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A Self-powered Sensing System for Continuous Fatigue Monitoring of In-service Pavements

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Abstract: The objective of this paper is to present an overview of on-going work aimed at the development of a sensing system that can be applied toward the long term monitoring of pavement structures. The paper addresses the different challenges related to the successful development and implementation of the system for pavement application. The novel module consists of a miniaturized battery-less wireless sensor capable of detecting the long-term strain history of the pavement structure. It is based on the integration of piezoelectric transducers with an array of ultra-low power floating gate computational circuits. The paper is split into four sections. First, a summary of the development of the sensor electronics is provided. Then, a description of the development of a reliable packaging system that ensures structure integration of the sensor, reasonable survivability under construction conditions, and longevity in harsh environments, is presented. Also, a damage prediction algorithm to estimate the remaining life of the pavement from the sensor output data is discussed. Finally, the use of a probabilistic based interpolation technique for the estimation of full field strain distributions, using measured data from a limited number of implemented sensors, is investigated in the context of exploring the feasibility of large networks deployment.

Key words: *Structural health monitoring; Low power sensors; Pavement management.*

Introduction

In the USA, each state highway agency currently spends several million dollars per year to inspect highway structures for damage. Two approaches are typically taken to monitor the condition of pavements: (1) manual distress surveys, (2) automated condition surveys using specially equipped vehicles. However, these monitoring approaches remain rather reactive than proactive in terms of detecting damage, since they merely record the distress that has already appeared. Other testing approaches, for example deflection testing, are also used. However, most of these methods either require significant personnel time or the use of costly equipment. Thus they can only be used cost-effectively on a periodic and/or localized basis. As a result, there is a continuing need for low-cost technologies that facilitate early damage detection and future condition evaluation in the context of pavement network management.

Currently, pavement instrumentation for condition monitoring is done on a localized and short-term basis. The existing technology does not allow for continuous long-term monitoring mainly because of the limitations caused by the use of batteries: The life span of a battery is about 1 to 2 years; in addition it is impractical to replace batteries for embedded sensors. Also, the deployment of existing systems on a network level remain unfeasible due to cost, unease of installation, the need for fixed and rather massive data acquisition systems, and low durability (because of the required wiring).

Though recently there has been significant research activity in distributed wireless sensors for monitoring industrial process parameters and environmental conditions (see for example [1]), all of the commercially viable sensors developed to date require either solar or battery power. It is unlikely that such powering means would be practical for monitoring pavement structures, where periodic replacement of batteries or the expense of solar power technology would be cost-prohibitive and in some cases impractical (e.g. due to safety on highly trafficked or inaccessible roads). It is widely believed that energy harvesting could constitute a viable alternative. Energy scavenging is the process of converting ambient energy (such as the kinetic energy from structural vibration or mechanical strain) into electrical energy that can be used to power the sensor. Thus, the creation of a low-cost, self-powered usage monitoring sensor would be a significant improvement to the field of pavement monitoring and management.

To characterize the integrity of pavements at lower cost and on a more frequent and broadly distributed basis, our research group has been involved in the development of a low-cost, self-powered, wireless strain sensor that can be economically attached to pavement structures either during construction, or anytime during routine maintenance operations. This sensor is able to communicate the pavement strain response under service conditions directly to a service vehicle using radio-frequency (RF) communications technology. The system has the following attributes:

- Self-powered, continuous and autonomous sensing; the sensor is capable of measuring and storing strain data using only self-generated electrical energy harvested directly from the sensing signal induced by a piezoelectric transducer attached to the pavement. Our research group has recently shown that for a small sensor (less than 5 cm^3 in volume), only very low electrical to mechanical energy conversion is achievable in civil engineering structures [2]. The convertible electrical power levels in structures are typically less than 1 μW. Given

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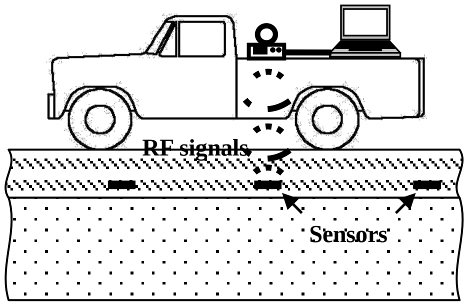


Fig. 1. Conceptual Implementation of an Array of Self-powered Sensors Capable of Monitoring Cumulative Pavement Strain History.

the strain levels observed in pavements, it is believed that the available harvestable energy is also around 1 μW. The sensor uses novel analog signal processing circuits that requires less than 1 μW of power [3].

