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Review Article

The State of the Art: Application of Green Technology in Sustainable Pavement

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A wide range of literature on predominant green technologies for sustainable pavements is summarized in this paper. It covers two major aspects: energy harvesting technologies and permeable pavement systems. Fundamental mechanics of energy harvesting techniques and possible designs of energy harvesters are described, with the evaluation of energy conversion efficiency, and advantages and disadvantages. In addition, the designs of permeable pavement systems are discussed, along with their advantages and disadvantages. The latest technical innovations are highlighted. It is found that green technologies are promising for developing more sustainable pavements. Application issues are also pointed out, including construction challenges, durability, and life-cycle cost-benefit assessment. Future research directions are suggested to address practical challenges, such as efficient design, construction challenge, timely maintenance, and life-cycle performance assessment.

1. Introduction

With the rapid urbanization, there are increasing movements of human beings and goods with transportation infrastructures. Pavements, for example, have been constructed over billions of miles long worldwide, with more than 4 million miles in the United States (Figure 1(a)). In the meantime, there is an increase in energy consumption, leading to environmental pollution and global warming. In 2016, the annual energy consumption worldwide is over 13,000 Mtoe [1], among which the U.S. alone consumed over 2,456 Mtoe [2]. Figure 1(b) shows the annual energy consumption in the U.S. from 1950 to 2015, demonstrating an increasing trend of energy consumption by different infrastructure sectors. On the contrary, Figure 1(c) presents a general increasing trend of SO_2 emission worldwide from 1850 to 2010. Consequently, a sustainability concern arises. Given the limited supply of traditional energy such as coal, petroleum, and natural gas, how can we satisfy the future human needs, consume energy efficiently, and also preserve the surrounding environment?

In this respect, there have been many studies working on the development of green technologies in order to implement the sustainability concept in pavements. As a part of the global effort, implementations of sustainable pavements have been conducted on developing efficient technology to harvest renewable energy. Typical sources of renewable energies are solar radiations, geothermal heat, and vibrations due to hydro, wind, wave, and mechanical load [6]. Pavements are continuously exposed to three of them: solar radiation, geothermal heat, and traffic-induced load, and all of the three energy sources provide a good opportunity to harvest renewable energy from pavements. Traffic-induced

