FIBER OPTIC MONITORING OF A NEW RAPID-SETTING, CURE-ON-DEMAND POLYMER RESIN FOR ROADWAY AND STRUCTURE REPAIR

Matthew Davis[†], Tyler W. Farnsworth, Ph.D.[†], Andrew Williams[†], Eric Smith[†], Alexander S. Brand, Ph.D., P.E.[‡], T. Trevor Painter, M.S.[‡]

[†]Luna Innovations Incorporated,
[‡]Virginia Polytechnic Institute and State University
Blacksburg, VA/United States

ABSTRACT

This paper presents the combination of a rapid-setting, cure-on-demand polymer resin with fiber optic monitoring to enable the repair and long-term assessment of concrete roadways and structures. The durability of pavement structures diminishes over time due to a number of factors, such as environmental weathering, thermal cycling, fatigue from traffic, and chemical attack, thereby requiring the roadway surface to be periodically inspected and repaired. Unlike commercial rapid-setting cementitious-based repair materials, the presented polymer repair material exhibits a long working life (>5 hours) with high strength being achieved in just 1 hour after the curing process has been initiated. This technology can be used to patch cracks and holes, restoring the original integrity of the structure or surface. In this study, High-Definition Fiber Optic Sensors (HD-FOS) were embedded during a repair and used to determine when the repair patch had stabilized and finished curing. The rapid-setting polymer patch exhibited a 2-hour compressive strength of 58.7 MPa (8,519 psi, ASTM C39), 1-day bond strength of 9.97 MPa to PCC (1,446 psi, ASTM C882, PCC = Portland Cement Concrete), and a 2-hour modulus of elasticity of 19 GPa (2,740 ksi, ASTM C469). The HD-FOS sensors were left in place to demonstrate a method of monitoring the repair and performing periodic non-destructive inspection. The combination of these two technologies enables the completion and monitoring of repairs on buildings, bridges, and roadways to increase the integrity of the country’s infrastructure.

Keywords: Fiber Optic Sensing; Polymer Concrete Repair; SHM

Corresponding author: Tyler W. Farnsworth, Ph.D.

INTRODUCTION

Concrete has been a fundamental building material throughout much of human history, and it is the single most-used manmade material in the world [1]. It is a mainstay for pavements, buildings, dams, ports, and storage container construction because of its high compressive strength and ability to be easily implemented in new construction. In recent years, alternative materials are being used to repair and patch concrete structures that restore the structure to its original strength and provide longer lasting stability under severe weather conditions compared to traditional repair or replacement approaches. Calcium sulfoaluminate cements and polymer-modified calcium-based products have seen increased use on roadway [2], bridge deck [2,3], and airfield [3,5] repair sites due to their high early strength, often reaching maximum compressive strength in 2–12 hours, compared to 28 days of Ordinary Portland Cement (OPC) concrete. The high initial strength can enable significantly shortened road or runway closures with promise of substantial cost savings;

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however, many of these early strength materials lack long-term longevity, resulting in premature structural failure due to mechanical and/or environmental instability [6,7]. Polymer-based repair materials are a second form of alternative concrete materials that have been investigated, most notably due to their enhanced chemical resistance compared to OPC concrete for use in extremely corrosive environments [3]. Beyond corrosion resistance, polymer concretes offer a fast setting time, reaching full compressive strength in 2–3 hours. Despite the initial advantage of rapid-setting repair, the long-term stabilities of these rapid-strength polymer-based repair patches remain unknown. To see increased use within the industry for rapid roadway and airfield repairs, more data is needed to validate the in-traffic performance and longevity of the repair material.

In many cases it is beneficial to periodically inspect both concrete and concrete alternative structures using non-destructive tools such as vison based camera systems coupled with artificial intelligence, acoustic emission and piezo devices, or ground penetrating radar. In many cases implementing a structural health monitoring system provides an alternative and complimentary approach to periodic inspections. This is particularly true in the case of bridges where full inspection of the deck carries safety challenges for the inspectors. Recently, Fiber Optic sensing has been implemented as a means of continuously monitoring repairs and new construction. One example of this in on the Silex 2 EDF Tower being constructed in Lyon, France [8]. Instrumented reinforcing structures have also been tested to demonstrate the ability to detect crack formation in the surrounding concrete and identify cracking on the surface of beams [9].

