Energy Harvesting Assessment Using PZT Sensors and Roadway Materials

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Abstract

The concept of utilizing networks of roads and highways for generating electricity has recently gained considerable attention; advances in the nanotechnology industry offer new opportunities for large-scale improvements in energy efficiency and energy production. In this field, Piezoelectric (PZ) energy harvesting technology has significant advantages over other renewable energy sources such as solar, wind, and geothermal. For example, the embedded roadway system produces little to no infrastructural footprint, and its energy generation span, on a busy highway, can continuously produce energy. However, current low-scale PZ manufacturing methods, and the lack of road-integrated PZ R&D, decrease the cost-effectiveness of this technology and may impact the mainstream adoption of piezoelectric systems. The primary objective of this project was to evaluate the technical feasibility of incorporating piezoelectric systems into roadways. The collaborative research team developed a lab-based Roadway Energy Harvesting System (REHS) using construction and piezoelectric (PZ) materials. The scope of the research project included investigation of the energy harvesting method, preparation of equipment and materials, durability tests of PZ materials and fabricating asphalt and concrete sections for structural and electrical testing. Structural and electrical characterization was completed by measuring the voltage generated in the sections, during a loaded wheel test (LWT), using an Asphalt Pavement Analyzer (APA.) Collected data and various plots developed using Matlab® revealed that deformation in asphalt was correlated to the produced electrical signal. The research results indicated that flexible roadway materials can produce more energy than rigid material such as typical concrete and Engineering Cementitious Concrete (ECC). Similarly, since typical concrete produced higher values than ECC, the magnitude of energy may be more related to strength and density than elasticity, especially in rigid material. Currently, the research team is developing a wafer box coupled with the pavement materials using a 3D printer on with CAD design. The results of this research project will contribute to the possibility of self-supporting energy-generating capacity for highways, for roadway sustainability.

Keywords: Energy harvesting, Piezoelectric Materials, Highway, ECC, Asphalt
1. Introduction

Piezoelectric (PZ) energy harvesting technology has significant advantages over other renewable energy sources such as solar, wind, and geothermal [1, 5, 2]. Using the pressure of vehicles caused by gravity, the method generates electric energy from the deformations in the paving materials [16, 3]. This technology has been tested for a variety of purposes, including sensors [4, 5, 6, 7], roadway lighting and bridge bearing [8, 9], structural health monitoring [5, 16, 3, 5], deicing [10] and traffic monitoring [11]. A privately-owned company, Innowattech, applied this technology to a 2 km-highway in Israel in 2009. It was expected that the four-lane highway could produce enough energy to provide sufficient electricity for average consumption in 2,500 households [16, 3]. According to a report developed by DMV KEMA under the California Energy Commission, a leveled cost of energy (LCOE) by Innowattech is $0.11/kWh with an averaged capital cost of $4000/kW CEC-500-2013-007-D [12, 13, 14]. Recently, several research projects have been performed to assess the possibility of using PZ-embedded roadways as an alternative energy source, and to identify the optimal magnitude of energy harvesting using this technology [10, 15, 16]. An important finding is that these projects indicate PZ-based energy harvesting technologies may be more cost-effective than solar panels. The results of this research indicated that load distribution, the number of PZ elements, and the frequency of activation are major factors in increasing voltages from piezoelectric materials [17, 18, 19]. Although there has been a recent uptick in piezo-based roadway energy harvesting research, there is very little published data to reference. Therefore, a research framework that enables the assessment of piezoelectric materials on highways is strongly required. Despite many advantages of this energy harvesting method, real-world situations typically have inconsistent or varying vibration frequencies, and this requirement severely limits its practicality CEC-500-2013-007-D [12]. The primary goal of this project was to provide energy generated by PZ components embedded in roadway materials used in the U.S. The research project was achieved by measuring the harvested energy from PZ materials under asphalt and concrete pavements. PZ materials were measured in the lab so that their economy and feasibility was determined prior to field experiments.

The research methodology was conducted in two phases: PZ materials were integrated into laboratory equipment to simulate field conditions, and structural and electrical tests were conducted to assess system lifetime performance. In this research piezoelectric materials were embedded in asphalt pavement, which is the most commonly used flexible pavement material; it is used for 94 percent of U.S. highway surfaces [16, 3]. Lifetime tests (durability) in this research, piezoelectric materials were tested with asphalt pavement, which is the most popular flexible pavement material; it is used for 94 percent of U.S. highway surfaces 4/23/14 [20]. Also, concrete pavement materials, including typical concrete and ECC (Engineering Cementitious Concrete), were tested.

