analysis will be synchronised around the timestamps of those events. Alongside the sensors, 3 distinct pieces of paving equipment are identified based on purpose and size: asphalt paver, small compaction roller and large compaction roller. A full timeline of the paving process and FOS interrogation is given in *Appendix I.* The process unfolded as presented in the flowchart below.

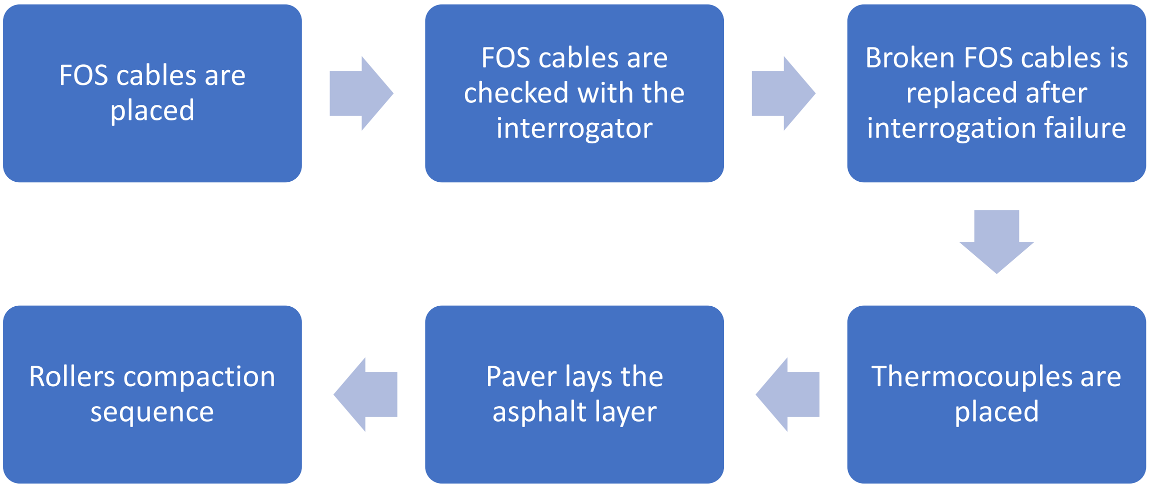

Figure 3: Project flowchart

Since the switch at 13:37 and by the end of the project only the data from the transversal sensor cable was retrieved and thus the data analysis will revolve around it. The observations of the passing compaction rollers and the interrogator and the thermocouple data have all been synchronised as accurately as possible in preparation for the process denoising and filtering. Lastly, only 3 of the 8 FBGs on the transversal fibre cable ended up providing pertinent data, so the analysis thereon will be done according to these data series and the respective thermo-logger (the one near the transversal fibre cable).

3. Data Filtering

A first look at the sets of data retrieved from the project indicated that the measurement timeframes of the FOSs and thermocouples are different. Thermocouples record temperature values once per second. For the purpose of both synchronisation and denoising, the analysis and evaluation are done for data aggregated and averaged over 1 second. The FOS interrogator records data entries of wavelength every microsecond. Thus, the denoising process involves aggregating up to a million measurements in one observation. In order to ensure this abstraction is not excessive a quick case study is made.
It was mentioned previously that the data from FOSs and thermocouples has a very different format.

One additional aspect of this is that recording temperature data with the thermo-loggers is a significantly less demanding task, thus granting the possibility for having a continuous-measurement data series throughout the entire project. Compared to that, the interrogator records a thousand times more measurements per second and has a logging cycle limit. Because of that the interrogator stops after a set number of cycles and needs to be reset, resulting in a discontinuous data series. Because of this discrepancy the synchronisation cannot be done over the entire duration and specific significant windows are chosen for the data analysis.

Wavelength measurements are first aggerated in smaller batches, resulting in the evaluation of the data in 4 stages of increasing abstraction. A set of wavelength data obtained during the 13:41 – 13:44 window is selected for denoising. The data is grouped as to resemble observations being made 10 times per second, 4 times per second, 2 times per second and every 1 second (respectively every 100 milliseconds, 250 milliseconds, 500 milliseconds and 1000 milliseconds). The results can be seen in Figure 4. It should be noticed that by increasing the abstraction level, the very high peaks of wavelength get tapered, so the peak values should be retrieved for a separate analysis. Despite that, making wavelength observations over 1 second does stay true to the behaviour presented in the other stages and could be the basis for pertinent analysis considering the peaks remain in phase.

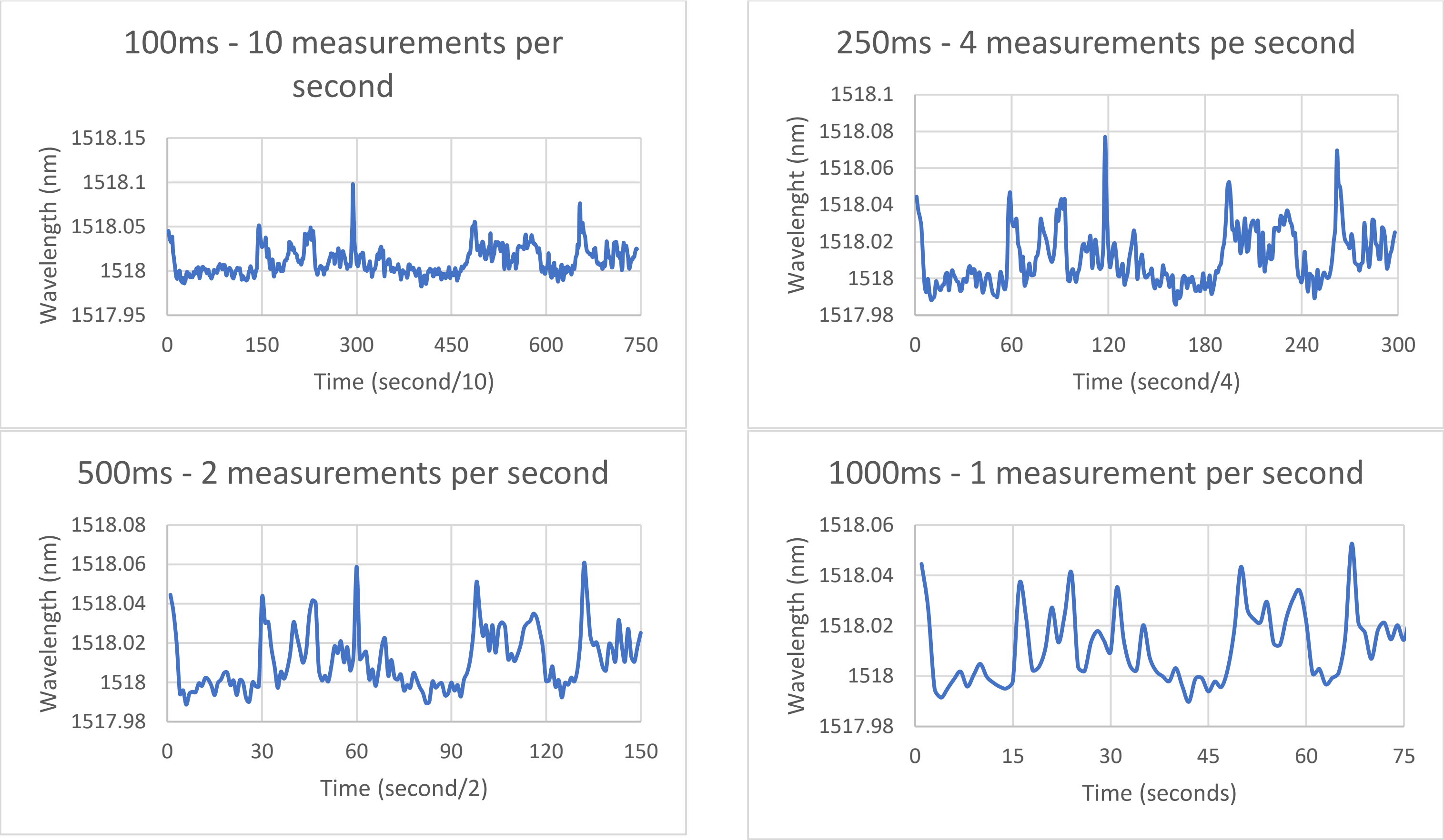

Figure 4: Data denoising and filtering stages (4 stages)

The peaks in wavelength measurements are meant to indicate the passing of a roller. Low level variations in wavelength could happen due to temperature changes or remaining noise. To further ease the access to relevant changes related to the strain component, a high-pass filter can be applied, thus isolating the peaks and facilitating the analysis.