Fiber Optic Sensing Technique

Many interrogation techniques utilizing fiber optic sensing exist and have been well-documented. Each of these techniques has advantages and disadvantages regarding sample rate, total length, measurement density, and measurement range. For this effort, the authors chose to use High Definition Fiber Optic Sensing (HD-FOS) due to its high spatial resolution of <1.3mm between independent measurements. This technique measures the shift in the Rayleigh Backscatter pattern using Optical Frequency Domain Reflectometry (OFDR). Technical details regarding this technique have been extensively published elsewhere [10]. Another major advantage of this method is the ability to use un-altered telecommunications grade fiber as the sensing device. This enables a variety of existing cable designs which have been developed specifically for embedding into concrete.

HD-FOS works on the principle of comparing the current dataset, or scan, to one that was taken during sensor manufacturing. As described by Kreger et al., the shift in the measured spectra vs the current spectra can be correlated to the strain or temperature applied to the sensor using a set of coefficients determined during a calibration process [10]. The cable used in this testing has calibration coefficients that were previously determined by Rahim et al. for the strain measurement [8]. A set of calibration coefficients valid between ambient and 65 °C for temperature measurement were determined prior to placement into the concrete by placing the sensor into an environmental chamber and stepping between ambient, 38 °C, and 63 °C and recording the spectral shift at those points. The same process was performed on a non-ruggedized sensor for comparison. Both a linear and quadratic fit were determined for the sensor and are shown on the plot in Figure 1.

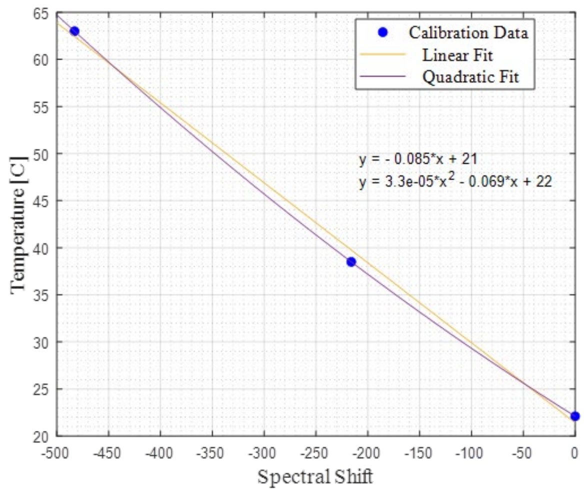

Figure 1. Temperature calibration of the ruggedized cable before installation into the test article

Optical fiber is well suited for embedding across a large spectrum of materials. Many applications that embed fiber into traditional composite structures have been published on by the authors [11] and by other institutions [12,13]. The fiber itself is comprised of fused quartz and tensile tested during manufacturing to 689 MPa (100kpsi) which is greater than the strength of the concrete that the fiber is being embedded in. The optical fiber has a very small cross-sectional area relative to the size of the structures it is embedded or attached to resulting in no effective change to the bulk properties of the test article.

Rapid-setting epoxy concrete

The rapid-setting epoxy concrete used in conjunction with the fiber strain measurements represents the next generation of rapid-repair concrete patch systems. The epoxy concrete [14] features a non-toxic cure-on-demand technology that is activated using a construction-grade, propane-powered infrared (IR) heater. A 101 mm (4 inch) thick repair patch reaches full strength after just 15 minutes of heating the patch surface. Unlike traditional epoxy repair materials, this next generation concrete exhibits a working life >5 hours prior to heating. The compressive strength, bond strength, and modulus of elasticity of this system were tested in accordance with the Tri-Service Pavements Working Group Manual for Rapid-Setting Rigid Repair Materials [15], as reported in Table 1. The 2-hour and 1-day flexural strengths (ASTM C78) were 2,830 psi and 3,075 psi, respectively, which is significantly greater than the typical 650 psi specified for opening a repaired pavement to traffic.