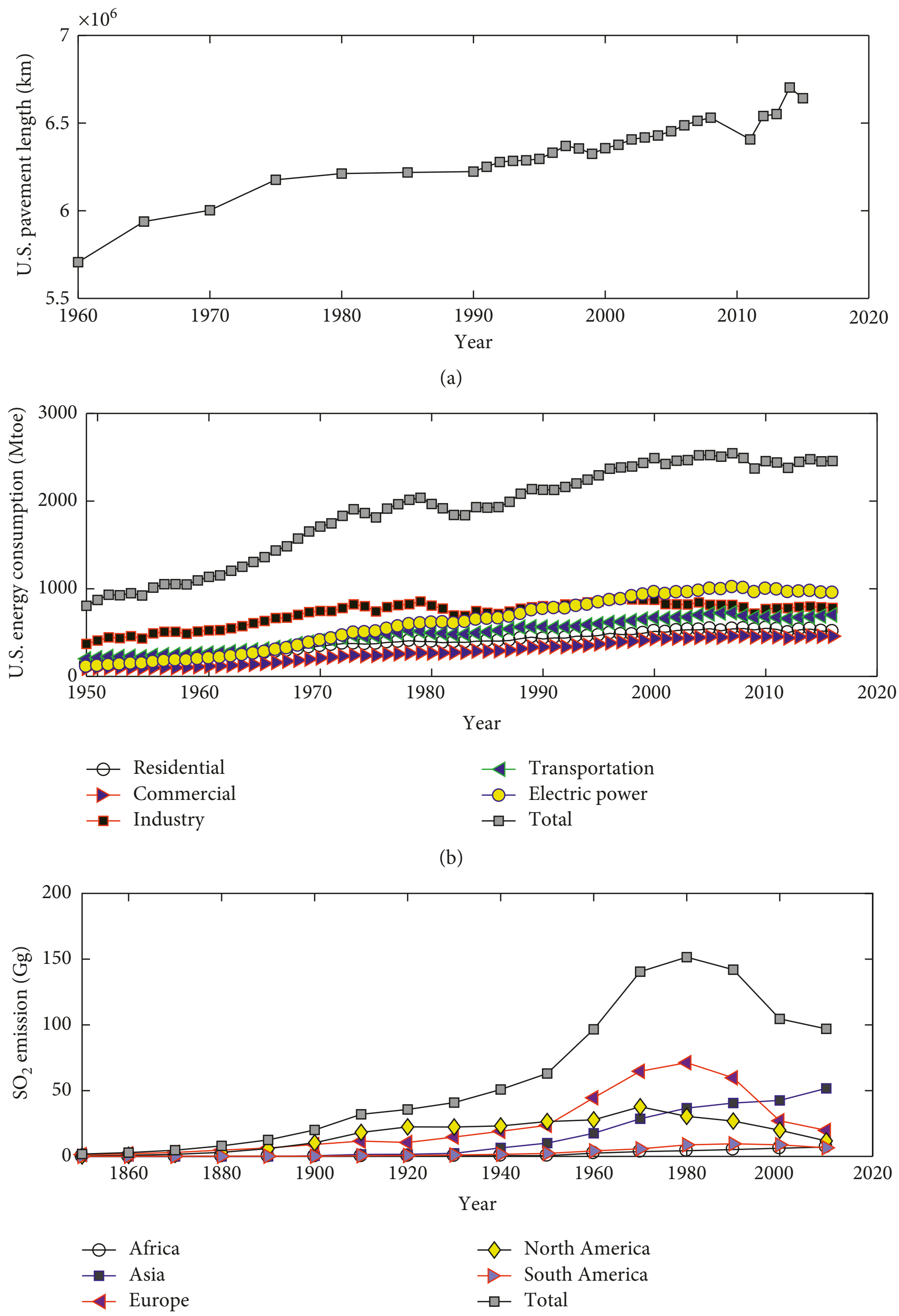


Figure 1: Increasing trends for pavement (a), annual energy consumption (b), and environmental pollution (c) (based on data from [2–5]).

vibrations on pavements can be harvested by piezoelectric energy harvesters. Solar radiations and resulting thermal gradients in pavement layers, as well as geothermal heat, can be transformed into useful energies through solar energy harvesting, thermoelectric energy harvesting, geothermal energy harvesting, and composite energy harvesting.

On the contrary, more than 90% of urban roads are covered with impervious surfaces, normally with a well-compacted (sub-) base layer covered with asphalt/concrete surface layers. The impervious pavement systems lead to the infiltration reduction and enlargement of peak flow, rendering urban flash floods and reduced water to recharge and reuse. Because of all these, impervious pavements have changed the city natural ecology and hydrological characteristics significantly [7]. In rainy days, accumulated water on the wet pavement surface is a major cause of traffic accidents, leading to significant socioeconomic losses. Comparing with the plant-soil system, the impermeable pavement system has lower specific heat capacity and higher solar absorptivity, which results in a high-temperature urban