3.1. Measurement data analysis

The 5 relevant data sets have been selected. Each of these contains synchronised data from the transversal FOS cable and the corresponding thermocouple, during a time window which contains the passing of at least one roller and windows without strain influences. Firstly after, the wavelength data from these 5 sets is processed with the interrogator's proposed method. For the method inspired by (Oh, Han, Paek & Chung, 2004), a double linear regression is run for each of the 5 sets and the results are checked with a 5-fold cross-validation of the regression parameters s_T and $s_{\mu\varepsilon}$. The calibration run of the first set can be understood from the following set of plots, illustrating micro strain and temperature profiles over time, in a timeframe starting at 13:46:39.

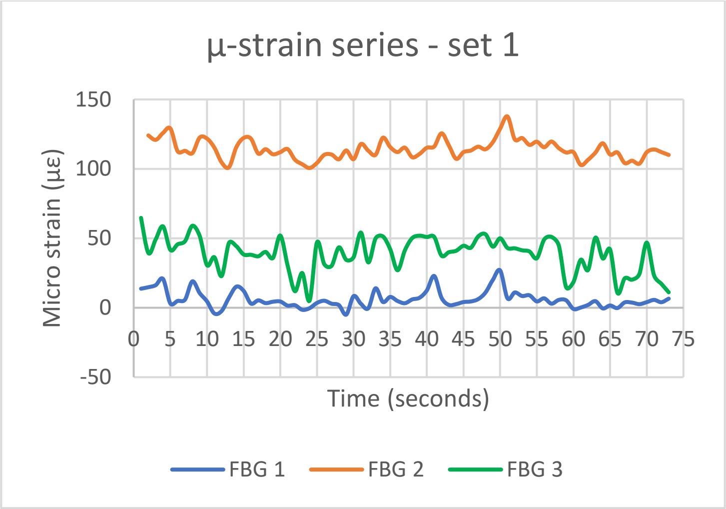

Figure 5: Micro strain profile over time – Dataset 1

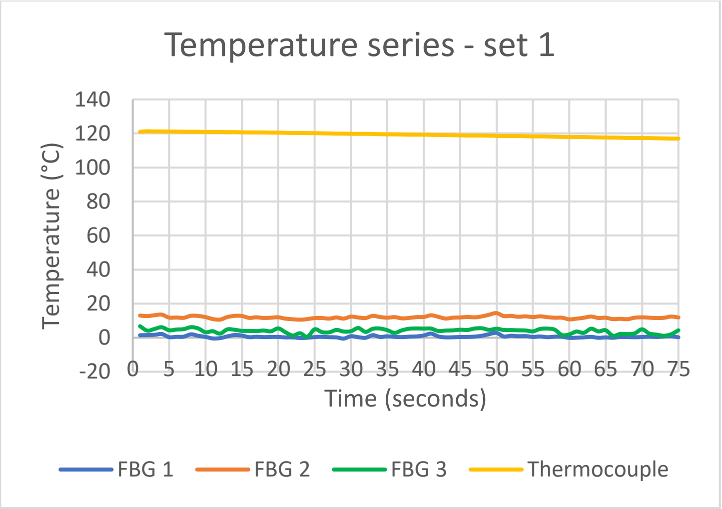

Figure 6: Temperature profile over time – Dataset 2

The corresponding second method regression leads to a $s_T = 7 * 10^{-16}$ and $s_{\mu\varepsilon} = 0.77$.

4. Results

All other sets behave somewhat similarly and can be observed in Appendix. As can be clearly seen in Figure 6, the FOS inferred temperature is not at all representative for the actual temperature measured with the thermocouple. This is also evident from the extremely low regression sensitivity coefficient for temperature $s_T = 7 * 10^{-16}$, which suggests the temperature has an insignificant influence on the wavelength changes. The micro strain profiles are not conclusive either, as the strain seems to be inconsistent among the 3 recording FBGs, although the pressure was applied by the same roller, which is expected to distribute loading, more or less, uniformly on all 3 FBGs at once.

Set	1	2	3	4	5
Timestamp (hh:mm:ss)	13:46:39	13:51:25	13:56:10	14:00:50	14:05:34
s_T (nm/K)	$7 * 10^{-16}$	$4.91 * 10^{-17}$	-0.89	$1.5 * 10^{-16}$	$8.23 * 10^{-17}$
$s_{\mu\varepsilon}$ (nm/με)	0.77	0.78	0.78	0.77	0.79
(constant) Intercepting wavelength (nm)	$1.1 * 10^{-14}$	$8.47 * 10^{-16}$	1.94	$-1.2 * 10^{-14}$	$-3.4 * 10^{-15}$

Table 3:Regression analysis

All regression results are given in Table 4. The cross validation would prove futile since there is such a big bias for the strain coefficient. It seems to maintain its value around 0.78 which is actually the value suggested by the interrogator manufacturer. However, the data does not prove reliable and there is even a bigger difference in magnitude for the third set. As similar behaviour can be seen in the case of the dataset 3 (*Figures 7 and 8*).