Table 1. Mechanical properties of the rapid-setting epoxy concrete

Property	ASTM	Requirement	Rapid-setting epoxy concrete
Compressive Strength	C39	2 hours: ≥ 17,200 kPa (2,500 psi) 1 day: ≥ 27,600 kPa (4,000 psi)	2 hours: 58.7 MPa (8,519 psi) 1 day: 71.1 MPa (10,311 psi)
Bond Strength	C882	1 day PCC: ≥ 6,900 kPa (1,000 psi) 1 day repair: ≥ 6,900 kPa (1,000 psi)	1 day PCC: 9.97 MPa (1,446 psi) 1 day repair: 32.9 MPa (4,770 psi)
Modulus of Elasticity	C469	2 hours: ≥ 1.4 x 10^7 kPa (2 x 10^6 psi)	2 hours: 19 GPa (2.74 x 10^6 psi)
Flexural Strength	C78	2 hours: ≥ 350 psi 1 day: ≥ 350 psi	2 hours: 2,830 ± 560 psi 1 day: 3,075 ± 260 psi

EXPERIMENTATION

Prototype Patch Cure

Initially, the optical fiber was incorporated into a 101 mm (4 inch) epoxy concrete cube in a three-tiered arrangement to monitor heat flow through-thickness when heated top-down using an electric infrared heater. During the cure process measurements were recorded using Luna's Optical Distributed Sensor Interrogator (ODiSI). The temperature was measured at points located every 0.65 mm along a 2 m fiber optic cable at a rate of 60 Hz. The fiber was woven into the concrete as it was being poured and tamped into place. The presence of the fiber in the patch provided a temperature profile of the exotherm heat transfer through the thickness of the patch to lead to a full cure (see Figure 2).

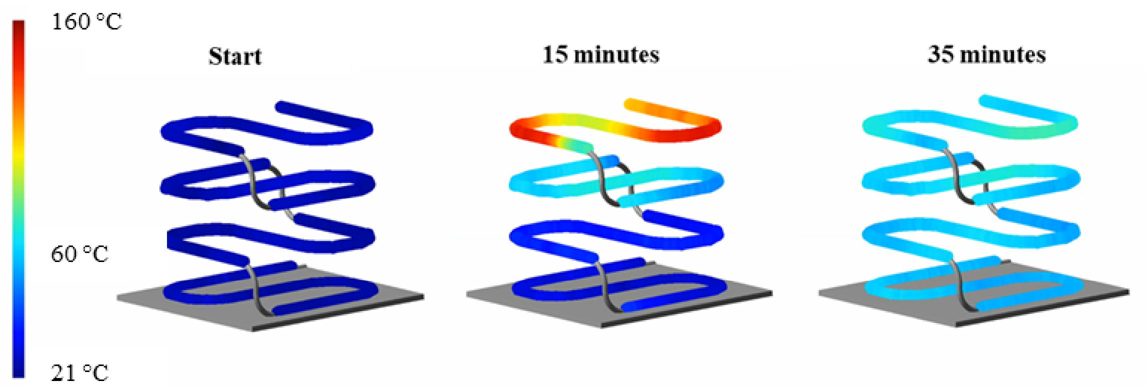

Figure 2. Data produced by the ODiSI platform shows a temperature gradient along a fiber that was woven within the epoxy concrete patch. Fiber layers are spaced in 25 mm (1 inch) increments

As shown in Figure 2, the fiber optic sensor was able to successfully monitor heat flow through-thickness as a function of time and 3D space. Even after the IR heater was turned off, the exotherm continued, with the fiber optic sensors showing an equilibration point of ~60 °C at the 35 minute mark. After 1 hour, the patch was flipped over to assess the cure through-thickness. The bottom of the patch was cured to hardness and was extremely durable as shown in Figure 3.