2. Research Objective and Scope

The primary goal of this project is to provide energy generated by PZ materials embedded in roadway materials used in the U.S. The research project was to be accomplished by measuring generated energy with PZ materials under asphalt pavement and concrete pavement; PZ materials were measured in the lab so that their economy and feasibility was determined prior to field experiments. The research project is to be accomplished in multiple phases: (1) Energy generated with PZ materials in pavement materials were measured in the lab. (2) Upon development of inclusive units of PZ materials, lab-scale tests were conducted to contribute to the following knowledge bases: Magnitude of electricity, Structural tests (foot traffic) and Lifetime tests (durability.) In this research, piezoelectric materials were tested with asphalt pavement, which is the most popular flexible pavement material; it is used for 94 percent of U.S. highway surfaces 4/23/14 [20]. Also, concrete pavement materials, including typical concrete and ECC (Engineering Cementitious Concrete), were tested.

3. Methodology

A loaded wheel test (LWT) in an Asphalt Pavement Analyzer (APA) performed the task of simulating real road conditions under pavement (See Figure 1). In this case study, the research team tested a piezoelectric product from PUI Audio with 100 lbs., loading in different HZ values including 30 HZ. HZ values can be referred to as frequency of force applied to samples. The contact area of the load wheel was approximately 6 in² and the depth of piezo elements was 2 inches from the top. The size of the specimen was 6 inches in diameter and 3 inches in thickness.

Fig. 1. A Loaded Wheel Test

3.1. Preparation of Samples with PZ sensors

Figure 2 illustrates the construction of the pad sensor structure. To build the concrete form, the research team first cut one piece of ¾ inch thick plywood 14” x 15” for the bottom of the formwork needed. The plywood was wrapped in 4 mil plastic to prevent the concrete from sticking. Next, the research team cut 2 1 x 4’s 14 inches long for one side of the formwork and 2 1x4’s 16 ½” for the other two sides. After all pieces were cut the sides by the research team members to form the plywood resulting in a slab with 3” depth (See Figure 3.) After finishing the concrete, 6 ptz sensors were placed, supported by ¾” wood for proper support. This was performed to ensure sensors maintained proper positioning throughout the curing process. The rest of concrete was then added to completely fill the form for a 3” thick slab. The concrete was finished again using a float and 2 x 4 to level concrete (See Figures 4 & 5.) The research team then submerged the slabs in a water tank.
Fig. 2. Sensors Embedded in Asphalt and Concrete

Fig. 3. Formworks and Mixing

Fig. 4. Placing Concrete to Embed the Sensor
To make concrete samples, mixing ratios of typical concrete and ECC, as shown in Table 1, were identified and used. The mix ratio of asphalt concrete is shown in Table 2. It shows the maximum size for aggregate and RAP (reclaimed asphalt pavement). PG 64-22 was used as the asphalt binder. This mix ratio is a typically used type for Georgia state roadways.

| Material         | Typical Concrete (lb) | ECC (lb) |
|------------------|-----------------------|----------|
| Cement           | 42                    | 55       |
| Water            | 15.5                  | 18       |
| Coarse Aggregate | 98                    |          |
| Fine Aggregate   | 81                    | 69       |
| DVA (fibers)     | 7.15                  |          |
| Admixture        |                       | 18       |

Table 2. Asphalt Concrete Mix Ratio

| Materials       | Superpave maximum nominal aggregate size | Ratio (%) | Remark                                      |
|-----------------|------------------------------------------|-----------|---------------------------------------------|
| New Aggregate   | 10.0mm                                   | 27        | Granite                                     |
|                 | 5.0mm                                    | 28.4      |                                             |
|                 | 2.5mm                                    | 19        |                                             |
| RAP             | 12.5mm                                   | 25        | Reclaimed Asphalt Pavement                  |
| Hydrated Lime   |                                         | 0.9       |                                             |
| Total           |                                         | 100       |                                             |
| Asphalt         | PG 64-22 (Unmodified)                    | 6.07      | Sample properties at OAC                    |
|                 |                                         |           | Density: 2.318 g/cm³                         |
|                 |                                         |           | Air voids: 4.2%                             |
|                 |                                         |           | Aggregate: 4.8%                             |