- Autonomous computation and non-volatile storage of sensing variables; the sensor uses the physics of floating gate transistor injection principles [4] for computing cumulative mechanical strain patterns experienced by the pavement structure that are linked to evidence of damage onset or distress. The method obviates the use of data converters and digital computational circuitry, thus reducing power requirement and cost.
- Wireless communication; capability to transmit and receive data wirelessly to and from a moving observation platform (Fig. 1).
- Robustness to withstand harsh environmental conditions; different robust packaging techniques are used to increase the sensor's longevity. Furthermore, it has been shown that piezoelectric transducers (such as lead zirconate titanate (PZT)) have good performance repeatability and long operational lifetimes even in harsh conditions [5-7]. Also, the wireless operation of the sensor would allow for longer lifetimes compared to conventional strain gauges since there is no risk of wire damage.
- Possibility of networks deployment; extensive sensor networks could be deployed in a given pavement structure. This would allow for simple statistical compensations for external parameters (temperature variations and traffic wander).

This paper describes on-going work aiming at fully developing the described system with all the needed attributes to make it a practical device that can be used for in-service pavement monitoring. The work is sponsored by a grant from the Federal Highways Administration. Four primary challenges between concept development and a real pavement monitoring system have been investigated:

1. Development of an analog self-powered sensor that uses piezoelectric material, which can act both as a sensor and a power source.
2. Development of a reliable packaging system that ensures structure integration of the sensor, reasonable survivability under construction conditions and longevity in harsh environments.
3. Prediction of fatigue damage and remaining life of an in-service pavement.
4. Development of a technique for estimating full field strain distributions using measured data from a limited number of implemented sensors.

Smart Sensor

Energy harvesting is a topic that has been given great attention in recent years [8-11]. A myriad of potential self-powering energy sources have been identified, yet few are capable of providing the 600μW of continuous power widely believed to be the absolute minimum required to operate a single sensor [11]. It has been shown that the only two possible self-powering schemes that are practical for civil infrastructure monitoring are vibration and strain powering [2, 12].

A viable approach to mechanical energy conversion is to convert strain energy into electrical energy, and typically involves the use of piezoelectric materials. As shown by Elvin et al. [13], strain energy powering has the added advantage of using the self-powering device (piezoelectric material) to act both as the sensor and as the powering means, thereby reducing the overall size, power requirement, and cost of the sensor system. The piezoelectric transducer can generate large voltage signals (> 10 V), but exhibit limited current driving capability (< 1 μA), limiting the level of extractable power. But, this ideally combines with the intrinsic properties of analog floating memories that can operate at very low current levels (pico-amperes).

A Complementary metal–oxide–semiconductor (CMOS) floating gate is a poly-silicon gate surrounded by an insulator, which in standard semiconductor fabrication process is silicon-dioxide [4]. The charge on the gate can be modified using hot electron injection or through tunneling [4]. Injection in a P-type metal-oxide-semiconductor (pMOS) transistor occurs primarily due to hot-hole impact ionization caused by high electric fields at the edge of the drain-to-channel depletion region. As electrons are added to the floating gate its potential decreases, thus implementing a long term non-volatile memory. Fig. 2(a) shows the measured injection characteristics of a floating gate transistor when the drain is excited by pulses of 1 second duration for different source current amplitudes. For each excitation pulse generated by a loading cycle, the floating gate injects a packet of charges on its gate. The figure shows a decrease in source to drain voltage as a function of time or load applications. This low power operation makes it possible to have a self-powered sensor that can monitor a pavement under in-service conditions. Based on the described technology, the sensor was developed, tested and calibrated [3, 14]. Measured results from a fabricated prototype in a 0.5 μCMOS (Fig. 2(c)) process have demonstrated that the processor can sense, store and compute usage cycles [14]. Connected to the piezoelectric, it is capable of continuously monitoring local strains within the host pavement structure, implementing a level-crossing cumulative time counting as shown in Fig. 2(b). A series of memory cells cumulatively store the duration of strain events, at a preselected level discretization, experienced by the pavement structure at the sensing node location. It measures the duration of events when the amplitude of the input signal, coming from the piezo, exceeds different thresholds. For the