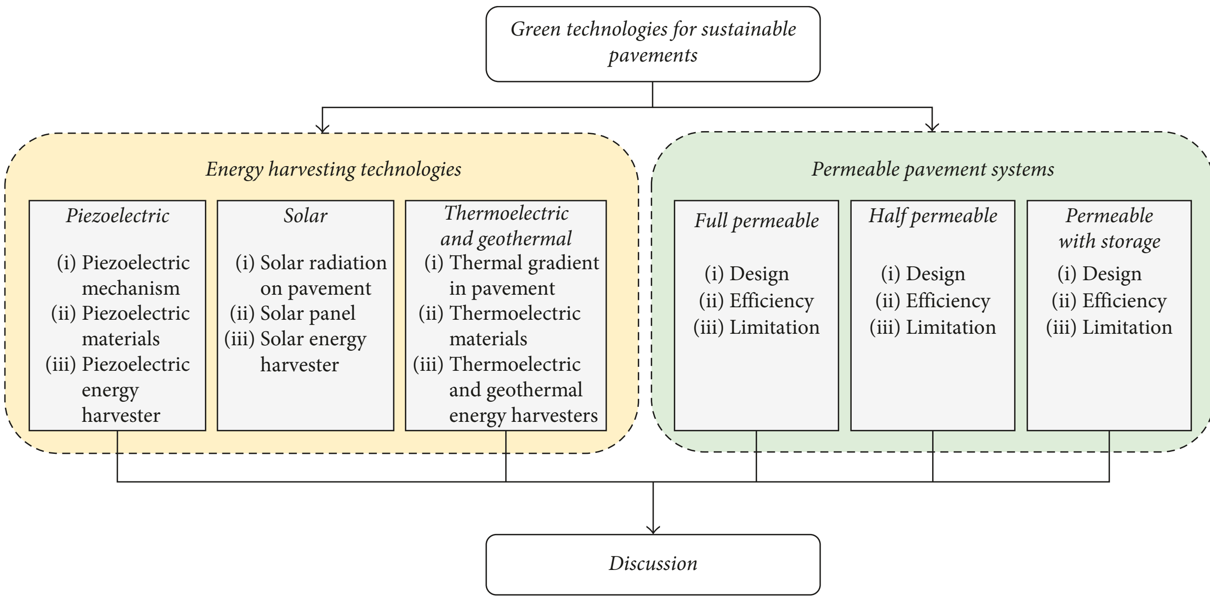


Figure 2: Outline of this study.

surrounded by the low-temperature suburb, the so-called urban heat island (UHI) effect [8]. To address the wet pavement problem and UHI, countermeasure strategies have been developed around the world. One of the environmental-friendly countermeasures is the permeable pavement system, which is to make urban surfaces more water-permeable and environmental-friendly. Australia has adopted the term "water sensitive urban design" (WSUD) to manage the water balance and maintain the water quality since 1990. In the United States, the strategies of best management practice (BMP) and low-impact development (LID) have been developed for the storm water runoff management and sustainable urban construction. Sustainable drainage systems (SuDS) in the United Kingdom consist of technologies to drain storm water/surface water in a manner, which is more sustainable [9].

In the area of green technologies for sustainable pavements, numerous studies have been conducted to critically review the emerging technologies and designs with different focuses. Dawson et al. described the advantages and limitations of energy harvesting techniques for pavements, focusing on the designs and construction issues in the collection, storage, and usage of energy [10]. Duarte and Ferreira reviewed the energy harvesting technologies for pavement applications, with general discussions on technologies to harvest solar and vehicle-induced energies [6]. Wang et al. comprehensively summarized working principles and application methods of energy harvesting techniques in roadways and bridges, with discussions on the emerging research trends and challenges [11]. However, none of them provided any descriptions about possible methods to reduce environmental impacts by using the same geomaterials with alternative pavement designs, such as permeable pavements. Conversely, Scholz and Grabowiecki discussed the advantages and disadvantages of different permeable pavement systems, without any description of making use of excessive energy from pavements [7]. Shi and Lai quantitatively summarized the number and specific research topic of green and low carbon technology in different countries from 1994 to 2010, without presenting detailed technical designs or addressing limitations for any green technology [12].

This paper complements that work with a critical review about previous efforts of green technology developments for the applications to road pavements, in terms of both energy harvesting technologies and permeable pavement systems. The first major contribution of this paper is that green technologies are comprehensively reviewed based on over 100 recent publications, including articles, reports, and book chapters. The second one is that the design of each green technology is reviewed, covering material types, energy conversion efficiencies, advantages and limitations, as well as implementation challenges. It also points out the great benefit of the integrated design by implementing both energy harvesting and permeable pavement in the same pavement structure. This paper serves as a useful starting point to new researchers in this field, and it also facilitates practitioners to choose the most appropriate technology for their local pavements.