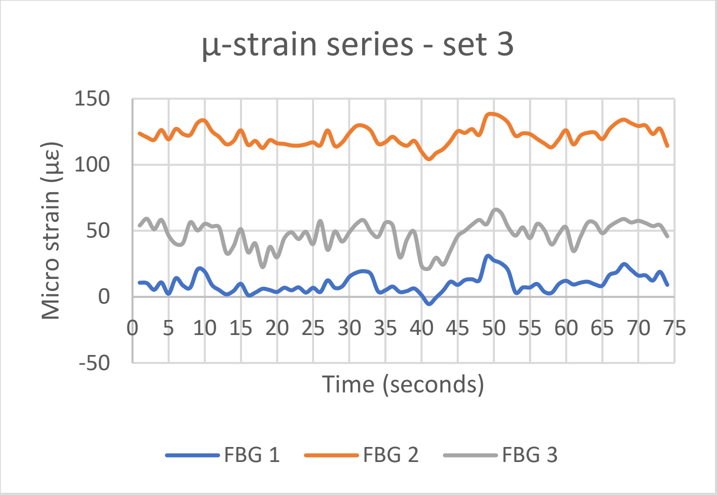

Figure 7: Micro strain profile over time – Dataset 3

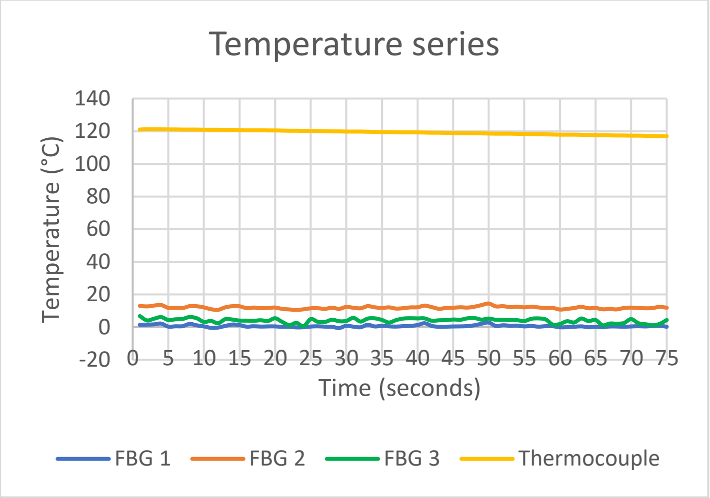

Figure 8: Temperature profile over time – Dataset 3

Unlike the usage of thermocouples for temperature measurements, no strain gauges or similar tools have been used for strain measurements. Because of the, we do not have a similar way of comparing and validating the FBG strain values. In order to draw any conclusion from the FBG strain recordings a few theoretical values are proposed for this comparison. If we think in the style of a finite element modelling paradigm, a small segment from the bottom of the asphalt layer can be studied. If we consider a cubic asphalt element that lies on top of the FBG we can do a theoretical analysis of that specimen. The behaviour of this specimen will inevitably be subject to a lot of abstraction and idealization, but for the purpose of a providing a theoretical strain value it can be fitting.

Thus, we consider a cubic specimen with an edge of 1cm. Since it is bound to the neighbouring specimens in the asphalt layer, the structure can be studied as a loaded double cantilevered beam. For such a system the strain at the bottom of the specimen can be computed in the following manner (Hjelmstad, 2010).

$$\mu\varepsilon = \frac{q \cdot l^4}{384 \cdot EI} = \frac{q}{32 \cdot E} \ (cubic\ specimen)$$

Where, W is the weight of the compaction roller, l is the length of the specimen's edge (1cm), q is the static load generated by the compaction roller, I is the second moment of inertia value and E is the stiffness value of the asphalt mixture.

Since the properties of the asphalt mixture, were not a direct point of interest in this study, the asphalt stiffness coefficients are assumed to be in plausible range of 4000 - 18000 MPa as per indication of (Zakaria, Yusoff, Hardwiyono, Mohd Nayan & El-Shafie, 2014). The load on top can be inferred from the distributed weight of a compaction roller. The rollers used during the paving project are similar to the Wirtgen Group tandem rollers (Tandem rollers for asphalt compaction | Hamm, 2022). The entire variety used in Europe can be found on the company website. These rollers can weigh roughly 1600 - 4800 kg and generate static loads of 9.6 - 16.5 kg/cm, as per manufacturer's description. These ranges are given because the rollers have not clearly been identified during the compaction process. With these assumptions in mind, we can assume that a roller passing on top of an FBG would generate micro strain values of roughly 170 - 325µε. The highest strain value we were able to record among the 3 available FBGs was 150με, as seen in *Figure 5*. While slightly lower than the theoretical range of values, we could say that the transversal FOS cable was able to come close to a realistic measurement, considering the gross abstractions that were made. Had other cables not broken, they might have as well been able to provide plausible measurements. Another iteration of the experiment could yield fruitful results.

Over the given time window, the micro strain profile is somewhat consistent in shape but not value across all 3 FBGs and the regression strain coefficient remains 0.78. However, this set has very distinct values for the intercepting wavelength and temperature coefficients. In fact, these are desirable values for the regression results. If the dataset were to be considered adequate, these would be plausible values for evaluation. However, since the other 4 sets make this one seem like an outlier, the 5-fold cross validation is not relevant for such little data.

As for the temperature measurements, again the FOS values are significantly lower than the thermocouple values and entirely unrealistic given the respective moment in the paving process.

Another way of assessing the temperature data is to compare the natural cooling process of the asphalt layer. Data from both transversal thermocouples and the FOS is aggregated in order to generate the cooling curve plot and compare the results.