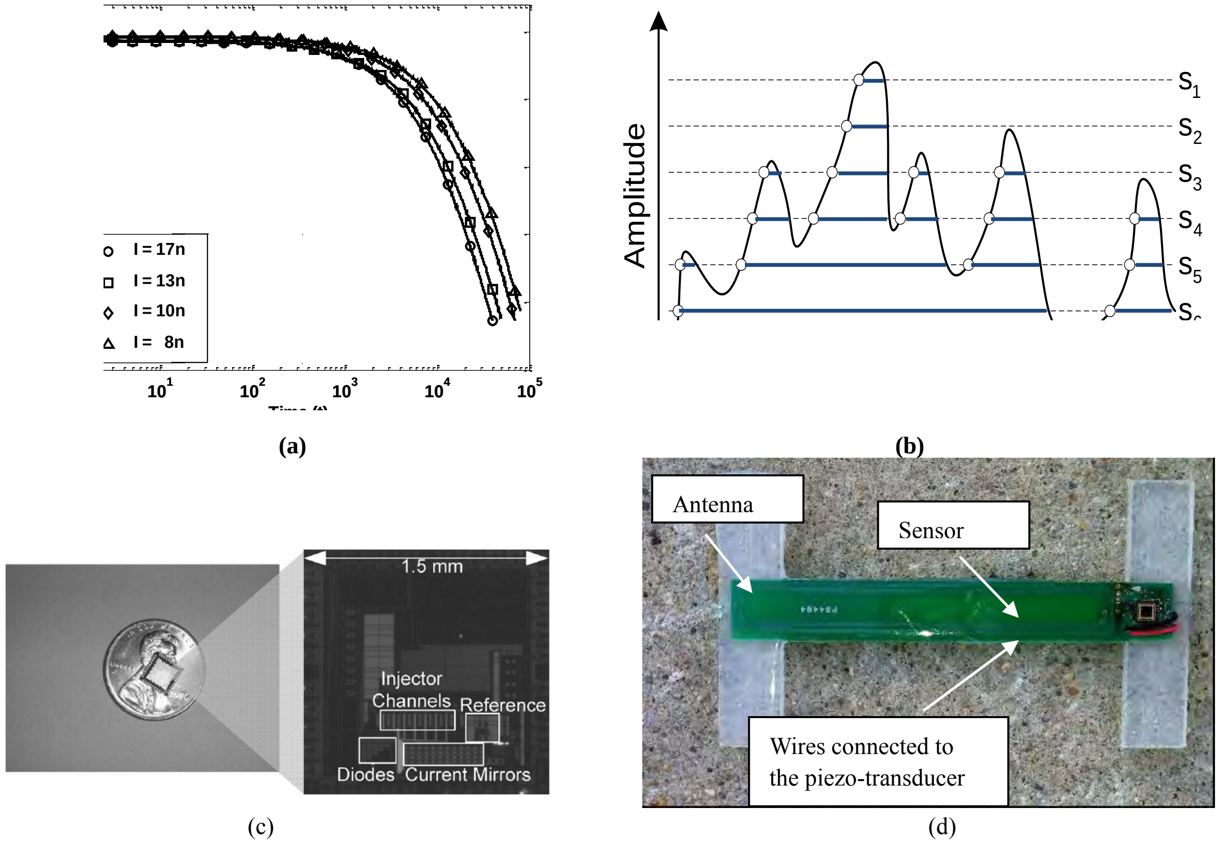


Fig. 2. (a) Measured Response of Floating Gate Transistor when Digital Pulses are Applied to the Drain with Varying Source Current (b) Illustration of the Level Crossing Cumulative Time Counting Implemented by the Sensor (c) Packaged Prototype of the Level-crossing Processing and its Photomicrograph (d) Full Sensor Embedded in an Epoxy Package.

current version, the piezoelectric transducer has to generate a voltage pulse with minimum amplitude of 5.15 V. When interfacing the piezoelectric transducer with the floating gate sensor array, this minimum supply voltage should be set to be equal to the piezoelectric voltage output representing the lowest fatigue (endurance) limit of the material.

In addition, a wireless communication capability was added to the sensor, enabling the communication of the data. This module still needs further development to optimize its performance. Fig. 2(d) shows the complete self-powered wireless sensor with attached antenna, and embedded into an epoxy packaging. The development of a reliable packaging system is necessary to ensure the durability of the embedded sensor during installation and under traffic. The performed work is discussed below.

Packaging System

Embedded strain gages made specifically for asphalt concrete have been widely used by several research programs. To ensure a good contact, most of the marketed gages are “H-shaped”. We therefore decided on similar packaging shapes, so that the sensor can be installed using existing procedures that are accepted by DOTs and will not constitute a major disruption to current practices. It should be noted that the existing commercially-available gauges don’t have thermal protection since they don’t have any electronic devices. In our design, the thermal protection is needed. The piezoelectric transducer is attached to the core reinforced epoxy, and a thin thermal insulator coating is added in order to protect the embedded electronics. A separate empirical study has been conducted to decide on the shape of the gauge, the epoxy material, the thickness and the thermal insulation.

Gauge Shape and Material Selection

The stiffness of the package must be close to or lower than that of the pavement material (in this case, asphalt concrete). The main frame of our package is made of epoxy on which the sensor and the piezoelectric transducer are attached. The layer used for thermal insulation has very low stiffness compared to the main frame epoxy The choice of the epoxy was based on several parameters including the thermal and electric conductivities, and most importantly the elastic modulus which defines the system’s stiffness. Two types of epoxy were identified, Conathane TU-981 and Araldite GY-6010. Both types have high tensile and flexural strength, above 4000 psi. Both are good electric insulators, but the Araldite GY-6010 has an upper thermal resistivity and an elastic modulus close to the asphalt pavement modulus at 25°C (300,000 psi), however the modulus of the Conathane TU-981 is much lower (30,000 psi).

