Piezoelectric Energy Harvesting System Assessment for Highway Sustainability

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A piezoelectric method of energy harvesting has advantages over other alternative sources, such as solar panels and wind power. The first phase of this research project is to determine the economical piezoelectric roadway materials available in the U.S. The research project is to be accomplished by measuring generated energy with piezoelectric materials under asphalt pavement and concrete pavement measured in the lab so that its economy and feasibility can be determined prior to field experiments. In this research, asphalt pavement materials were tested with piezoelectric materials is the most popular flexible pavement material, which is used for 94 percent of surface of US highways (NAPA, 2014). Also, concrete pavement materials including typical concrete and ECC (Engineering Cementitious Concrete) were tested. The scope of the research project includes investigation of the energy harvesting method, a feasibility study, developing framework of the piezoelectric method, preparation of equipment and materials, conduction of lab experiments, and identifying potential future research. The amount of generating capacity will be recorded and compared with other energy harvesting methods to determine economic competitiveness. This research results indicates that voltages increase as increased HZ which represents frequency and piezo material with concrete can generates more than that with asphalt. That indicates rigid materials including concrete may generate more energy than flexible materials such as asphalt pavement. In addition, with ECC generates more voltages than typical concrete. Since this data collected is limited in number of data, further data collection will be required to discuss further about the reason of difference. Research results indicate that the levelized cost of energy (LCOE) is relatively high, but potential energy generation can be improved by several variables. Thus, there is an urgent need to conduct studies regarding this technology in laboratory conditions with available products in the U.S. The results of this research project will contribute to the possibility of highways' self-supporting energy capacity.

Key Words: Energy harvesting, Piezoeletric Materials, Highway, ECC, Asphalt

Introduction

The benefits of a roadway energy harvesting system are potentially great, given the lane-miles and high traffic volume in specific areas of state highways. There are several alternative energy generating methods available for state highways, including solar panels, piezoelectrics using pressure of vehicles, and wind power plants adjacent to highways. Of these options, using the compression roadway piezoelectrics has advantages over other alternative energy sources as follows (FHWA, 2013, Xiong et al., 2012):

- Provides consistent source of energy that is not affected by temperatures and environments
- No additional space required; does not require purchase of real estate
- Theft and damage proof because it is integrated with the infrastructure
- No other way to use the wasted energy generated from vehicle movements' force
- Low unit cost because of low installation fee for production

Using the pressure of vehicles caused by gravity, the method generates electric energy from the deformations in the paving materials (Ali et al., 2011). Although recent research projects have paid attention to this energy harvesting technology, only a few studies have been conducted on-site to determine its feasibility and economic competitiveness. No data are available for highway pavements (Huang et al., 2012, Chang-Il Kim and Jong-Hoo Paik, 2011). Therefore, it is necessary to develop a research framework that enables assessment of the technology of piezoelectric materials on state highways.

This technology can be used for a variety of purposes, including sensors (Gkoumas et al., 2012, Yu et al., 2013, Yu et al., 2009, Vijayaraghavan et al., 2006), roadway lighting and bridge bearing (Baldwin et al., 2011, Wang et al., 2003), structural health monitoring (Xiong et al., 2012, Yu et al., 2013, Ali et al., 2011), deicing (Symeoni, 2013), and pavement to traffic monitoring (Huang et al., 2012). A privately-owned company applied this technology to a 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 (Ali et al., 2011). According to a report developed by DMV KEMA under the California Energy Commission, a levelized cost of energy (LCOE) by Innowattech is $0.11/kWh with an averaged capital cost of $4000/kW (Hill, 2013). This indicates that piezoelectric-based energy harvesting technology may be more economical than solar panels. Figure 1 shows that the company published the system installation procedure.

Vibration-based roadway piezoelectric technology can be as competitive as wind, nuclear, and coal (Hill, 2013, Roundy et al., 2003, Jeon et al., 2005). However, Table 1 shows the wide variation in magnitudes of power generation that resulted from unknown parameters that may include design of prototypes, vibration or compression, speed, and vehicle weight (Office of Research, 2013, Hill, 2013). Despite many advantages with this energy harvesting method, real-world situations typically have inconsistent or varying vibration frequencies, and this requirement severely limits its practicality (Hill, 2013). No research projects in the U.S. have proven in the lab, in asphalt, and in the field that it is reliable, safe, and economically competitive for use in roadways. Only a few field data results are available for highway pavements. Therefore, it is necessary to develop a research framework that enables assessment of the technology of piezoelectric materials on state highways.