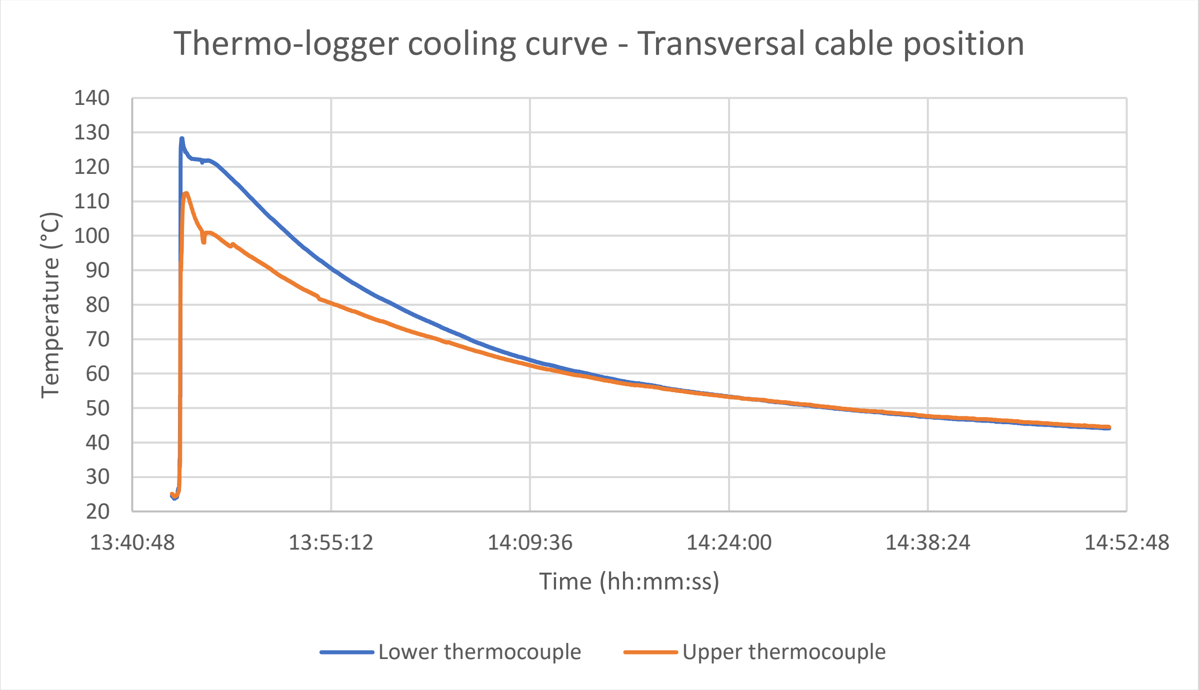

Figure 9: Thermo-logger cooling curve

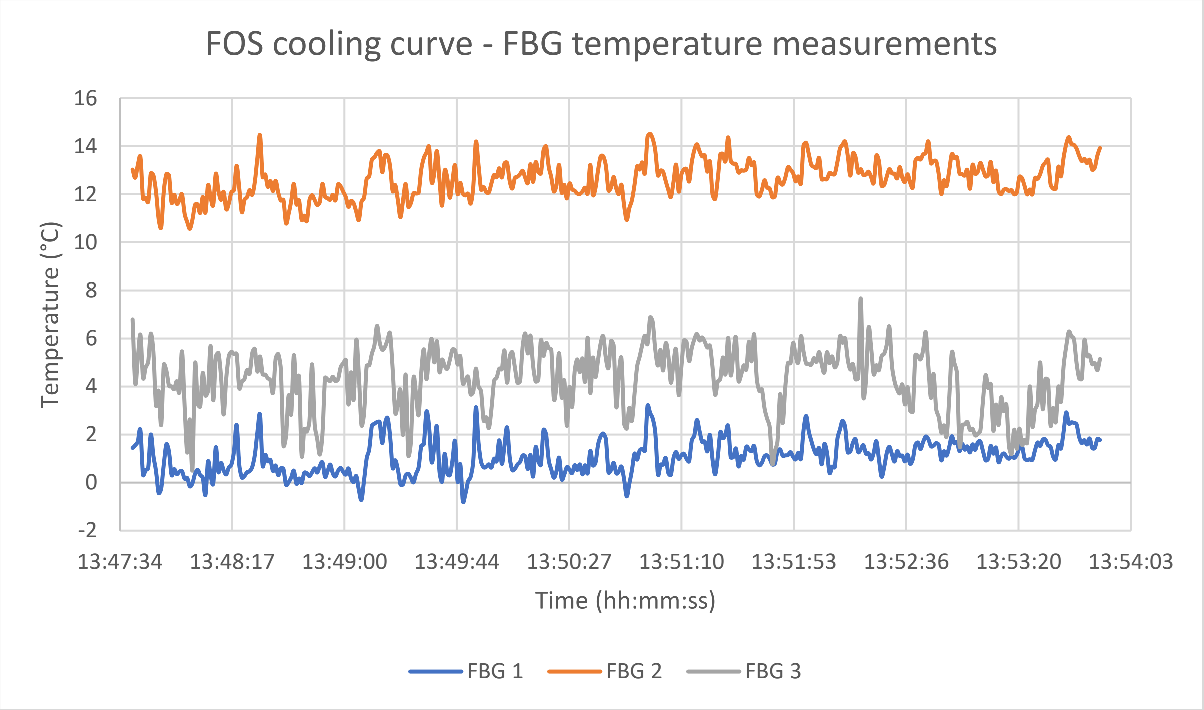

Figure 10:FOS cooling curve

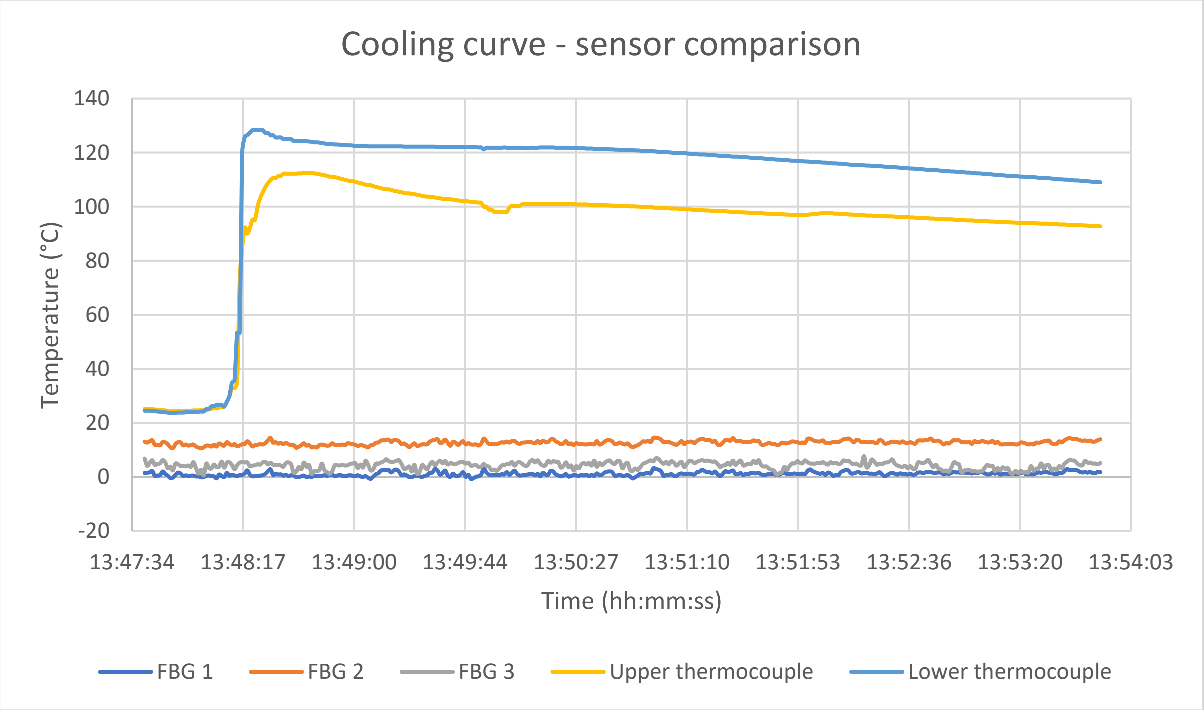

Figure 11: Cooling curves comparison by sensors

As expected from previous analysis, the FOS temperature data is not accurate and does not replicate the natural cooling process as can be observed in *Figure 11*. That might be caused by an error in the proposed methodology, improper calibration or a failure mechanism. Besides that, the temperature component of the wavelength data (as presented in *Figure 10*) is largely consisting of noise and the values are overall too low compared to the thermocouple data. One last possibility would be that the interrogator-FOS system may have been chosen poorly, which makes a point in the further discussion.

4.1. Discussion

An immediately apparent issue is the quick failure of the FOS without any possibility of recovery or timely replacement. There can be a few speculations for why the bare FOS cables failed. Some of the most plausible failure mechanisms are discussed below. Moreover, a few considerations are given with regards to thow such failures could be avoided in future experiments.

4.1.1. Failure mechanisms

1. Faulty implementation

It has been established by now that the bare FOS are very fragile. Even though the installation process has been previously tested and executed to success, it is still possible that some particularities of this specific working site caused new complications. Two aspects of the of the sensor placement seem could have been problematic.

For once, the interrogator and the laptop are located on the side of the road during both installation and recording. This implies that the longitudinal FOS required an angled turn of the cable's positioning. In this case, the cables have been laid in a 90° angle which may have been too sharp for the bare fibre optic cable. The installation scheme for the longitudinal cables can be seen if Figure 12. An adjustment has been made in order to not stretch the thin cable around that sharp corner. Instead of one 90° angle, the longitudinal cables were bent around two 135° angles. However, this could have still generated too much friction and direct contact strain, likely causing the first-hand failure of both longitudinal cables.