In most of the commercialized asphalt strain gauges the anchors are metallic to avoid damage to the corners due to stress concentration and to ensure a better strain transfer. However, in our case, we cannot use any metal since it would interfere with the RF

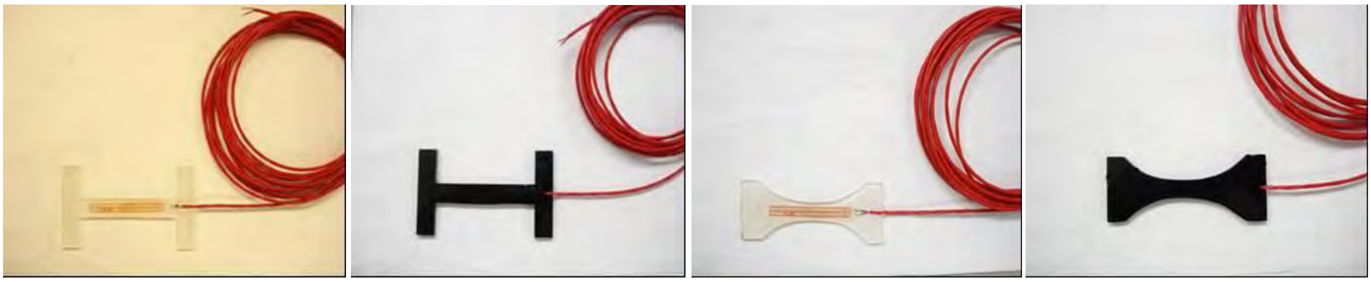
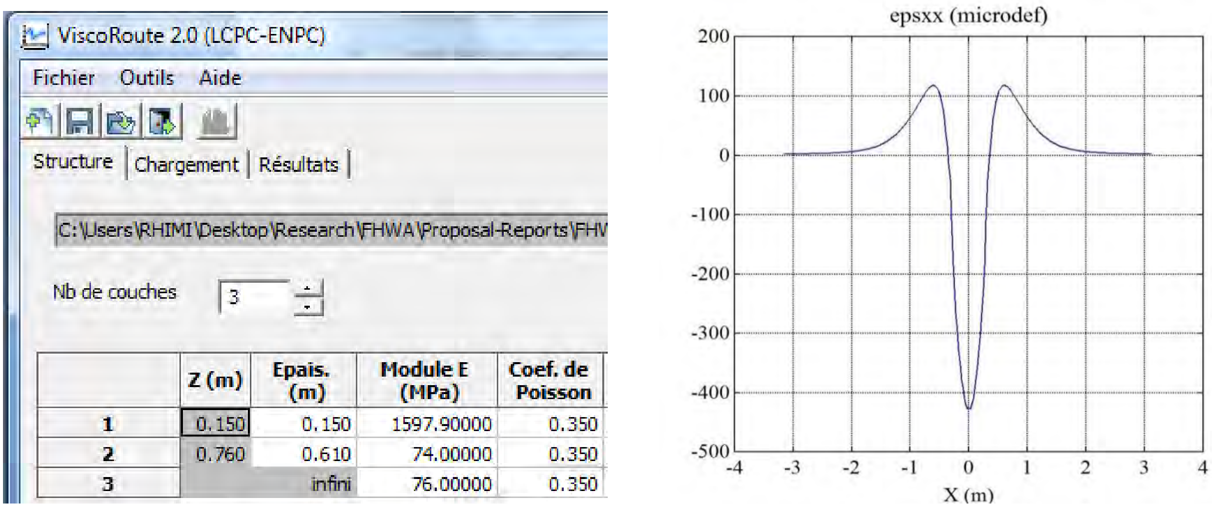


Fig. 3. Asphalt Strain Gage Prototypes.



(a) (b)

Fig. 4. (a) Viscoroute Input Parameters for Pavement Structure (b) Simulated Longitudinal Strain Using Viscoroute.

communication device. In addition, it can be argued that using anchors with a modulus close to that of the asphalt would allow for better structure integration. Thus, we decided to also test the bone shape, since it would reduce stress concentration and can be made from the same material.

A total of eight gauges were tested at the APT facility at the Turner-Fairbank Highway Research Center (Fig. 3). Two shapes (regular H-shape and bone shape), two different thicknesses each (1/4 in and 3/8 in) and two different epoxy materials (Araldite GY-6010 and Conathane TU-981), were evaluated.

Simulations using the Viscoroute program were conducted to estimate the strains in the tested structure. Information on relevant pavement layer parameters was obtained from the research report provided by TFHRC [15]. Fig. 4(a) shows the input elastic parameters for the Viscoroute program. The layer moduli, used in the simulation, were back-calculated using EVERCALC at 26^{o}C [15] and then corrected to 19^{o}C [15]. Fig. 4(b) shows the computed strains. Strain gage responses were recorded at 19^{o}C and under a wheel load of 16,000 lb. Fig. 5 shows a comparison of the measured strains between the different shapes, the different thicknesses, and materials properties. Theoretically, if the bonding of the strain gauges to the pavement surface is perfect, the transferred strain can never exceed the strain induced in the pavement. The configuration that records the higher strains is thus the best.

Fig. 5(b) and 5(d) show the strain measurements from the H and bone shapes for the two considered thicknesses, using the Araldite epoxy. The noise to signal ratio in these measurements is high, and the peak strain is relatively low compared to the numerical values. This is due to the high tensile modulus of the Araldite epoxy. Fig. 5(a) and 5(c) show the strain measurements from the H and bone shapes for the two considered thicknesses, using the Conathane epoxy. It can be seen that the noise level is much lower; however the peak strain recorded using the H shape is very low, this is due to the softness of the anchors.