Figure 1. **Significant Power Density over Competing Technologies (Hill, 2013)**

Table 1. Wide Range of Power Generation Using Piezoelectric Materials (Hill, 2013)

Parameter	Genziko	ODOT	Innowattech	Berkeley and Virginia Tech
Power per km (single lane)	13-51 MW	486 kW	100-200 kW	0.0018-0.5 kW
Vehicles per hour (single lane)	600-2250	600	600	600

Several companies have been developing power generation using alternative methods. A report funded by the California Energy Commission indicated that depending on the method of generation with piezo material's shape, size, vibration form, etc., energy can vary significantly. (See Figure 2).

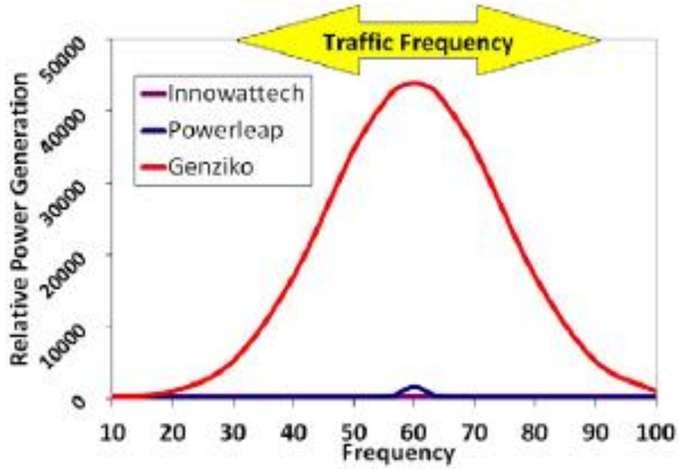

***Figure 2*. Significant Power Density over Competing Technologies (Hill, 2013)**

The first phase of this research project is to determine the economical piezoelectric roadway materials available in the U.S. The research project is to be accomplished by measuring generated energy with piezoelectric materials under asphalt pavement and concrete pavement will be measured in the lab so that its economy and feasibility can be determined prior to field experiments. In this research, asphalt pavement materials are tested with piezoelectric materials is the most popular flexible pavement material, which is used for 94 percent of surface of US highways (NAPA, 2014). Also, concrete pavement materials including typical concrete and ECC (Engineering Cementitious Concrete) were tested.

Method

A preliminary lab experiment was conducted to develop the framework of this research project and to test equipment and materials, including the asphalt analyzer ($40k), the electricity measurement device ($13k), and commercially available piezoelectric materials ($8k) (See Figure 3). Using equipment at Georgia Southern, voltages from two leading piezoelectric material companies were measured, and possible power and energy values were calculated. This experiment was conducted under the assumption of 600 vehicles per hour at 45mph. Loads on the asphalt mix from each vehicle were 50, 100, and 150 lbs (See Figure 4). Based on this preliminary research results indicate that loads, number of layer of piezo materials, and frequency are major factors of increasing voltages from piezoelectric materials. Pictures in Figures 5 and 6 show steps taken for measuring voltages under asphalt and concrete materials. The research team collected data from two different laboratory conditions shown in the following pictures.

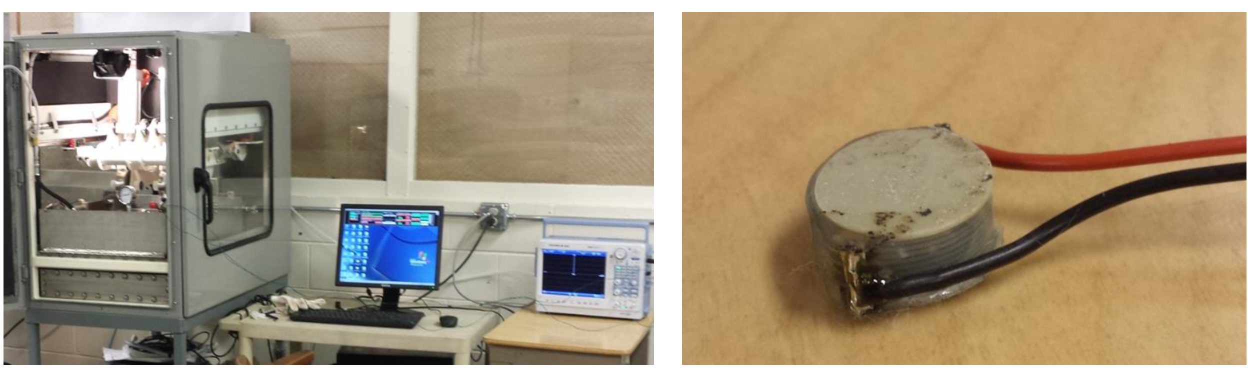

***Figure 3*. Equipment (Left) and Raw Piezo Materials (Right)**

Loads (lbs)	**Noliac**		**Kinectic Ceramic**	
	Voltage			
	Min	Max	Min	Max
50	-5	5	-10	5
100	-5	5	-20	10
200	-15	15	-40	20