Figure 3. 4" x 4" x 4" prototype patch containing the ODiSI thermal sensing fiber, cured with the IR Heater. Image at right shows the bottom of the patch 1 hour after cure

Application of epoxy concrete with fiber

The initial prototype cube was scaled to a 304 x 457 x 101 mm (12 x 18 x 4 inch) thick specimen that would simulate a repair patch. As shown in Figure 4, ruggedized fiber was carefully woven into a nylon net was placed in a two-tiered arrangement at the bottom and middle sections of the patch. The epoxy concrete was poured and tamped around the fiber, ensuring good packing of the resin and aggregate around the fiber. Following surface finishing, the concrete patch with incorporated fiber was cured top-down using a propane-powered IR heater.

Figure 4. Incorporation of fiber optic within repair patch

Monitoring of patch temperature with fiber

Patch temperature

The patch temperature was monitored using the ruggedized cable and it was observed that the maximum temperature exceeded the calibration. While the fiber was not damaged, the results were not consistent with the readings from thermocouples that were also embedded. This demonstrated that while the rugged cable was suitable for monitoring the strain on the patches once they had been cured, it would not be suitable for monitoring the temperature of the patches during the curing process. The data from the ruggedized cables used for this cure can be seen in Figure 5. Once the temperature exceeded ~60 °C the cable relaxed and provided a lower than expected measurement. Plots of the thermocouples are presented in Figure 6.

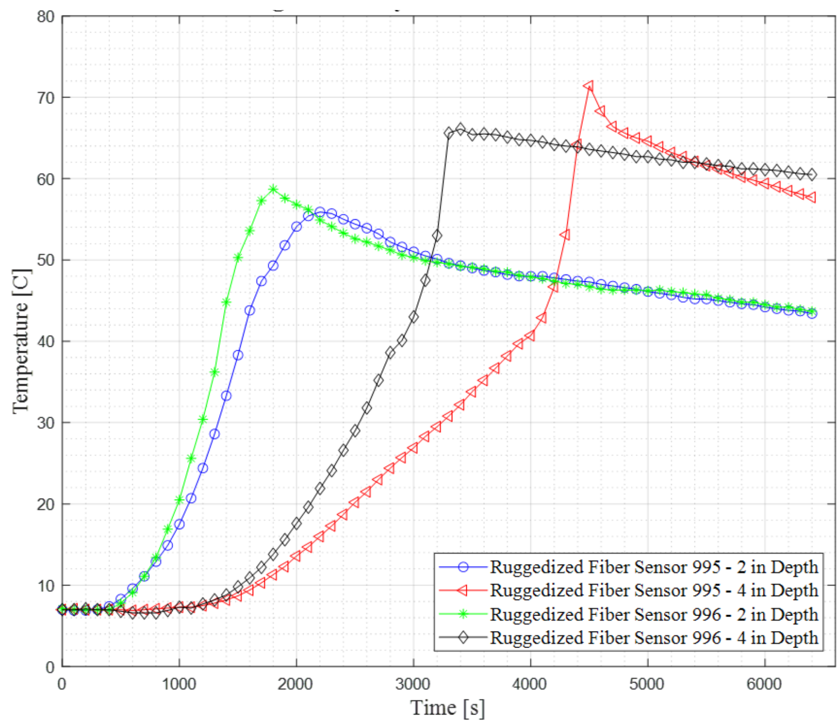

Figure 5. Temperature measurements using a reinforced cable during test article curing