Due to the mentioned reasons, the bone shape made with the Conathane TU-981 epoxy is estimated to be the best fit for the packaging of the sensor: it allows for a better strain transfer (higher signal), and it has no anchors, thus ensuring a better survivability rate by avoiding stress concentrations at corners.

Thermal Protection

According to the results shown in David et al. [16], the typical mix temperature in a paving project will decrease from around 150^{o}C to around 70^{o}C in about 2 hours, and then will oscillate between 70 an 100^{o}C as lifts are applied. From a simple finite element simulation in which the external temperature is assumed to be constant all the time at 150^{o}C (very conservative condition), it was concluded that the conductivity of a 1cm isolating material layer should be less than 0.08 W/mK in order to adequately protect the circuits. Polyurethane foam was identified as a viable candidate for thermal protection. Its thermal conductivity is lower than 0.05 W/mK, and it has a high abrasion resistance and impact strength. The selected foam was tested in high temperature environment. Three thermocouples where placed inside an environmental chamber with a controlled temperature increasing gradually from 30^{o}C to 110^{o}C

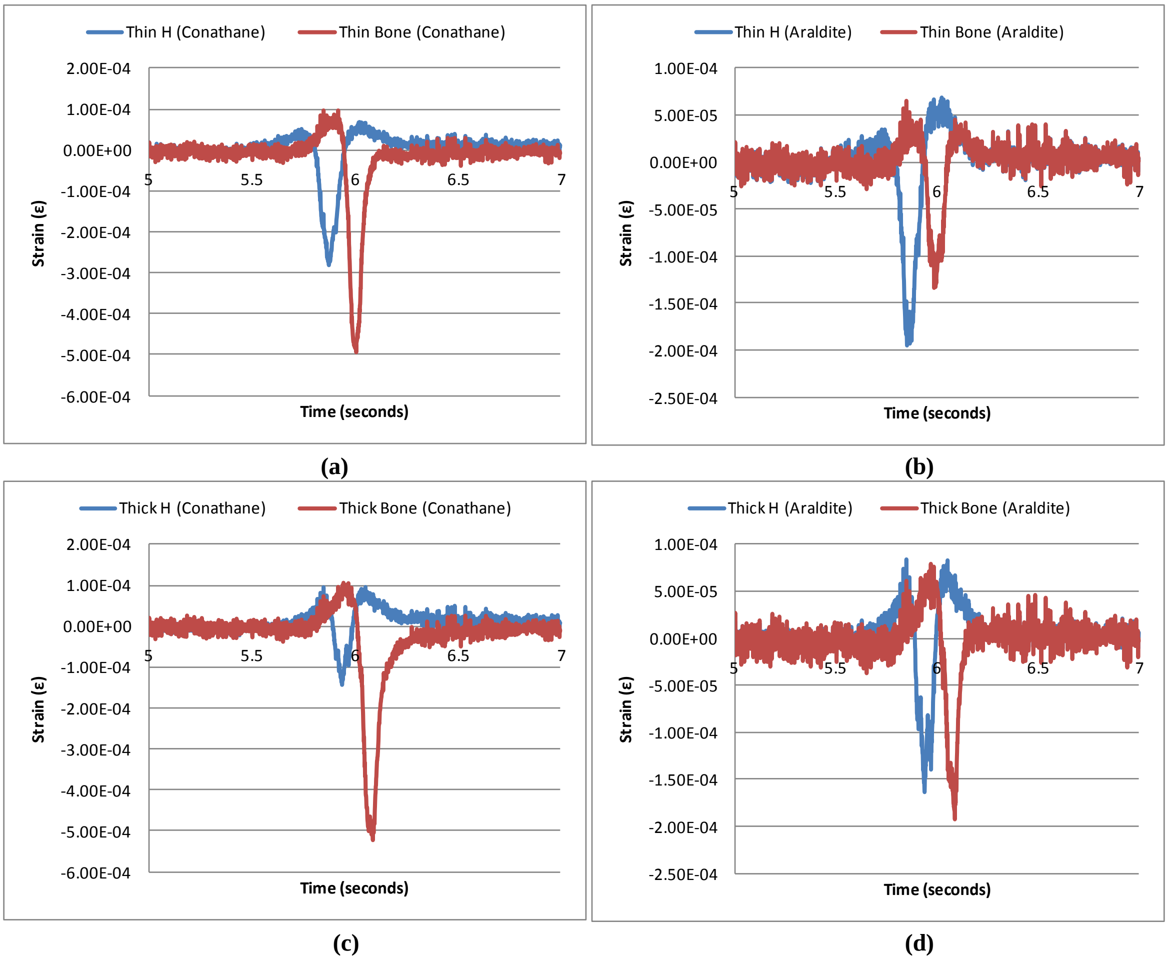


Fig. 5. Measured Longitudinal Strain Using (a) thin H and Bone Shape Made of Conathane (b) Thin H and Bone Shape Made of Araldite (c) Thick H and Bone Shape Made of Conathane (d) Thick H and Bone Shape Made of Araldite.

and then maintained at that level for 60 minutes. The first thermocouple was placed with no protection, while a coat of 2 mm and 7.6 mm was placed respectively on the second and third thermocouples. Fig. 6 shows the variation of temperature for different sensors. It is shown that a Polyurethane layer significantly decreases the observed temperature.