Note: 60HZ

Figure 4. **Preliminary data (Roundy et al.)**

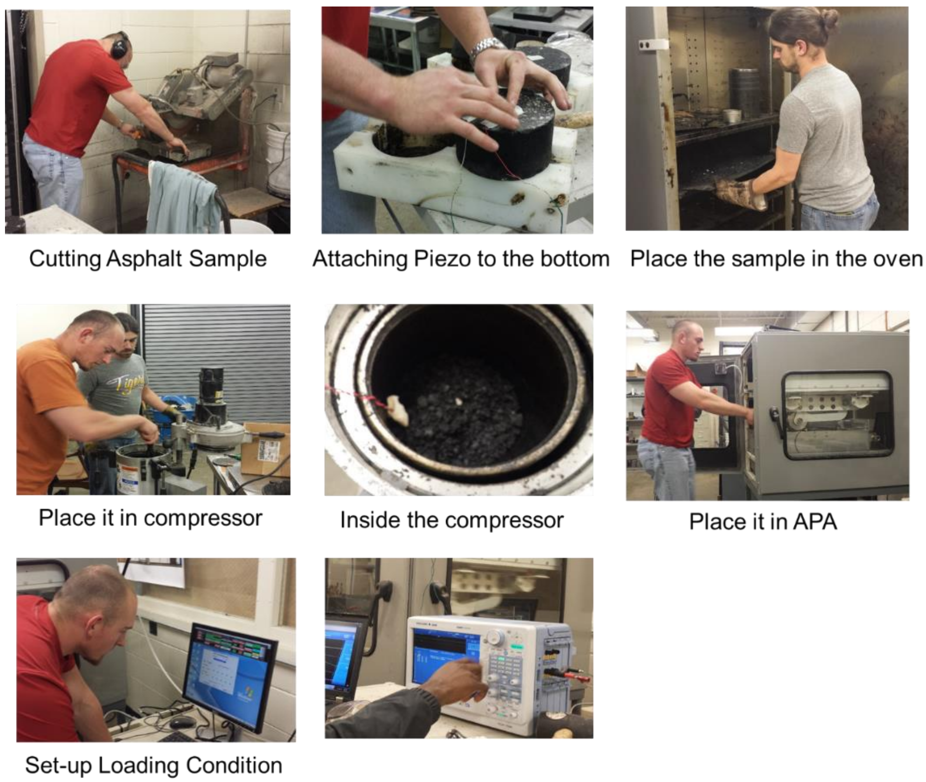

Figure 5. **Testing Procedure on Asphalt**

***Figure 6*. Testing Procedure on Concrete**

Data Collection

A loaded wheel test (LWT) in an Asphalt Pavement Analyzer should admirably perform the task of simulating real road conditions under pavement (See Figure 7). In this case study, we tested a piezoelectric product from PUI Audio with 100 lbs loading in different HZ values including 1, 10, 30, and 60 HZ. HZ values can be referred to be as frequency of force applied to samples. Contact area of load wheel is approximately 6 in2 and depth of piezo elements is 2 inches from the top. The size of the specimen is 6 inch diameter and 3 inches in thickness. As can be seen on Table 2, voltages are increased as HZs increase. Table 3 shows piezo material with concrete can generates more than that with asphalt. In addition, with ECC generates more voltages than typical concrete.

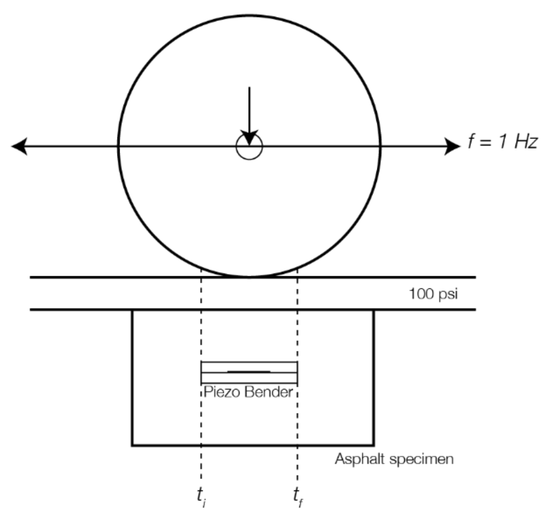

***Figure 7*. A Loaded Wheel Test**

Table 2. Voltages on loads and different products (Roundy et al.)