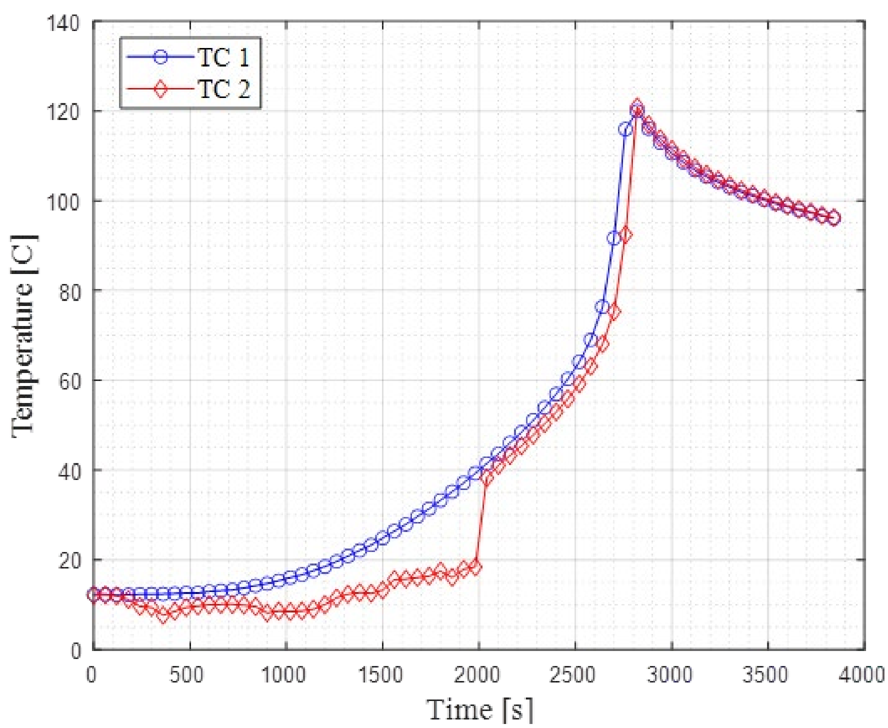

Figure 6. Temperature measurements using a thermocouple during test article curing. The thermocouples were placed at the base of the test article, 102 mm (4 inch) below surface.

Oven calibration temperature

The use of the standard temperature sensors as a method of monitoring the cure process was validated during a test which compared the standard fiber temperature sensor to the ruggedized cables. Thermocouples were also included to provide a baseline temperature measurement. Two each of the standard fiber sensors, ruggedized fibers, and thermocouples were placed into a 76 x 76 x 305 mm (3 x 3 x 12 inch) polymer concrete prism. The concrete cure was initiated by placing the sample in an oven set to 100 °C. During the cure, the temperature readings of the standard fiber sensor and ruggedized fiber sensor were within 6% of the baseline thermocouple reading. This is considered to be good alignment given the ability to co-locate the fiber sensors. At 65 °C, the ruggedized sensor began to provide significantly lower readings due to the softening of its coating above the maximum-rated glass transition temperature of the fiber's protective coating. However, the thermocouples and the standard fiber sensors exhibited a sharp slope above 65 °C as the cross-linking exotherm was initiated. The temperature began to plateau around 85–90 °C before reaching a peak at approximately 115 °C. More investigation is needed to determine if the slope at ~65 °C corresponds to the beginning of the exothermic reaction and crosslinking points for the polymer resin.