Additional Mechanical Protection Layer

Using a slab compactor, H-package prototypes were embedded in asphalt and subject to compaction (Fig. 6(b)). The compaction curves, uploaded from the compactor's controller unit are shown in Fig. 6(c). Compressive loads exceeded 2000 kPa, which is higher than the estimated in-field stresses. Temperature was around 150°C. Initial results showed a relatively low survivability rate (66%). So modified prototypes with an added very thin layer of urethane casting resin (1 mm), were manufactured and tested. The added resin proved to adequately bond to the epoxies, providing the required external resistance (Fig. 6(d)). Five samples were tested under compaction; they all survived the test and showed much greater resistance to local damage induced by aggregates (Fig. 6(e)).

Fatigue Prediction

Embedded in the pavement, each cell of the sensor records the strain events at a specific preset level. As described in the second section, the output is organized in the form of a histogram where each bin represents the cumulative time of occurrences at a certain strain level. However, compressing the data in this manner results in some loss of information, since it is not stored as function of real time, but rather as a function of frequency (cumulative time at each strain level). The load spectrum in a pavement structure is assumed to be normal, similarly to traffic speed distributions and thus the frequency of loading. As a consequence, the sensor output, which is the cumulative density function (CDF) of strain loads of randomly distributed amplitude and frequency, is characterized by the CDF of a normal distribution.

Fatigue damage is a time, moisture, temperature, and loading dependent process and is a major factor in the loss of material structural integrity. It is evaluated from the relative change in the elastic modulus or compliance over time. Given the broadly accepted mechanistic-empirical definition of damage for pavements, defect in pavement should result in a change in the induced strain under ambient loads. Damage would reduce the pavement's resistance to load.

The considered hypothesis is that a shift in the distribution toward higher strains over time is indicative of damage accumulation. Thus monitoring the mean, the standard deviation and the total