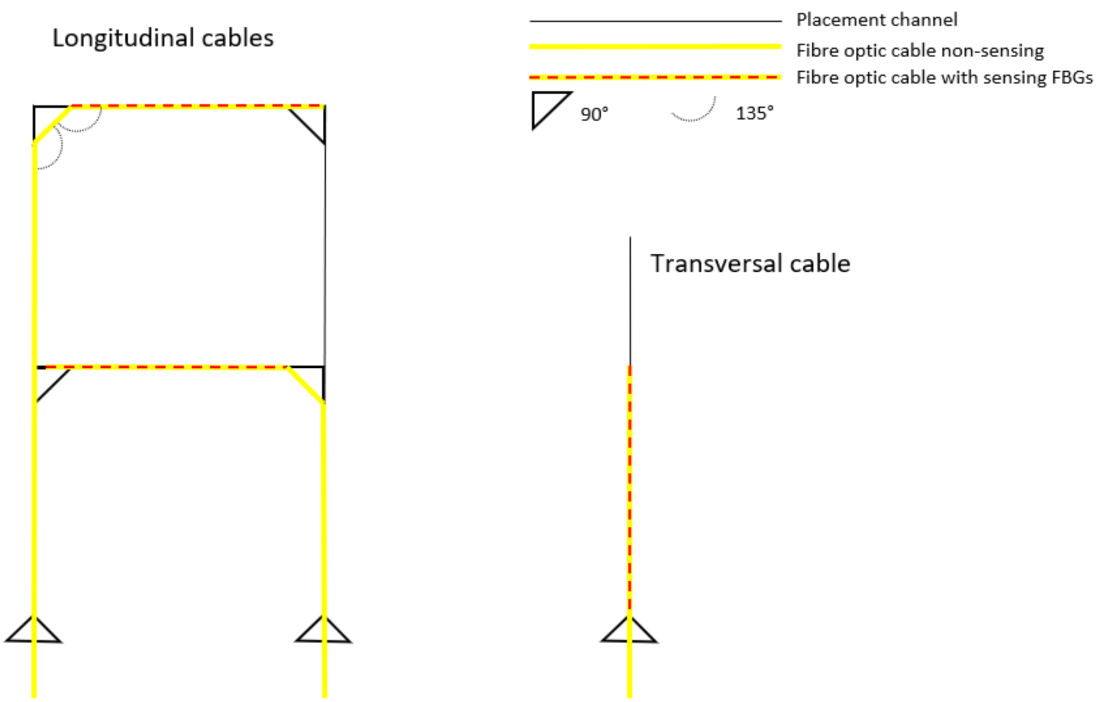

Figure 12: Layout of the sensor cables

Secondly, the installation crew dug individual rectangular channels for every cable to go through before being covered with the surface layer of asphalt. However, these channels could have been too big compared to the section of the bare cable. This on its own can lead to two alternative issues. One being that the aggregate in the asphalt mixture needs to be small enough to fill the respective crevasses somewhat uniformly, which is not guaranteed, and the second being that, if the aggregate is forcefully jammed in the channels by the paver or the rollers, it could cut off the sensor cable.

2. Improper interrogation

The sensor interrogation process is very simple and requires little active supervision once properly started. As mentioned in the section that describes the tools used, the convention was to use the ‘Gator’ interrogator software to observe changes in wavelength. There is one task that needs to be done before the interrogation starts, namely the initialization of the fibre cable’s first and last FBG central wavelengths as found in *Table 1*. These are needed in order for the interrogator to read precisely localized wavelength measurements. This is the only step during interrogation where failure may have occurred. However, the FOS cables used are standardized, meaning they have roughly the same FBG distribution, and the software remembers the previously initialized input. Seeing that all cables used have been previously tested and the interrogation tests have been successful, it is very unlikely the failures in situ started from this mechanism.

3. Overheating

The interrogator that is connected to the bare FO cables is, by manufacturer's specification, tested at temperatures between -40° and 85°C. These parameters define the boundaries of the environments in which the combination of the fibre optic cables and the interrogator have been tested. The possible confusion is that there are multiple types of sensors depending on the harshness of the environment in which they are used. The differences among these lie in the types of FBGs used in the sensor, and the thermoresistant material they are made out of. Even silica-based type 1 gratings, which are the most common but also the least resistant (also the ones used during this study), should withstand temperatures up to 450°C without any issue. (Mihailov, S., 2012)
There is a clear discrepancy here. The cables are built to resist to temperatures higher than 85°C, but the manufacturer specifies in the 'Gator' manual that the gator has not been tested above such temperatures. Simultaneously, the highest temperature recorded by the thermocouples (right at the moment of pouring the surface asphalt layer) is 130.4°C, which is still considerably above 85°C. Looking at the normal circumstances of asphalt usage, it is ordinary to expect temperatures up to 160°C. The of burning of the sensor cable is a possible failure mechanism here, but it is unclear whether there was a knowledge transfer incoherence, or a complete mismatch of the project conditions and the tools provided for the measurement study.

4. Overloading

One last possible failure mechanism comes in the form of overloading, or rather high strain peak occurrence with a non-uniform pattern. If the load is distributed uniformly through a heterogeneous layer structure, then there could exist significantly high-pressure points along the cable profile. This can be the case in pavement structures, where the aggregates in the heterogeneous asphalt mixture that can push into the bare sensor or even one of the FBGs and prevent the signal transfer entirely if not break the bare fibre. Moreover, there is the possibility of having a strain profile that avoids the FBG placement, by having two pressure points in the places where measurements are not recorded and a valley, with little to no contact, on top of the FBG that is hypothetically located in-between the two pressure points. It is hard to assess if this is a valid failure mechanism, since, in our case, the failure is clearly a lot more general than a localized FBG issue. Some of the previous failure mechanisms seem more plausible, but this aspect is still fruitful for the later points of the discussion.

4.1.2. Issues of data analysis

During the process of working with the data it became apparent that even the little amount of data that could be obtained was indeed still faulty and misleading for the evaluation process. In Figure 4 it can be seen that the highest occurring wavelength peak creates a net difference of about 0.1 nanometres. Considering any significant load would be applied by the roller this difference is expected to be in the order of at least tens of nanometres. We can deduce that the transversal fibre optic cable had likely broken down as well. And the data that was collected is largely signal noise with confounding properties. This renders the data analysis inconclusive, while as of now the FOS cannot be considered a reliable measurement tool, and thus an accuracy assessment cannot be provided.

One more problem that would have occurred, had the data been adequate, is that there would be no concrete way to validate the strain measurements. The FOS inferred temperature can be compared to the thermocouple data, there is no comparative data for the strain. One proposition is to rerun the (Oh, Han, Paek & Chung, 2004) method after the regression and extract the strain. If it is indeed the case that the strain sensitivity coefficient is approximately the one suggested by Gator ($s_{\mu\varepsilon} = 0.78$), then the analysis would prove fruitful, and the proposed calibration method is expected to be reliable. Otherwise, a classic strain gauge can be installed next to the FOS cables for evaluation by direct comparison.
Furthermore, to address the accuracy of the sensor measurements, a more substantial output would be required. Normally, on top on the regression error, some statistical test would be required for evaluation. However, due to the lack in both the quantity and the quality of the recorded data such a test would be futile. As a recommendation for further research, a regression residuals comparison, and a confidence interval for the measured and expected values could lead to better conclusions for the first three research questions, should the data be appropriate.

4.1.3. Coating as a preventive measure

Until now I have described how the project was executed with bare FOS and the reasoning, circumstances, and implications of this choice. In the introduction, I alluded to the decision process of using bare or coated cables. Up until this point, the study focused on the issues that were observed during the usage of bare fibre optic cables and the probable failure mechanisms. This further section is reserved to the discussion of using various coatings as an alternative to the bare FOS and how each of the proposed failure mechanisms could be avoided. It is meant to provide insight for further projects and help decide when and how to use coatings in order to take full advantage of the capabilities of the FOS cables.

1. Coatings for better implementation

A simple rubber coating could help against both failure mechanisms related to the installation of the sensors. On one hand, the coating would prevent the direct contact with the channel walls avoiding friction and tension around the two 135° angles. On the other, coating would help better fill the crevasses in which the FOS cables are placed, thus better fixing the sensor and preventing aggregate form pushing into the sensor and breaking it.

2. Coatings for better interrogation

This is one aspect in which coatings would not improve the functionality, as coatings have little to do with interrogation process. If anything, their effect can generally be assessed during the data analysis phase. As mentioned previously, this is one area where failure is already unlikely to occur, and coatings would not change this matter at all.

3. Coatings against overheating

In the publication (Mihailov, S., 2012), many types of sensors and coatings are mentioned, especially with regards to heat resistance. The literature makes clear that silica and other polymer coatings are very often employed when using FOS in high temperature environments. The advantages against overheating are undeniable, although the bare type 1 grating cables are meant to withstand temperatures lower than 450°C. The usage of thermal coatings is especially advised in our project’s case, since there is an uncertainty between the temperature thresholds specified by the interrogator and the cable manufacturer.

