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Fabrication and performance of a power generation device based on stacked piezoelectric energy-harvesting units for pavements

Chaohui Wang[a,*], Shuai Wang[a], Qiang Joshua Li[b], Xingju Wang[c], Zhiwei Gao[a], Lu Zhang[d]

[a] School of Highway, Chang'an University, Xi'an 710064, China
[b] School of Civil and Environmental Engineering, Oklahoma State University, Stillwater, OK 74074, USA
[c] School of Traffic and Transportation, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
[d] Hebei Branch of China State Construction Engineering Corporation, Shijiazhuang 050011, China

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ABSTRACT

Although piezoelectric power generation for pavements is technically feasible, harvesting energy in a stable and efficient manner still presents several challenges. This paper designs and assesses stacked piezoelectric energy-harvesting power generation devices for pavements, in which energy output and road coupling are considered. Following corresponding technical specifications, the dimensions of the proposed power generation device are determined, and the unit is assembled for subsequent testing in terms of its electrical energy outputs. The energy outputs are analyzed in various series and parallel configurations of the units, different loads, and frequency conditions. Results indicate that power generation device with the dimension of 100 mm × 100 mm achieves optimal power generation outputs. The electrical output is positively correlated to the number of parallel piezoelectric energy-harvesting units, the magnitude of load, and the frequency of traffic action. The maximum output at the 0.2 MPa load magnitude and 10 Hz load frequency is 0.88 mW, and the corresponding optimum load is 20 kΩ. The maximum output at the 0.7 MPa and 15 Hz load level can reach up to 11.67 mW, and the corresponding optimum load is 10 kΩ. Subsequently, Mechanical Testing and Simulation (MTS) is performed with 40,000 load cycles, and the overall deformation of the power generation device is minimal and the electrical outputs of the piezoelectric energy-harvesting units remain stable. Finally, future research plan is discussed.

1. Introduction

Environmental micro-energy collection and utilization has gradually become an important research direction in various industries due to environmental pollution, energy shortage, and other issues. Existing piezoelectric energy harvesting techniques could convert mechanical vibration energy into electrical energy through the piezoelectric effect of piezoelectric materials [1–6]. If such techniques could be applied to road pavement engineering to develop piezoelectric power pavements, then the concept of green transition from the abundant mechanical vibration of roads to electrical energy can be realized. At present, the research on piezoelectric power technologies for pavements have proved that piezoelectric power pavements are feasible in technical aspects. The two technical approaches are the technology of power pavements based on the integration of piezoelectric materials and pavement materials and the technology of power pavements based on embedded piezoelectric energy-harvesting units [7].

The technology of power pavements based on the integration of piezoelectric materials and pavement materials involves the combination of piezoelectric and pavement materials and the preparation of piezoelectric composite materials for pavements through a certain process used directly in pavement paving. However, limited by material properties and restrictions of the preparation process, the studies about piezoelectric composite materials only produced a weak electro-mechanical response. Tan et al. [8] prepared 0–3 piezoelectric ceramic/asphalt composite piezoelectric material by hot embossing and achieved a maximum output voltage of 7.2 V under dynamic load. Wang et al. [9] prepared two forms of piezoelectric asphalt concrete with d_{31} and d_{33} by using tourmaline, piezoelectric ceramic, and graphite. The output voltage reached up to 2.4 V under the combined treatment of three measures, namely, insulation treatment, piezoelectric material fibrosis, and polarization treatment. Many problems arise in the preparation of high-efficiency piezoelectric composites for pavements. For instance, the technical difficulties and interference factors involved are numerous, and the energy output effect of piezoelectric composites is poor. Meanwhile, road performance is difficult to

* Corresponding author.
E-mail address: wchh0205@chd.edu.cn (C. Wang).

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ensure. Therefore, studies should explore the research and development of piezoelectric materials, the method of polarization and optimization of the preparation process, and the improvements of road performance to improve the comprehensive application performance of road piezoelectric composites.

In power pavements based on embedded piezoelectric energy-harvesting units, the power pavement is embedded with piezoelectric energy-harvesting units for energy conversion. Compared with the technology of power pavements based on the integration of piezoelectric materials and pavement materials, power pavements embedded with piezoelectric energy-harvesting units exhibit high energy output level, strong controllability, and relatively simple implementation. Hence, the latter type is likely to realize pavement piezoelectric power generation in the future. At present, many countries have carried out relevant research. Zhao and Najini et al. [10,11] used finite element software to compare the energy output efficiency of multi-layer cantilevers and cymbals in the road environment and concluded that the energy output of a multi-layer transducer is relatively superior. Xiang et al. [12] studied the theoretical parameters of piezoelectric energy-harvesting units embedded in pavement and found that driving speed, basic conditions, and system damping exert a significant effect on the output voltage and output power of piezoelectric energy-harvesting units. Kim et al. [13] found that load case, loading frequency, and layers of energy-harvesting units are the key points to increase output voltage. Moure et al. [14] optimized the structure parameters of cymbal harvesters through a laboratory test and found that a single cymbal harvester can collect up to 16 μW power under a single driving load. The technology of power pavements based on embedded piezoelectric energy-harvesting units is clearly still in the exploratory stage. Although the technology has prospective application in energy acquisition, problems such as the imperfect optimization of the matching of piezoelectric energy-harvesting units and road traffic environment and the non-ideal energy output require immediate solutions.