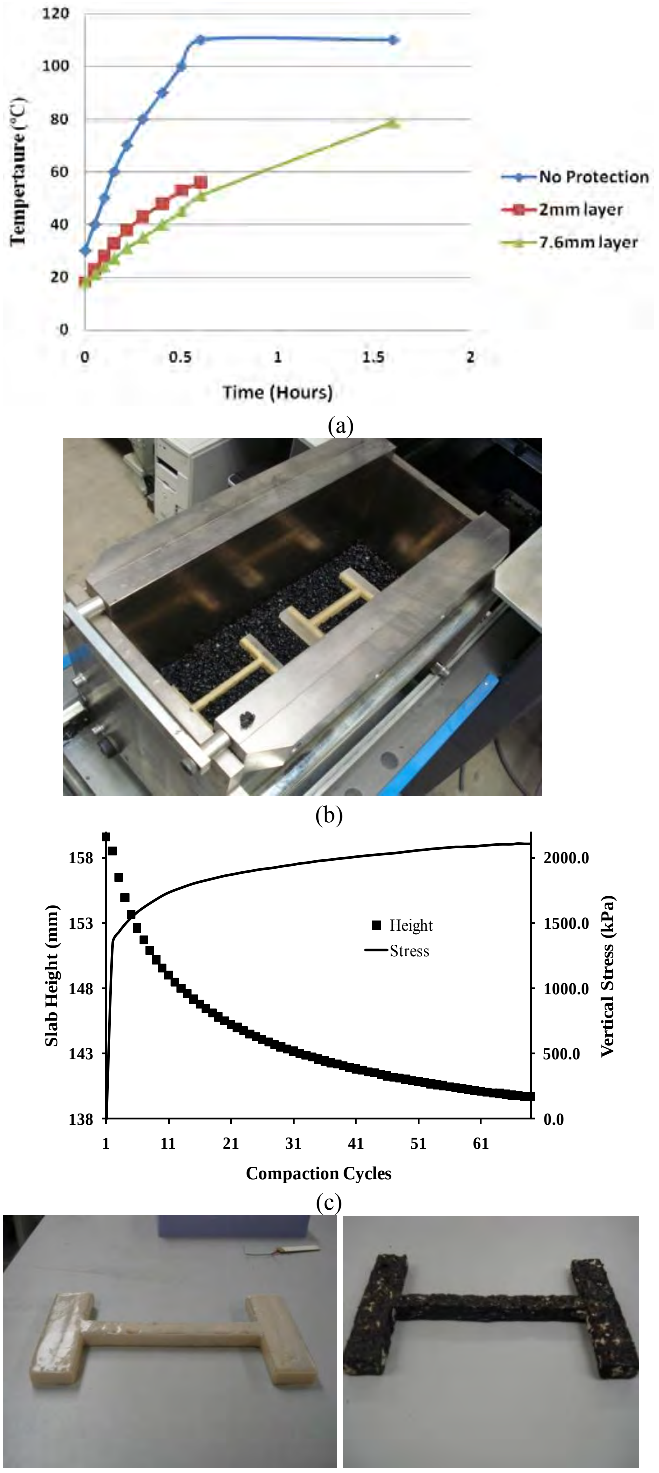


Fig. 6. (a) Measured Output from Protected and Unprotected Thermocouples (b) Specimens Placed in the Compactor (c) Measured Compaction Curves (d) Final Version of the Prototype with an External Resin Layer (e) Recovered Specimen.

cumulative strain loading time of the distribution, allows for determining the levels of strains that are induced in the specimen. The damage coefficient can then be evaluated. The actual applied strain amplitude can be evaluated from the variation of the mean of the Gaussian distribution with respect to the total cumulative loading time.

Feasibility of Network Deployment

It was shown in the previous section that using the sensor can help track local damage. To extend this ability to whole structure, a network of sensors is needed. The objective of this section is to determine the optimal number of discrete sensors to install while generating continuous behavior profile of the complete structure at acceptable error levels. A probabilistic-based approach was used to generate the missing data in the full field using a limited number sensors installed at specified locations.

A network of N implemented sensors will generate N random variables $(X_1,\ldots,X_N)$ that describe the response of the system at a given state. The cumulative strain data at each sensor node can be fit to a variation of the exponential discrete probability distribution of the form $f(y) = \theta_1 e^{-\theta_2 y^2 + \theta_3 y}$, where y = (1, 2, ..., m) is the memory cell number (also associated with a strain amplitude level), and $\theta^T = (\theta_1, \theta_2, \theta_3)$ represents the parameter of the strain distribution. The vectors θ^T are specific to a location and a system's state, they are the parameters to estimate at the missing locations.

The Kriging estimation technique was first used. In its simplest form, its basic goal is to estimate the attribute value at an unobserved location by interpolating the observed values in the neighborhood locations. If we denote $(u_i, i = 1 \ldots\ldots, n)$ n locations in a region of interest R where the field data X has been observed, and u denotes a specified but arbitrary unobserved location in the region R, then the value to estimate X(u) at location u is given by the following equation:

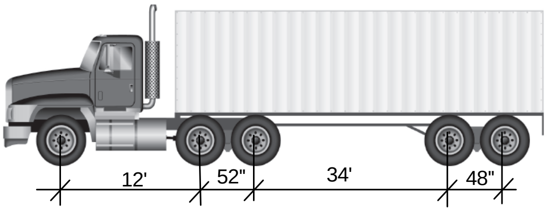
$$X^*(u) = \sum_i \alpha_i(u) X(u_i) + |1 - \sum_i \alpha_i(u)| m(u) \qquad (1)$$

where $m(u)$ is the mean of $X(u)$ and $\alpha_i(u)$ are the Kriging weights which can be determined, for the case of an ordinary Kriging formulation, by solving the following system of equations:

$$\begin{cases} \sum_{j=1}^{n} \alpha_j(u)\gamma(u_i - u_j) + l(u)\left(\sum_{j=1}^{n} \alpha_j(u)\right) = \gamma(u_i - u) \\ \sum_{j=1}^{n} \alpha_j(u) = 1 \end{cases} \qquad (2)$$

where $(u_i - u_j)$ is the distance between location i and location j, $(u_i - u)$ is the distance between location i and the location to be estimated, $l(u)$ is the Lagrange parameter, and γ is a predefined semi-variance property which expresses the degree of spatial dependence between points.

The algorithm was tested to prove the validity of the methods for pavement structures. The 3D response of a layered system under a moving load with static and dynamic components has been modeled. The properties of the used layered system were obtained from Chabot et al. [18]. The three-layer system consists of a top viscoelastic layer modeled through the Huet-Sayegh model [19-21], a road base (0.08 m in thickness), and a subbase layer (0.42 m in thickness) both assumed to be elastic and dependent on thermal and moisture characteristics. Detailed properties are given in Chabot et al. [18] and Nilsson et al. [22]. Traffic distributions were generated and applied as input loading to the pavement structure. Four different types of trucks were considered in the analysis: class 9, class 11, class 5, and class 16 [23]. To simulate traffic wander, five