Fig. 5. Slump Tests and Finishing

Fig. 6. (a)Asphalt, (b)ECC, (c)Typical Concrete
3.2. Voltage and Power Testing with Samples
This lab experiment was conducted to develop the framework using the asphalt analyzer, the electricity measurement equipment, and commercially available piezoelectric materials (Figure 2). PZ samples were embedded in asphalt, concrete composite, and ECC concrete, respectively, and then voltages from the PZ elements were measured under simulated traffic loads using the APA. This experiment was conducted under the assumption of 600 vehicles per hour at 45 mph. The load on the asphalt mix from each vehicle was 100 lbs. To identify which PZ materials generate the most energy, the research team conducted testing with 6 different resistance values.

3.3. Voltage and Power Tests
A custom test system was fabricated to accurately determine power and energy. Data using various magnitudes of resistance and load distributions were collected. The first test was direct voltage/open circuit voltage measurement, achieved by simply connecting the oscilloscope channel wires directly to the piezoelectric sensor’s leads. The next test measured the rectified voltage with no load. The same set-up of wires was used for all other tests. The rectified voltage was then measured with the load attached to produce a flat DC signal to calculate power output. The first test was with a 1 MΩ load and a 10μF capacitor.

4. Results

4.1. Voltages vs Deformation on Concrete & Asphalt
Tests were conducted on the embedded PZ system configuration in asphalt and two types of concrete, two inches from the wheels as shown in Figure 2. A fatigue test was run at 30 Hz for the PZ system embedded in these three materials. The thickness of the asphalt slab and concrete slabs was 3 inches; the test was conducted for 8000 APA cycles which lasted for 4 ½ hours. It was observed that the voltage continuously decreased, indicating a direct correlation with material deformation and voltage drop as shown in Figure 3. However, in the case of concrete it was not a significant decrease; the voltage remained constant with time (Figures 4 & 5). A plot of voltage vs. deflection for asphalt material is shown in Figure 6. A correlation between voltage drop and deflection was not observed.

5. Data Analyses

5.1. Statistical Analyses
Voltage values, on average, were compared as shown in Table 3. As deformation was highest with asphalt, the voltage values for asphalt were the highest ~ 1.413 Vrms -- while the two concrete types generated significantly lower voltages ~ 0.029 Vrms and 0.01 Vrms, respectively. Regular concrete was slightly higher than ECC as shown in Table 3. Based on the average values, the results indicated that the four treatments produced different average values. As composite concrete produced higher values than ECC, the magnitude of energy may be more related to strength and density than elasticity, especially in rigid material. The research team employed Analysis of Variance (ANOVA) because this tool effectively allows the simultaneous comparison of populations to determine if they are identical or significantly different. After meeting the assumptions for this test, the research team conducted a one-way ANOVA test.
5.2. ANOVA Test

Analysis of Variance (ANOVA), the most common type of test in experimental result analysis [21], was conducted to identify if there were significant differences between the four treatments using the three different roadway materials used for this project. The test was also conducted to strengthen the result observed with averaged data shown on Table 3. In this test, the observed variance represents the sum of squares that are partitioned into components because of different explanatory variables. The test determines which factors affect the experiment by comparing them with errors. ANOVA with F statistic provides information if the variance is statistically significant and p value provides if any of differences between the means are statistically significant. Assumptions for the ANOVA test, which are relatively simple, are presented as follows:

1. The populations corresponding to each treatment have equal variance.
2. The populations corresponding to each treatment have a normal distribution.
3. Observations for each significance level are randomly collected and independent.

Voltage values from these four treatments as shown Table 4. The null hypothesis (H0) and alternative hypothesis (H1) for these analyses are as follows:

\[ H_0: \mu_1 = \mu_2 = \ldots = \mu_n \quad H_1: \mu_1 \neq \mu_2 \neq \ldots \neq \mu_n \]  

where \( \mu_n \) is nth treatment or material coupled with PZ material for generating voltages.

Using the one-way ANOVA test, the null hypotheses were rejected at the 5% significance level, as the p value is 1.1102e16 (shown in Table 5). These results indicated that statistically there were no differences between voltages measurements taken by four different treatments. The p value corresponding to the F-statistic of one-way ANOVA is lower than 0.05, indicating that the one or more treatments are significantly different. The F-ratio value is 682.16615. The p value is < .00001. Therefore, the null hypothesis that voltages from four treatments are the same was rejected. Analysis results with significant p values lower than .05 indicated that, statistically, the means of the three populations are not all equal.