4. Coatings against overloading

Overloading and improper distribution of pressure could also be prevented by the usage of a rubber coating. The evident drawback here is the hinderance in strain transfer from the asphalt layer to the FOS. However, this can be accounted for in the data analysis phase.
Coatings could help against the aggregate breaking the cable and better distribute the strain, even if a pressure point is not directly on top of the FBG. Sometimes coating can actually help propagate the strain to the sensor by increasing the surrounding volume and allowing more and safer contact with the load.

5. Conclusion

This study revolved around the usage of FOS cables in order to measure temperature and micro strain. The main objective of the study is to generate a calibration and evaluation framework for the respective measurements, in turn offering the opportunity to replace other types of sensors in the future. On top of that, the paper describes the installation and implementation process of such a study in-situ and provides an extensive discussion with regards to possible failure and the means to prevent it.
Unfortunately, the study is largely inconclusive due to a lack of pertinent data for evaluation, but this paper is meant to remain a solid starting point for a reiteration of the study.
Although, the data is not optimal, the regression results over all 5 data sets point towards a possibly valid procedure for the evaluation of strain measurements. On top of that, one series of transversal strain measurements appears to be plausible and close to a realistic estimate. This could suggest that the FOS can indeed be a functional replacement for the traditional strain gauge. As for the other research questions, it is rather clear that the data retrieved from bare FOS is not satisfactory, and the temperature measurements are also not in line with the thermocouple values this could be due to the sensors breaking or a methodological error. Because of that, for the moment, the bare FOS cables cannot be recommended as a functional replacement for temperature measurements.
Lastly, in the final segment of the discussion, there is high emphasis on the downfalls of bare FOS and the usage of coating, suggesting that adequate coatings can indeed improve the quality of the study were it to be reiterated. Many possible failure mechanisms are presented and some ways to mitigate or avoid them are proposed. For that matter, the following section provides a set of final recommendation for future research in the area.

5.1. Recommendations

The in-situ study presents in itself a lot of possibilities for failure. The asphalt pavement structure is generally rough and largely heterogeneous and creates a suboptimal environment for the usage of bare FOS despite the desire for accuracy.

The first suggestions come in the form of practical matters pre and during implementation. Firstly, it is suggested that a proper coating is selected for further iterations of the project. This comes at the possible cost of accuracy in measurements but will likely provide more overall reliability. Secondly, the channels dug for the cables bring additional issues. If possible, another way should be found for fixing the FOS in position.

As for the data analysis, the filtering and aggregating procedures as well as the theoretical basis are all considered pertinent and can be entirely reused for further research. The suggestion here is to add another means to validate the strain measurements. Since no strain gauge has been used during this project and the theoretical values presented could either vary too much or be subject to too much abstraction, another validation method is advisable.

Lastly, the statistical test for evaluation have been mentioned but are not fully presented in this paper. In the current state, the suggestion is to follow the regression error and confidence interval analyses as they have neither proved nor disproved the results, due to the lack of adequate data, and they are as well still considered pertinent elements of the study case.

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Appendix

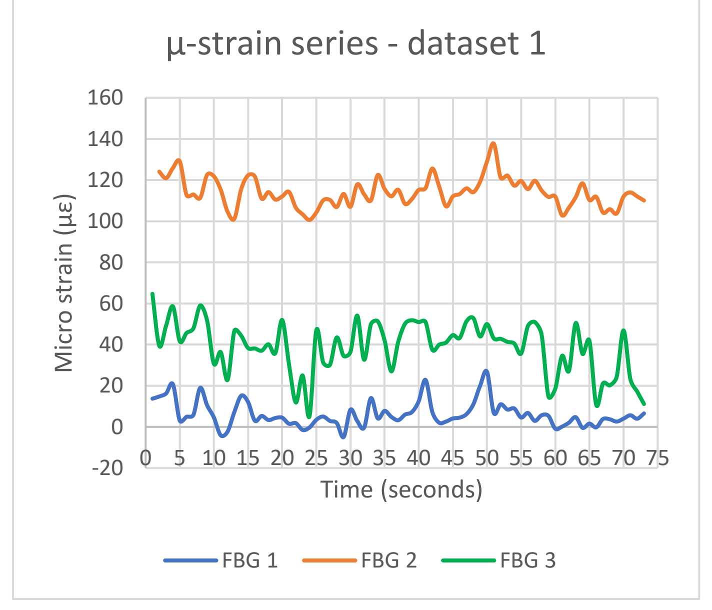
I. Project timeline

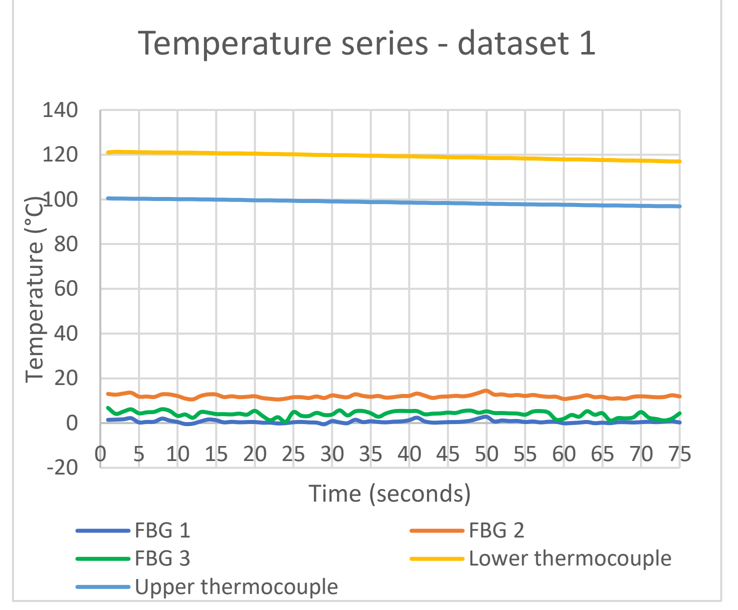
Timestamp	Event
12:40	Placed the first longitudinal sensor cable (the one closer to the centre of the road)
12:45	Fixed the cable part at the corners with tape
12:50	First interrogator check of the longitudinal sensor is successful
12:55	Second longitudinal sensor cable is placed and fixed with tape (the one closer to the edge of the road)
13:03	Interrogator check for the second longitudinal sensor cable
13:05	Placed and fixed the transversal cable
13:08	Interrogator check for the transversal cable indicates failure and the issue is investigated
13:14	It is concluded that the transversal cable broke and is replaced
13:17	Interrogator check confirms all 3 sensor cables are functional and working properly before the paving process.
13:20	All thermocouples are connected to the respective thermo-loggers and the placement process of the thermo-loggers begins
13:30	All thermocouple stands are placed, checked, and prepared for the paving process.
13:32	Interrogation is started for the first longitudinal sensor cable
13:33	Paver starts laying the asphalt layer over the sensors
13:35	Large compaction roller passes on top of the sensor quadrant
13:35	The longitudinal sensor cables appear to no longer provide satisfactory measurements and failure of the cables is suspected
13:37	The transversal sensor cable is interrogated and appears to work properly
13:37	Large compaction roller passes on top of the sensor quadrant
13:39	Large compaction roller passes on top of the sensor quadrant
13:40	Large compaction roller passes on top of the sensor quadrant
13:41	Large compaction roller passes on top of the sensor quadrant
13:43	Large compaction roller passes on top of the sensor quadrant
13:44	Large compaction roller passes on top of the sensor quadrant
13:46	Large compaction roller passes on top of the sensor quadrant
13:48	Large compaction roller passes on top of the sensor quadrant
13:50	Large compaction roller passes on top of the sensor quadrant
13:52	Large compaction roller passes on top of the sensor quadrant
13:53	Small compaction roller passes on top of the sensor quadrant
13:56	Large compaction roller passes on top of the sensor quadrant
13:57	Small compaction roller passes on top of the sensor quadrant
14:00	Large compaction roller passes on top of the sensor quadrant
14:01	Small compaction roller passes on top of the sensor quadrant
14:03	Large compaction roller passes on top of the sensor quadrant
14:04	Small compaction roller passes on top of the sensor quadrant
14:06	Small compaction roller passes on top of the sensor quadrant
14:07	Small compaction roller passes on top of the sensor quadrant
14:08	Small compaction roller passes on top of the sensor quadrant
14:09	Small compaction roller passes on top of the sensor quadrant
14:15	Measurements are ceased and loggers and the interrogator are all retrieved

