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Modeling a new energy harvesting pavement system with experimental verification

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HIGHLIGHTS

- A new energy harvesting pavement system is built using conductive asphalt mixtures and piezoelectric materials.
- A three-degree-of-freedom electromechanical model is used to analyze and optimize the new system.
- The feasibility of this new system is verified by laboratory tests.
- The maximum electrical power from the new system can reach to 300 mW.

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ABSTRACT

A novel design of an energy harvesting pavement system (EHPS) is introduced in this paper. The basic concept behind this design is to transform asphalt layers into a piezoelectric energy harvester to collect dissipated vehicle kinetic energy in a large-scale system. This EHPS design consists of two conductive asphalt layers and one piezoelectric material layer. To verify the feasibility of the design, this ongoing study theoretically analyzed the EHPS via a three-degree-of-freedom electromechanical model and practically tested a prototype in the laboratory. As a result, voltage outputs measured in the laboratory from the prototype design matched those estimated from the electromechanical model. Through testing the effects of several components in the EHPS on electricity generation, this study confirms that using more flexible conductive asphalt mixtures and arranging more piezoelectric elements with a higher piezoelectric stress constant can increase electrical outputs from the EHPS. Regarding specific external vibration conditions, a high frequency of external vibration can lead to a dramatic effect of each piezoelectric element's capacitance on increasing electrical outputs, but also can reduce the benefit from adding more piezoelectric elements to produce higher electrical outputs. After optimizing this EHPS prototype by adding more piezoelectric elements with higher piezoelectric stress constant and improving the flexibility of conductive asphalt mixtures, the maximum electric power from the proposed EHPS can be increased from approximately 1.2 mW to 300 mW under a high frequency (30 Hz) external vibration. The levelized cost of electricity of this EHPS can be $19.15/kWh on a high-volume roadway within a 15-year service life.

1. Introduction

One potentially important component for energy harvesting in the transportation sector is pavement. On the six million-km roadways in the U.S., a huge amount of vehicle kinetic energy is wasted every day due to rolling resistance and vehicle vibration [1–3]. Given that such wasted energy is collectible and convertible into electrical energy through different techniques [4,5], an advanced pavement system may be turned into a new "energy farm" to reduce society's need for coal consumption for electricity production.

Photovoltaic (PV) panels, pipe systems, thermoelectrical generators, piezoelectric transducers, and pyroelectric materials recently have been studied and developed for collecting wasted energies from pavement [4]. Most of these, however, either are impractical or have limited efficiency. For example, the performance of PV panels paved on the surface of roadways can be challenged by the abrasion and contamination on its transparent layer [6] and also can be highly dependent on sunlight [7]; the pipe system that stores thermal energy can significantly affect pavement internal structures [8–10]; the efficiency of thermoelectrical generator based on the Seebeck effect is relatively low, especially under the constraint of insufficient temperature difference between asphalt layers in a traditional asphalt pavement [11]; and

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the low electrical output from pyroelectric materials inside pavement layers remains an issue [12]. Among all energy harvesting techniques, the application of piezoelectric transducers on producing electricity from pavement seems promising and has been developed in the last 10 years.

In 2010, a study was conducted at the University of California Pavement Research Center (UCPRC) to analyze the electric power generated from a cymbal transducer embedded in pavement using the finite element method (FEM). That study estimated that a 32 mm diameter cymbal transducer can produce 1.2 mW electrical energy under a 20 Hz vehicle load [13].

In 2012, Yao et al. modified a trapezoidal bridge transducer to an arc bridge transducer as an energy harvester in the pavement. Based on FEM, they found that the latter generated 232 V electric voltage under a pressure of 0.4 MPa, which had 78 V more from a trapezoidal bridge transducer [14]. Li verified this finding but stated that an arc bridge piezoelectric transducer may have a shorter service life due to higher stress [15]. In the same year, Kim et al. installed piezoelectric cantilevers as speed bumps above ground and compared them with the piezoelectric cantilevers embedded underground in the field. They captured a significant drop in electrical output from the piezoelectric cantilevers after moving them from underground to above ground (7.6 mW versus 63.9 mW) and also observed that if vehicle speed exceeded 20 km/h, more piezoelectric cantilevers were able to generate more electric power [16].

In 2013, several studies on using piezoelectric transducers to produce electricity from pavement were performed. Sun et al. modified the size of a piezoelectric transducer to 280 × 280 × 20 mm and suggested embedding it in pavement at a depth of 40 mm. Based on FEM, they estimated that the electrical output from their design could reach to 1.8 mW [17]. Daniel et al. simulated finite element models with different external factors (traffic load and electric load) and internal factors (geometry and material) and evaluated that 1.2 mW electric power under a dynamic load with 50 N amplitude and 2 Hz frequency can be produced from their metal-protected cymbal design [18].