Given the limited energy output of a single energy-harvesting unit, a substantial number of piezoelectric elements must be paved in a pavement structure in a specific array for the pavement to achieve a substantial piezoelectric energy output. If piezoelectric energy-harvesting units were buried one by one, construction operations will become complex, power generation performance will weaken, and structural damage problems will arise. Therefore, the development of a power generation device that is based on integrated piezoelectric energy-harvesting units will serve as the mainstream technology for the future realization of piezoelectric power pavements. The Innowattech Company of Israel [15,16] pioneered the application of piezoelectric technology in power pavement systems and implanted a large number of piezoelectric crystals in ordinary asphalt pavements; for 1 km of road, about 100–200 kW·h of electricity can be produced, but so far, this application has not been widely promoted. The University of Texas in the United States [17] developed a power generation device comprising three layers of PZT prism in a series connection. The output power was measured to be 3.5 mW under a 10 Hz simulated driving load. Jiang [18,19] combined three stacked piezoelectric energy-harvesting units and built a simple power generation device for analog testing; the results showed that the maximum output power is up to 85 mW with the matching load size of 350 kΩ. Roshani [20] carried out a uniaxial compression test on an assembled power generation device with piezoelectric energy-harvesting units clamped by two pairs of copper; the results indicated that the number and arrangement of piezoelectric energy-harvesting units can cause changes in output power. Wang [21,22] investigated the ways to achieve piezoelectric power pavements and designed the basic structure of a piezoelectric power generation device; this work provides a reference for the research and application of piezoelectric power pavements. Nevertheless, many problems still need to be addressed in the development of integrated power generation devices. For example, the optimization of the matching of road traffic environment is not perfect, and the energy output is not ideal. Moreover, most studies conducted preliminary explorations with software simulations or simple indoor tests on plants. Hence, substantive research into integrated power generation devices for improving energy output is still limited.

In summary, many countries have studied different types of piezoelectric power pavement technologies from different levels and different angles. The mainstream ideas are biased toward integrated power generation devices based on piezoelectric energy-harvesting units. However, the design and implementation methods of the devices disclosed in existing studies are few, and the research and development of high-efficiency power generation devices for pavements based on piezoelectric energy-harvesting units is still in the initial stage.

To realize the application of piezoelectric power generation pavements, we design a power generation device for pavements that integrates energy output and road coupling. The structure and size of the power generation device are optimized based on traffic load characteristics. The complete production and assembly process are established. The energy output of the piezoelectric power generation device is studied comprehensively by means of a test platform. Then, the energy output status of different power generation devices is analyzed in different series and parallel configurations, different loads, and different frequency conditions. Finally, the working durability of the proposed power generation device is evaluated.

2. Design of piezoelectric power generation device for pavements

A piezoelectric power generation device is essentially a carrier device integrated with piezoelectric harvesting units. the energy output of the device is directly affected by the power generation performance of the piezoelectric energy-harvesting units, and the device must be laid in the pavement structure to create a piezoelectric effect under driving load rolling. Therefore, based on power generation theory of energy-harvesting units, the structure of the proposed device is designed based on electro-mechanical conversion principles of the energy-harvesting units and the structural characteristics of roads. The size of proposed device is optimized for driving load characteristics on pavements.

2.1. Power generation theory of energy-harvesting units

Since piezoelectric energy-harvesting units are consisted of energy conversion components of power generation devices, the type of piezoelectric material has a significant impact on energy conversion efficiency. Piezoelectric Ceramic Transducer (PZT) is the most widely used material for energy-harvesting units, and its power - electric conversion modes are mainly d_{31} (the direction of electric field is perpendicular to the direction of axial stress) and d_{33} (the direction of the electric field and the direction of the stress are the same). Cook-Chennault et al. [4] found that the piezoelectric coefficient d_{33} of PZT is much larger than d_{31}, indicating that d_{33} mode has higher energy conversion efficiency. The third type of piezoelectric equations is used to analyze the power generation performance of PZT. The piezoelectric equation with d_{33} mode is shown below [23].

$$S_3(t) = s_{33}^D T_3(t) + g^t D_3(t) \quad (1)$$

$$E_3(t) = -g_{33} T_3(t) + \beta_{33}^T D_3(t) \quad (2)$$

where S is strain tensor, T is stress tensor, D is electric displacement tensor, E is electric strength tensor, s^D is open elastic compliance constant matrix, β^T is free dielectric isolation rate matrix, g is voltage constant matrix, g^t is transposed matrix of g. If the PZT is subjected to vertical load ($F = F_{\max}\sin(\omega t)$), then D_3, T_3, E_3, S_3 and F are sinusoidal functions of time t and have the same frequency.

Stacked piezoelectric energy-harvesting unit is one of the d_{33} mode piezoelectric structures, which can effectively improve the voltage output, and also enhance the energy conversion efficiency under low frequency state [24]. Therefore, stacked piezoelectric energy-