Table 4: Project timeline: paving process and interrogation

II. Appendix – Dataset 1 (timestamp 13:46:39)

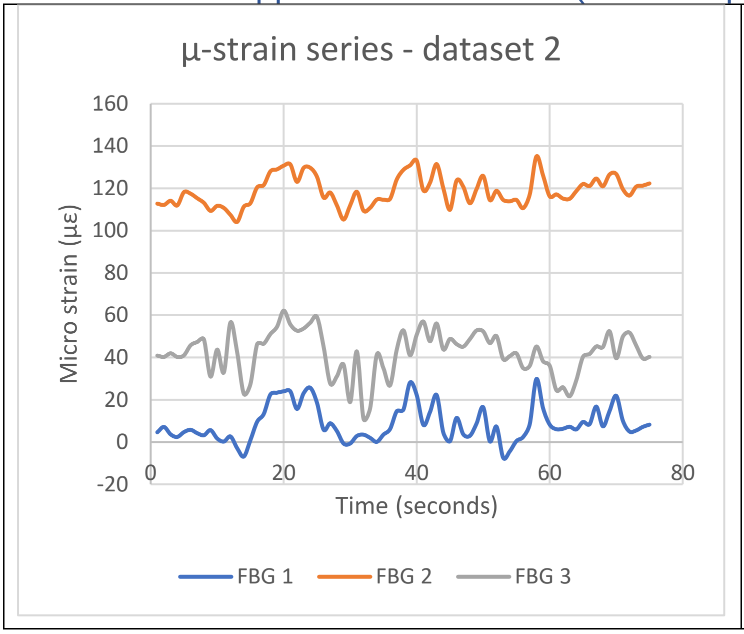
The measurement data was previously split into 5 sets for analysis, all based on the recordings of the transversal FOS. The filtered FOS strain and temperature values according to the Gator conversion and the regression tables used for the second evaluation method are all grouped per data set and presented here.

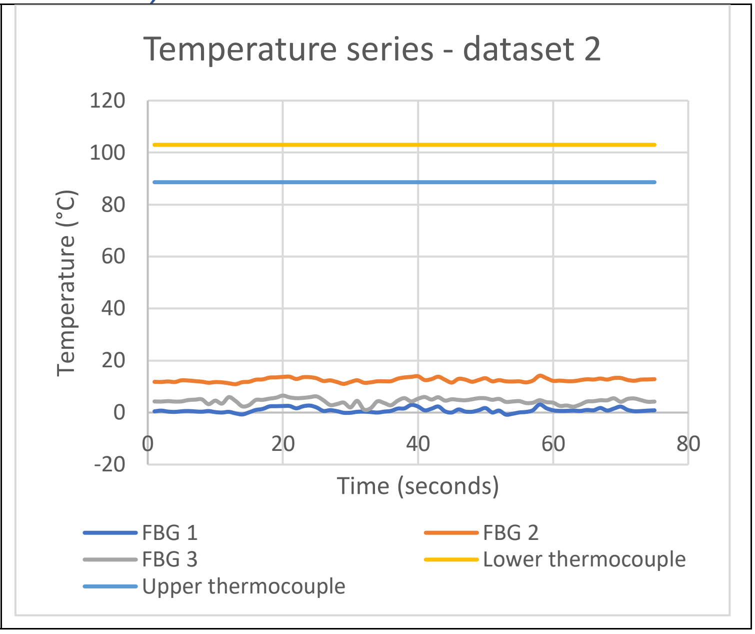




	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.101E-20	9.713E-21	-1.134E+00	2.607E-01	-3.037E-20	8.351E-21	-3.037E-20	8.351E-21
temp	7.031E-23	8.159E-23	8.617E-01	3.917E-01	-9.235E-23	2.330E-22	-9.235E-23	2.330E-22
micro_strain	7.800E-07	1.767E-23	4.414E+16	0.000E+00	7.800E-07	7.800E-07	7.800E-07	7.800E-07

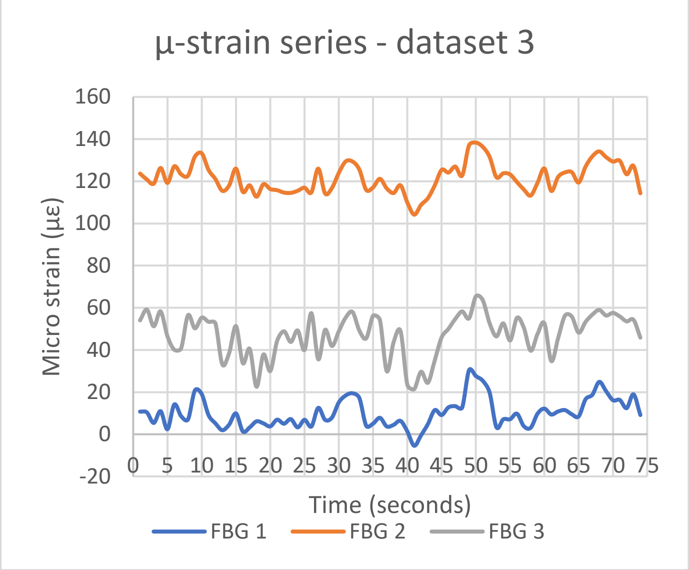
III. Appendix – Dataset 2 (timestamp 13:51:25)

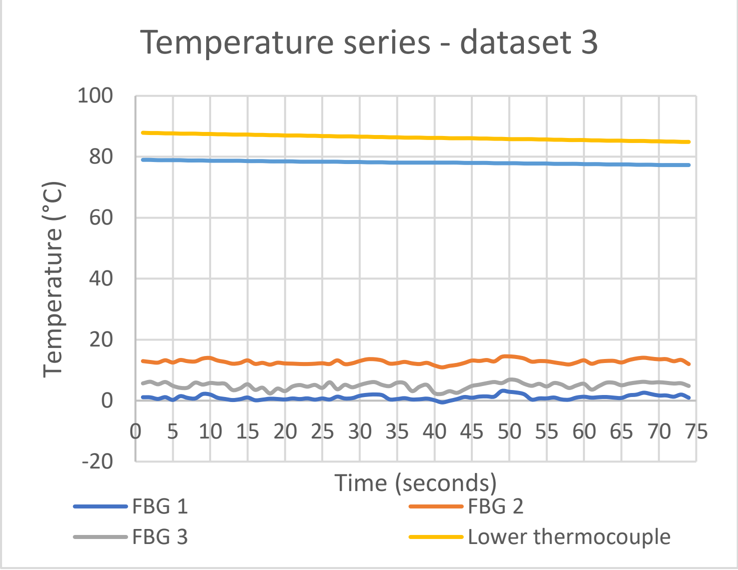




	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	8.470E-22	9.140E-21	9.268E-02	9.264E-01	-1.737E-20	1.907E-20	-1.737E-20	1.907E-20
temp	4.914E-24	9.060E-23	5.423E-02	9.569E-01	-1.757E-22	1.855E-22	-1.757E-22	1.855E-22
micro_strain	7.800E-07	1.452E-23	5.371E+16	0.000E+00	7.800E-07	7.800E-07	7.800E-07	7.800E-07