### Table 3. Average Values from Three Different Materials (Four Treatments)

| No                | Asphalt (Bottom 1 inch) | Asphalt (Bottom 2 inch) | Typical Concrete | ECC Concrete |
|------------------|------------------------|-------------------------|-----------------|-------------|
| **Average**      | 1.413                  | 0.922                   | 0.029           | 0.010       |

### Table 4. Descriptive statistics of four independent treatments

| Treatment | Asphalt Bottom 1 inch | Asphalt Bottom 2 inch | Plain Concrete | ECC | Total |
|-----------|-----------------------|-----------------------|----------------|-----|-------|
| Observations N | 142                  | 141                   | 64             | 48  | 395   |
| Sum \( x_i \) | 200.5830             | 129.9640              | 1.8867         | 0.4841 | 332.8998 |
| Mean \( \bar{x} \) | 1.4126               | 0.9217               | 0.0292         | 0.0101 | 0.8428 |
| Sum of squares \( \Sigma x_i^2 \) | 288.5804            | 157.9743             | 0.0546         | 0.0049 | 426.6142 |
| Sample variance \( S^2 \) | 0.0372               | 0.1299               | 0.0000         | 0.0000 | 0.3707 |
| Std Dev. \( s \) | 0.1929               | 0.3604               | 0.0004         | 0.0008 | 0.6088 |
| std. dev. of mean \( SE \) | 0.0162               | 0.0303               | 0.0001         | 0.0001 | 0.0506 |

### Table 5. One-way ANOVA of Four Independent Treatments

| Source   | Sum of squares SS | Degrees of freedom \( v \) | Mean square MS | F-statistic | P-value |
|----------|------------------|----------------------------|----------------|-------------|---------|
| Treatment | 122.6233         | 3                          | 40.8744        | 682.1661    | 1.1102e-16 |
| Error    | 23.4282          | 391                        | 0.0599         |             |         |
| Total    | 146.0515         | 394                        |               |             |         |

### 6. Conclusions

The main objective of this research was to determine, based on power output and durability, the most promising roadway substrate materials to be coupled with PZ materials for future highway applications. The research was accomplished by measuring generated energy with PZ materials under asphalt pavement and concrete pavement in the lab using the APA. To achieve this, multiple tests were conducted to evaluate the output performance of the PZ materials, durability of selected PZ materials, and voltage generation in a variety of scenarios using a loaded wheel test with an APA.

Statistical analyses, descriptive statistics and ANOVA test results indicated that the PZ system embedded in the ECC concrete was the lowest producer of power; the PZ system embedded in asphalt produced the highest electrical output. Flexible roadway materials (asphalt) can produce more energy than rigid materials such as composite concrete and ECC. As composite concrete produced higher values than ECC, the magnitude of energy may be more related to strength and density than elasticity, especially in rigid material. The research project revealed that deformation in asphalt is correlated to the magnitude of energy harvesting, however, deflection may not be that significant as deformation.

Further studies will be performed providing insight into the difference in magnitudes of voltages for asphalt, composite concrete and ECC. Since this research framework was successfully developed to provide objective research results, highway agencies or private industry can apply it to newly-developed and advanced piezoelectric technologies. Currently, the research team is developing a wafer box coupled with the pavement materials using a 3D printer with CAD design. If the wafer box is developed successfully, the APA machine will be used to test environmental stresses including moisture and freeze-thaw tests. In addition, further research can be performed to identify effects on generated energy from permanent deformation of asphalt concrete as a viscoelastic materials.

Results of this lab-scale research project will make several major contributions to the advancement of transportation performance and management, and highway sustainability. Outcomes can be expected to: (1) increase the self-supporting energy capability of highways, (2) increase the ability of highways to provide electricity to areas that are remote and far from main electric lines, and (3) improve the performance of the system to generate energy from both vertical and horizontal forces of vehicles.

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REFERENCES

[1]. Harnessing Pavement Power: Developing Renewable Energy Technology in the Public Right-of-Way. 2013, Federal Highway Administration. p. 2p.