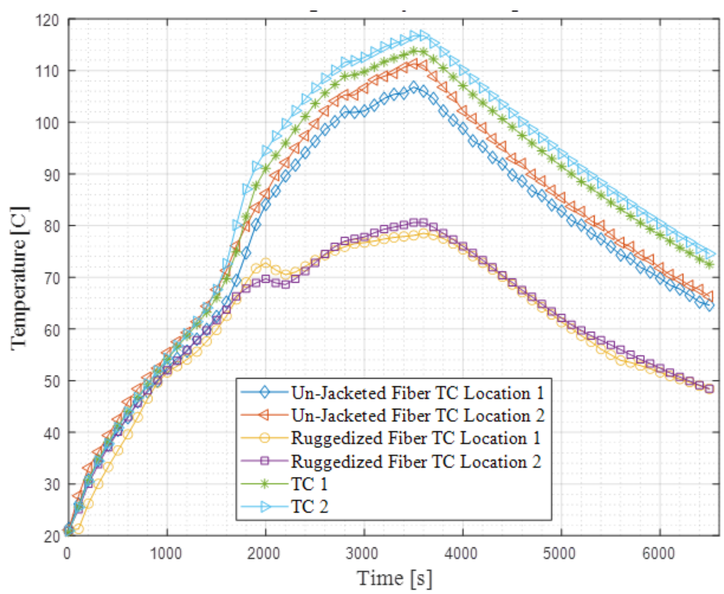

Figure 7. Temperature calibration of the standard [un-jacketed] fiber sensor, ruggedized fiber, and thermocouple (TC) using a 76 x 76 x 305 mm (3 x 3 x 12 inch) concrete prism. The polymer concrete was oven cured at 100 °C for 1 hour.

Monitoring of fiber strain

The monitoring of the two patches was conducted by periodically scanning the fiber using an ODiSI 6100 Series optical interrogator and comparing the resulting strain measurements over time. Each day during the test period a vehicle with a minimum front axle weight of ~ 816 kg (1800 lb) (Vehicle 1) was parked on the test articles for approximately 9 hours. On days where a heavier vehicle (Vehicle 2) with a front axle weight of ~1590 kg (3500 lb) was available, the team would remove the lighter vehicle and conduct five (5) roll-on–roll-off cycles with the heavier-weighted vehicle while simultaneously monitoring the patch strain with the fiber sensor.

Figure 8. Vehicle 1 sitting on patch for 9 hours/day, 5 days/week.

RESULTS

Long-term monitoring of epoxy patch

Figure 9 shows the strain profile of both vehicles both as a function of sensor length. The peaks in the plot indicate the locations where the most strain was observed, correlating to the top center of the test article. The section on the left of the plot is the portion of the sensor closer to the neutral axis, and hence experiences less strain. Due to the small strains that the team could place on the test articles, minimum change over time due to fatigue was expected at the time of writing this paper. It can be noted that the heavier vehicle induced roughly 50% more strain on the test article.

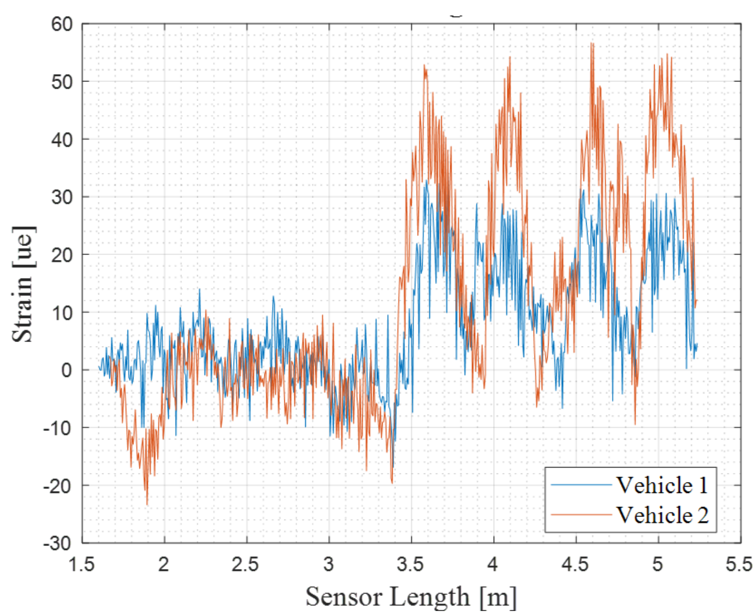

Figure 9. Strain measured by the sensor for both vehicles as a function of the sensor length

An example of the timeseries data from two points along the fiber during one loading cycle is shown in Figure 10. The magnitude peaks are slightly different for each cycle due to the specific location of the load on the test article but remain close in peak values.