HZ	**1**	**10**	**30**	**60**
Load (lbs)	mV (p-p)			
100	10.77	23.03	43.02	116.58

Note: mV (p-p) refers to be a peak to peak mili voltage (mV = 10^{-3} voltage)

Table 3. Voltages on Frequency at 100 lbs

Materials	**Asphalt**		**Typical Concrete**		**ECC**	
Loads (lbs)	Min	Max	Min	Max	Min	Max
100	-0.060	0.060	-0.093	0.093	-0.298	0.298

Results

Comparison of voltages among samples from five companies in the US is shown in Table 4. This experiment was conducted under 60 HZ, equivalent value that 600 vehicles per hour at 45mph, the most typical road traffic condition. Loads on the asphalt mix from each vehicle were 50, 100, and 150 lbs, respectively. One with multilayers produces higher voltages (range from -32 to 66 V) than single layer. However, as shown in Table 4, peak to peak voltage values of PUI Audio are ranged only from -0.06 V to 0.06 V, which is considerably low voltages compared some companies, but the lowest unit price. And then, the power and energy were calculated.

Table 4. Voltages on loads and different products (Roundy et al.)

Company	**Noliac**		**Kinectic Ceramic (Single layer)**		**Kinectic Ceramic (Multi layer)**		**Piezo Institute**		**PUI Audio**	
Unit Price	**$20**		**$70**		**$300**		**$30**		**$3**	
Loads (lbs)	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
50	-5	5	-10	5						
100	-5	5	-20	10					-0.06	0.06
150	-15	15	-40	20	-32	66	-1	1		

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

More in-depth study needed to conduct to determine results of this research, especially reason of difference in magnitudes of voltages between concrete and ECC. If this research framework is successful, highway agencies or private sectors will apply any newly developed and advanced piezoelectric technology for practically implementing it. The system development, beyond the initial lab work, includes two future phases: 1) whether a prototype generator should be developed with selected piezoelectric materials and 2) field experiments to be performed on the US highway system.

The research team developed the research framework (Figures 8 and 9). Figure 8 shows the block diagram of piezoelectric-based sensor voltage measurement. A preamplifier is required for piezoelectric sensing electronic circuits. The main task of this preamplifier is to transform the high impedance of the sensor to the low impedance measuring devices. In this project, we will use a charge amplifier as a preamplifier. The major advantage of the charge amplifier comes from the fact that the circuit sensitivity, and therefore, the output voltage, is unaffected by the capacitance of the sensor and stray capacitances like the input cable capacitance. Figure 9 shows the preamplifier circuitry. The charge q(t) generated from the piezoelectric sensor due to compression/pressure is amplified by the charge amplifier, and the output voltage V(t) can be captured for measurement or stored for harvesting. The voltage and current output by the harvester need to be conditioned and converted to a form usable by the load circuits. There are several methods of conditioning this harvester output voltage. A full wave rectified circuit can be used to harvest the power.

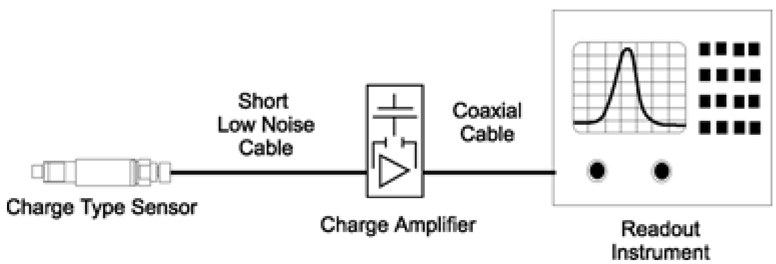

Figure 8: **Block Diagram for Measuring Generated Voltage from the Piezoelectric Devices**

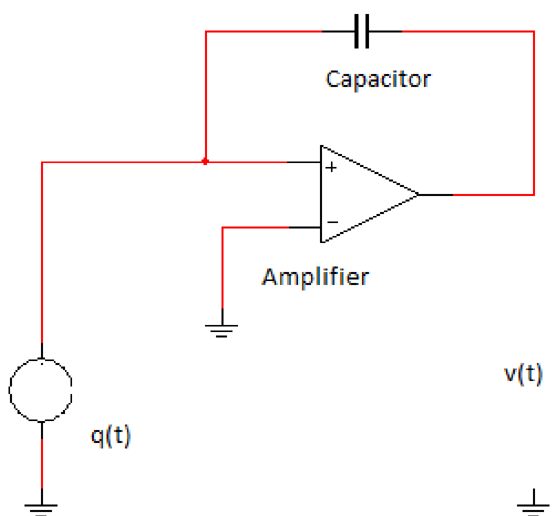

Figure 9: Preamplifier to Capture PZ Charge to Form an Output Voltage and Current