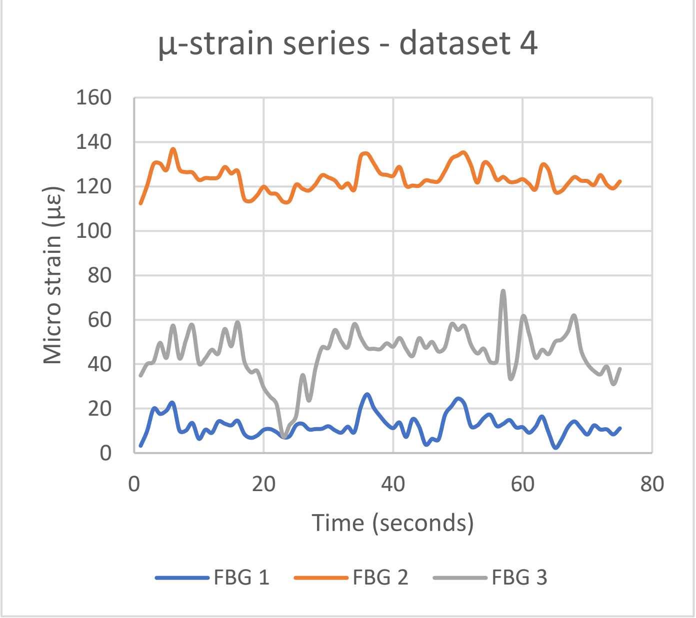
IV. Appendix – Dataset 3 (timestamp 13:56:10)

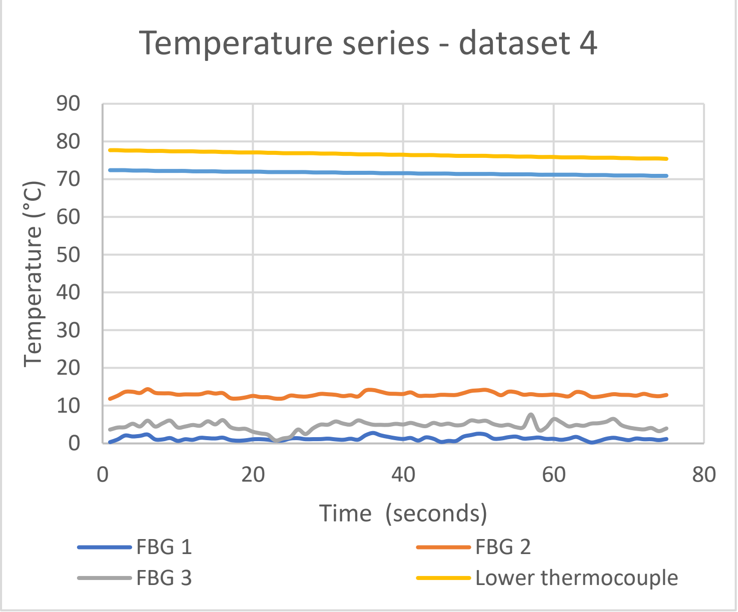




	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.936E-06	2.632E-05	7.354E-02	9.416E-01	-5.055E-05	5.442E-05	-5.055E-05	5.442E-0
temp	-8.900E-07	2.913E-07	3.055E+00	3.167E-03	-1.471E-06	-3.092E-07	-1.471E-06	-3.092E-07
micro_strain	6.800E-07	3.585E-08	1.896E+01	1.661E-29	6.085E-07	7.514E-07	6.085E-07	7.514E-0

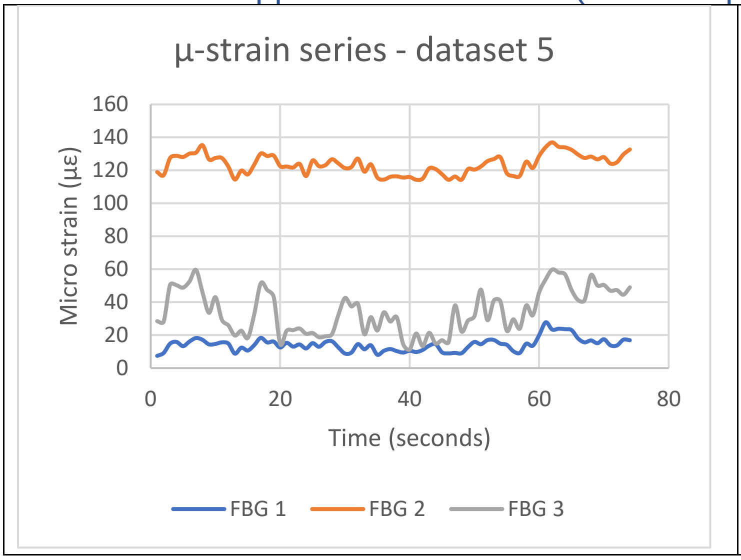
V. Appendix – Data set 4 (timestamp 14:00:50)

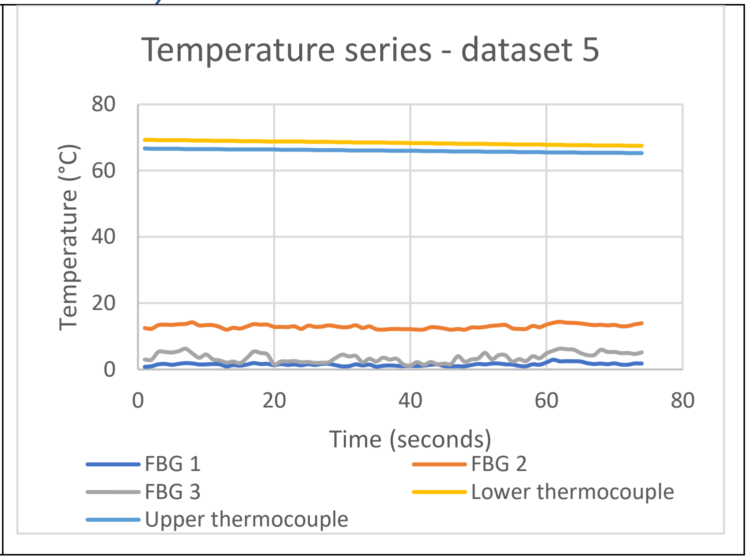




	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.186E-20	1.236E-20	-9.597E-01	3.405E-01	-3.650E-20	1.278E-20	-3.650E-20	1.278E-20
temp	1.489E-22	1.617E-22	9.209E-01	3.602E-01	-1.735E-22	4.714E-22	-1.735E-22	4.714E-22
micro_strain	7.800E-07	2.262E-23	3.449E+16	0.000E+00	7.800E-07	7.800E-07	7.800E-07	7.800E-07

VI. Appendix – Dataset 5 (timestamp 14:05:34)





	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3.388E-21	1.554E-20	-2.180E-01	8.281E-01	-3.439E-20	2.761E-20	-3.439E-20	2.761E-20
temp	8.229E-23	2.254E-22	3.651E-01	7.161E-01	-3.672E-22	5.318E-22	-3.672E-22	5.318E-22
micro_strain	7.800E-07	3.027E-23	2.577E+16	0.000E+00	7.800E-07	7.800E-07	7.800E-07	7.800E-07