In the same year, Xiang et al. developed a pavement dynamic deformation model using Fourier transform and Cauchy's residue theorem to better analyze the effect of pavement structure on the electric power output from a piezoelectric transducer inside pavement. Their results demonstrated that vehicle speed and pavement damping property can influence the electric power output from the piezoelectric transducer [19]. In 2015, Zhang et al. updated the system model by replacing a beam model with a Kirchhoff plate model for pavement. They found that the wheel load can only trigger the transducers within a distance of 4 m, and the instantaneous electric power from each transducer can reach 47.3 mW under a four-wheel load [20].

In 2016, Roshani et al. built an energy harvester using piezoelectric disks sandwiched by two copper plates. They set two polystyrene sheets to fix the piezoelectric disks and glued them onto the copper plates using electrically-conductive epoxy containing silver adhesive. Based on a power level of around 10 mW from their energy harvester, their study confirmed the feasibility of using such energy harvester to activate multiple sensors and power LED traffic lights in a roadway infrastructure system [21].

In 2017, regarding the brittle property of piezoelectric ceramic materials, Jung et al. replaced lead zirconate titanate (PZT) ceramic with polyvinylidene fluoride (PVDF) film to develop a flexible piezoelectric polymer-based device for harvesting energy in a roadway [21]. An instantaneous power output of up to 200 mW was generated from their energy harvester module under a traffic load of 2450 N at a speed of 8 km/h [22].

For field tests, Virginia Tech demonstrated six prefabricated energy harvesters in the pavement at the I-81 Troutville weigh station [7,23]. To prevent potential damage to the brittle piezoelectric materials, the stress on piezoelectric disks was analyzed first by FEM simulation and controlled by adjusting the shape and spacing of the disks. Multiple rectifiers with diodes were connected with energy harvesters to avoid neutralization of the opposite voltages generated from the piezoelectric disks. To ensure sufficient damage resistance and electrical outputs of the piezoelectric disks under heavy traffic loads in the field, laboratory tests were conducted prior to the field installation [7,23]. They collected around 116 mW instant power output with 3.1 mW average power output from each energy harvester. However, the results from their field tests at the Troutville weigh station also showed significant degradation of power generation from the energy harvesters over one year after the installation [7,23].

As can be seen, the main concepts in the previous studies were limited by embedding prefabricated piezoelectric transducers into pavement to generate electric power, which can power only sensors and some low-power infrastructure utilities. To maintain a traditional layer structure of asphalt pavement while exploring efficient ways of energy harvesting from pavement, this study introduces a new system into asphalt pavement to collect kinetic energy from traffic. Compared to the piezoelectric energy harvesting methods designed in previous studies, which embed pre-fabricated piezoelectric harvesters into pavement, the approach proposed in this study may transform an entire pavement layer into a piezoelectric energy harvester to collect more dissipated kinetic energy on a larger scale. A prototype of a new energy harvesting pavement system (EHPS) was first designed in this study. A multi-degree-of-freedom electromechanical model (MDOF-EM) was then built for the EHPS. To verify the feasibility of the EHPS design and the accuracy of the MDOF-EM, a series of laboratory tests were conducted. After ensuring the accuracy of the MDOF-EM, the effect of each component of the EHPS on the electrical output is discussed based on the MDOF-EM to optimize the proposed EHPS.

2. Design of an EHPS in asphalt pavement

The concept for developing an EHPS is basically trying to "transform pavement layers into a massive piezoelectric transducer," as shown in Fig. 1. This new system consists of two conductive asphalt layers and one piezoelectric material layer. The two conductive asphalt layers are made of conductive asphalt mixtures with conductive additives, such as steel wool, graphite, and carbon black. The piezoelectric layer integrates piezoelectric materials with asphalt mixtures and other insulation materials.

When the piezoelectric layer is vibrated, each piezoelectric cell is polarized because of the deviations of positive and negative charge centers (piezoelectric effect). Then, the piezoelectric layer will charge the upper and lower conductive layers. Since the piezoelectric layer itself is insulated, electric charges will be stored in the upper and lower layers without leakage. The EHPS assembles conductive asphalt mixtures, regular asphalt mixtures, and piezoelectric materials into one large-scale energy harvester for the first time. Three basic advantages of this EHPS design are as follows:

- The cover area of the EHPS can be adjusted to a large extent to collect more dissipated kinetic energy than traditional piezoelectric transducers.
- Embedding conductive asphalt layers instead of inserting metal panels into the pavement structure may have less impact on the original pavement performance.
- Designs of the piezoelectric layer and the conductive asphalt layer can be customized by choosing different sizes (from large to powder size) and shapes (e.g., pile, ball, and roof) of piezoelectric elements and selecting proper aggregates and conductive fillers (e.g., steel fiber, graphite, and carbon), respectively.

The most important rule behind this EHPS design is that the upper and bottom conductive asphalt layers should never be connected; if connected, the electric power produced from this EHPS will be consumed under a short circuit condition. Since the piezoelectric elements