Research Questions: Throughout the experiments, the research team realized specific research questions for the proposed research to determine:

1. More data collection on the magnitude of power generation in asphalt vs. concrete.

2. Influencing factors in the magnitude of power, such as materials, depths, and surface conditions. (To determine significant factors, linear and multiple regression modeling will be used.)
3. Any new technologies that can be developed to promise efficiency and feasibility (Figure 10)

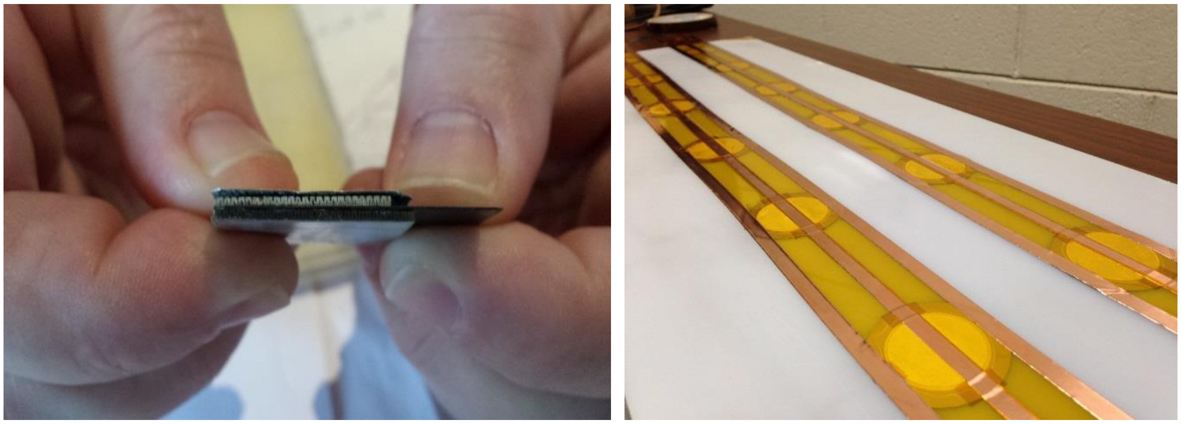

Figure 10. Serpentine Shape to Increase Vibration (Left) and Geosynthetic Reinforcement to Enhance Workability and Efficiency (Right)

4. Specific reasons why different voltage curves, magnitudes, and cycles occur as shown in Figure 11.

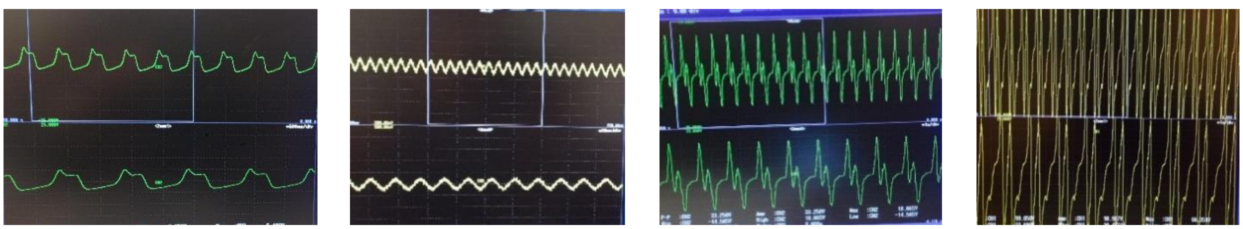

Figure 11. Shape of Output Curves Shown on the Oscilloscope

If further lab experiment data are successfully collected and analyzed, interested parties or users will be able to focus on developing a piezoelectric-based energy harvesting system. The system development, beyond the initial lab work, includes two future phases: 1) determination of whether a prototype generator should be developed with selected piezoelectric materials, and 2) field experiments to be performed on Georgia highways. Completion of these three phased research projects will make several major contributions to the advancement of transportation performance and management, and highway sustainability. Therefore, the research team will propose significant project outcomes that are 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 from main electricity lines, and (3) improve the performance of the system to generate energy from both vertical and horizontal forces of vehicles.

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