[2]. Xiong, H., et al., Piezoelectric Energy Harvesting from Traffic Induced Deformation of Pavements. International Journal of Pavement Research and Technology, 2012. 5(5): p. pp 333-337.

[3]. Ali, S.F., M.I. Friswell, and S. Adhikari, Analysis of energy harvesters for highway bridges. Journal of Intelligent Material Systems and Structures, 2011. 22(16): p. 1929-1938.

[4]. Gkoumas, K., F. Petrini, and F. Bontempi. Energy harvesting for the life-cycle of structures and infrastructures: State of art, recent trends and future developments. in Life-Cycle and Sustainability of Civil Infrastructure Systems: Proceedings of the Third International Symposium on Life-Cycle Civil Engineering (ALCCE’12), Vienna, Austria, October 3-6, 2012. 2012. CRC Press.

[5]. Yu, L., et al. In-situ health monitoring on steel bridges with dual mode piezoelectric sensors. in Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2013, March 11, 2013 - March 14, 2013. 2013. San Diego, CA, United states: SPIE.

[6]. Yu, L., et al. Piezoelectric based sensing in wireless steel bridge health monitoring. in Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2009, March 9, 2009 - March 11, 2009. 2009. San Diego, CA, United states: SPIE.

[7]. Vijayaraghavan, K., A. Kossett, and R. Rajamani, Passive Roadside Reflectors and Communications Systems for Improvement of Radar Reliability. 2006. p. 54p.

[8]. Baldwin, J.D., et al., Energy Harvesting on Highway Bridges. 2011. p. 24p.

[9]. Wang, M., P.C. Chang, and R. Newcomb. Power scavenging from highway bridge vibration. in 1st International Conference on Structural Health Monitoring and Intelligent Infrastructure, SHMII-1’2003, November 13, 2003 - November 15, 2003. 2003. Tokyo, Japan: A.A. Balkema.

[10]. Symeoni, A., A REVIEW ON ENERGY HARVESTING FROM ROADS. 2013.

[11]. Huang, R.-B., et al., Technical approach and research prospect of piezoelectric energy harvest from highway. Zhongguo Gonglu Xuebao/China Journal of Highway and Transport, 2012. 25(6): p. 1-8.

[12]. Hill, D., Tong, N. , Assessment of Piezoelectric Materials for Roadway Energy Harvesting. 2013.

[13]. Sustainability, D.K.E., ASSESSMENT OF PIEZOELECTRIC MATERIALS FOR ROADWAY ENERGY HARVESTING. 2014, California Energy Commission.

[14]. Commission, C.E., Solicitation for Advance Development of Breakthrough and Piezoelectric-Based Systems 2015.

[15]. Sun, C.-H., et al. Designing piezoelectric harvesting unit from road vibration, in 4th International Conference on Manufacturing Science and Engineering, ICMSE 2013, March 30, 2013 - March 31, 2013. 2013. Dalian, China: Trans Tech Publications Ltd.

[16]. Zhao, H.D., J.M. Ling, and P.C. Fu. A review of harvesting green energy from road. in 8th International Conference on Road and Airfield Pavement Technology, ICPT 2013, July 14, 2013 - July 18, 2013. 2013. Taipei, Taiwan: Trans Tech Publications Ltd.

[17]. Seonghoon Kim, I.S., Junan Shen, Mohammed Ahad, and Zolly Tucker. Piezoelectric-Based Energy Harvesting Technology for Highway Sustainability. in the 95th Transportation Research Board Annual Meeting. 2016. Washington, D.C.: Transportation Research Board.

[18]. Seonghoon Kim, I.S., Junan Shen, Mohammed Ahad, and Zolly Tucker. Approved Workshops on SEIT 2016. 2016; Available from: http://cs-conferences.acadiau.ca/seit-16/#workshop_approved.

[19]. Seonghoon Kim, J.S., Mohammed Ahad, Piezoelectric-Based Energy Harvesting Technology for Roadway Sustainability. International Journal of Applied Science and Technology 2015. 5(1): p. 20-25.

[20]. NAPA. Asphalt Pavement Overview. 2014 [cited 2014 4/23/14]; Available from: http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=14&Itemid=107.

[21]. Frigon, N.L. and D. Mathews, Practical Guide to Experimental Design. Chapter 3: Statistical Test, ed. S. Distribution. 1997, New York, N.Y.: Wiley. 75-92.