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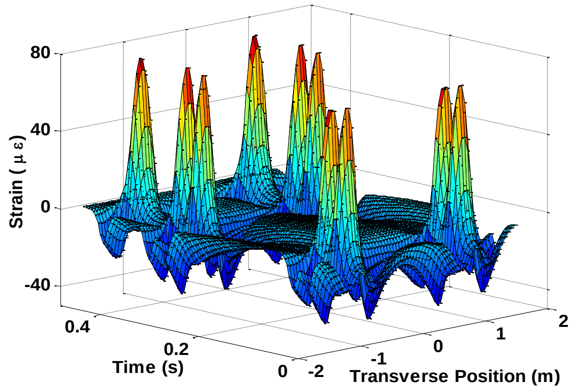
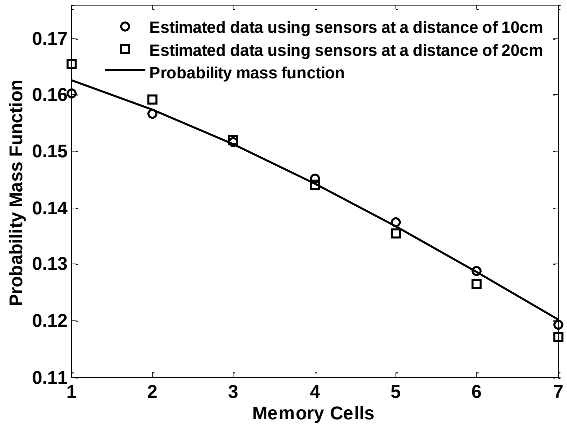


(b)

Fig. 7. (a) Example of a Truck (Class 9) Used for Strain Response Data Generation, (b) Example of Longitudinal Strain Profile Evaluated at the Bottom of the HMA Layer for a Moving Load Induced by a Class 9 Truck.



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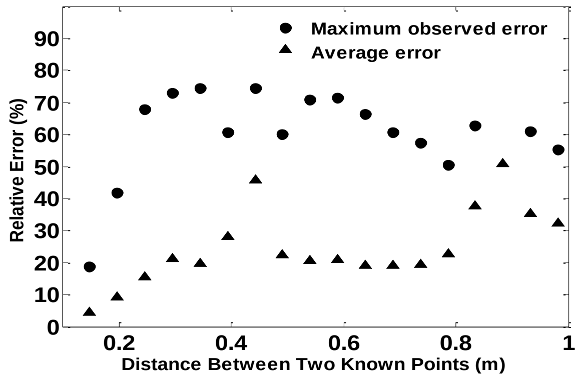

(b)

Fig. 8. (a) Theoretical and Estimated Strain Probability Distributions at a Selected Transverse Location (23cm Away from the Center of the Wheel Path) Using Data from Groups of Two Sensors at Different Spacing Distances. Load Generated by Random Traffic Distributions of Four Different Types of Trucks (b) Maximum Observed Relative Error and Average Relative Error from Generated Data at all Field Points Using Known Nodes at Different Spacing Distances.

different possible positions within the wheel path were selected. One thousand passing truck events were simulated. Each event corresponds to a randomly selected truck type passing at a randomly selected position within the wheel path. The loading per axle as applied in this analysis was as follows: steering axle 68.5 kN, single axle 80.07 kN, tandem axle 71.17 kN, and tridem and higher axles 57.83 kN. Fig. 7 shows an example of generated longitudinal strain response for the class 9 trucks at the bottom of the viscoelastic layer. The results indicate a significant interaction between the axles and relatively large tensile strains (compressive strains at the surface of the pavement). At each node location in Fig. 7, the cumulative strain data induced by randomly generated truck traffic distributions were compressed into probability mass function histograms using the piezoelectric generator and the sensor models.

The objective of this exercise is to recreate the probability mass functions of cumulative strains induced by all the loading events at all locations within the pavement section, using only a finite number of sensors implemented at determined node locations. The frequency distribution of strain levels at a selected location at 23 cm away from the center of the wheel path under the moving load is shown in Fig. 8(a). Estimated probability mass functions using two sensors placed on each side of the unknown data node are also shown. Results from known nodes at 10 cm and 20 cm spacing (5 and 10 cm from the location to estimate) are shown. Values of γ in Eq. (7) were extracted using cubic variograms. It was determined that higher order variograms do not improve the obtained estimations for the considered strains. Fig. 8(b) shows the computed relative error obtained from estimated probability distributions at all the nodes in the pavement section for different known nodes spacing distances varying from 10 cm to 1 m (the nodes spacing resolution is 5 cm). The averaged and maximum observed values are shown for each case. It can be seen that to achieve full reconstruction of the data in all the field points with an average error less than 10%, the maximum spacing between placed sensors has to be less than 20 cm.

Conclusion

In this paper the feasibility of a smart autonomous pavement monitoring system was discussed. Measured results show that the self-powered piezo-floating-gate array can be used to sense, compute and store statistics of periodic loading events. A durable packaging system of the sensor to survive both during construction and throughout the lifetime of the pavement structure, has been studied and developed.

The effects induced by the data compression format rendered by the self-powered sensor on the fatigue prediction capabilities of the system, compared to predictions using complete strain history, have been studied. A data interpretation and damage prediction algorithm was developed. Also the feasibility of a sensor network has been studied by developing a way of estimating missing full field data from a finite number of sensors.

The successful development of the sensing system and associated interpretation algorithms could help improve pavement preservation and management, design and construction operation, and ultimately the serviceability of pavements.

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