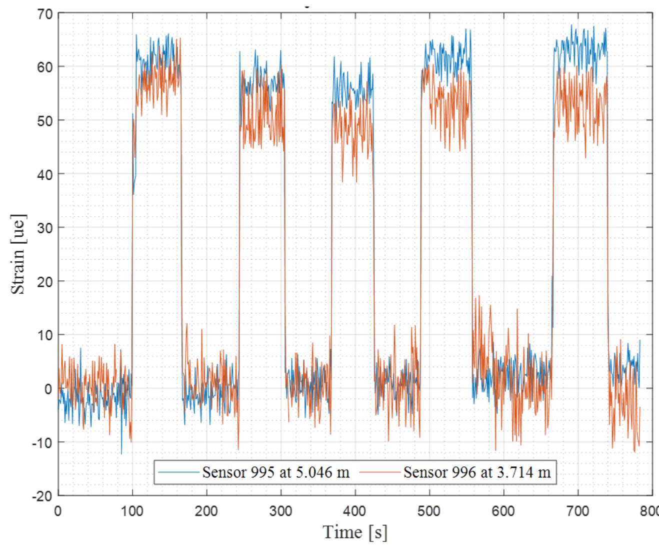

Figure 10. Strain monitoring of five (5) cycles of vehicle roll-on–roll-off of the repair patch

To evaluate the sample for fatigue, the magnitude of the strain will need to be tracked over time. Five locations along the sensor have been selected for monitoring during testing. The peak values at the writing of this paper are shown in Figure 11. The days in which the heavier vehicle was used are evident by the higher strain loads. In general, the slope of the peak values for a given vehicle remain flat. As fatigue begins, the peak values will increase as load is placed. This will be validated through further experimentation over the course of a year.

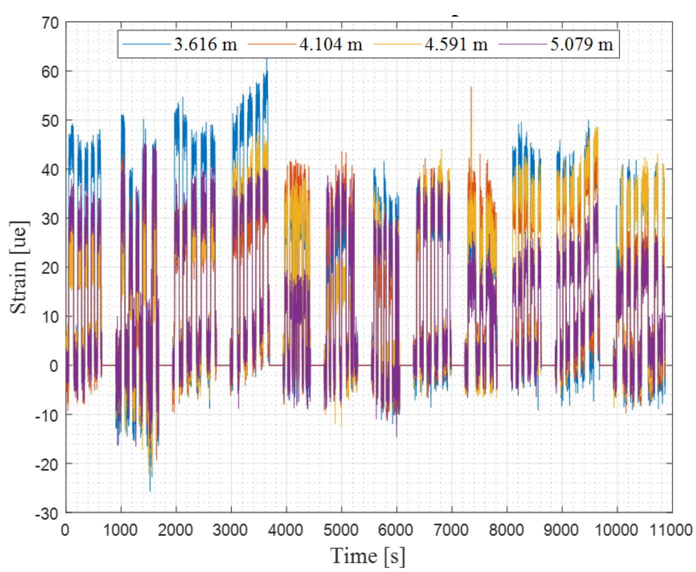

Figure 11. Time history of the strain measured at 4 points within the test article with max depth of 102 mm (4 inch). As the test article develops fatigue-related failure the magnitude at each of these points will increase

SUMMARY AND CONCLUSIONS

The objective of this paper is to introduce a method for the monitoring of an alternative material to concrete intended to be used for highway repair. Polymer-based, rapid curing systems offer an attractive solution to maintaining civil infrastructure that is exposed to severe conditions. These materials will also prove to be cost competitive and longer lasting as they experience greater utilization in industry. Integrating a method of monitoring both the curing process and the long term performance of the systems will assist in increasing confidence in these materials and also capture data that can be fed into performance models. The fiber optic monitoring method described here is capable of monitoring the strain and identifying unexpected changes in magnitude that indicate mechanical failure of a repair. It may also be possible to identify the class of vehicle that is loading a patch as demonstrated by the different magnitudes in strain observed when Vehicle 1 and Vehicle 2 were used to load the test article. It is expected that experimentation over the course of several years will be necessary to quantify fatigue damage as well as comparing these results to a similar concrete control sample. This is expected to occur during a future research effort.

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