The rest of this paper is organized as follows, as shown in Figure 2. First, different energy harvesting technologies for pavements are presented, in the aspects of materials, fundamental mechanics, energy efficiency, and advantages and limitations. After that, permeable pavement systems are presented, with discussions of designs, efficiencies, limitations, and the state of practice. Major findings and future research recommendations are presented at the end of this paper.

2. Energy Harvesting Technology in Pavement

Figure 3 depicts a representative power density of three green technologies: piezoelectric, solar, and geothermal.

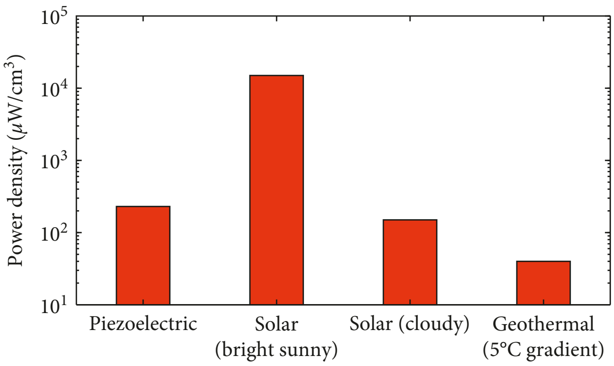


Figure 3: Power density of different green technologies (based on [13, 14]).

Energy collected from pavements in the form of electricity can either be carried away for powering electric devices of signage and traffic lights, or deicing in cold weather, and monitoring pavement features such as temperature, deflection, and traffic.

2.1. Piezoelectric Energy Harvesting Technology

2.1.1. Piezoelectric Materials. Piezoelectricity was discovered by Jacques and Pierrer Curie in 1880 [15]. The piezoelectric effect refers to a reversible process of using piezoelectric materials to generate electrical energy in response to applied mechanical stress. The direct piezoelectric effect represents the generation of electric charge with piezoelectric materials from an applied mechanical loading, whereas the reverse piezoelectric effect refers to the generation of mechanical strain resulting from an applied electrical force. The direct piezoelectric effect is utilized to directly harvest energy from pavements with piezoelectric materials, and the reverse piezoelectric effect is useful to detect very low-frequency vibrations [16], which will be discussed later.

As shown in Table 1, prevalent piezoelectric materials include inorganic piezoelectric materials, organic piezoelectric materials, and composite piezoelectric materials. Inorganic piezoelectric materials applied in pavements include piezoelectric crystalline and piezoelectric ceramics. Piezoelectric ceramics are usually applied as sensors for pavement monitoring. Due to the fragile nature, piezoelectric ceramic materials are less resistant to the vibration loading at high frequency [17]; the advantages of piezoelectric ceramics are greater physical properties and high electromechanical conversion efficiency. For example, PZT (lead zirconate titanate) is one of the most popular piezoelectric ceramics. Its electromechanical coupling factor is nearly twice as high as that of barium titanate ceramics, and its mechanical properties and temperature stability are significantly higher than that of barium titanate ceramics [18]. By contrast, piezoelectric crystalline materials are usually obtained from necessary treatments of raw polycrystalline materials through molding, high-temperature sintering, and fine grain random harvesting [18, 19].

Organic piezoelectric materials are also known as the piezoelectric polymers. In 1969, it was found that PVDF (polyvinylidene fluoride) had strong piezoelectric properties after uniaxial stretching and polarizing at high temperature with strong electric field. Piezoelectric polymer materials have the characteristics of high elasticity conversion efficiency, low density, and low impedance. The materials are usually soft and therefore easy to be made as different sizes, which can adapt well to the high-frequency vibration environment [23]. PVDF has very stable chemical properties with high toughness. Therefore, it is more resistant to fatigue damage compared with piezoelectric ceramics.

Combining the advantages of both inorganic and organic piezoelectric materials, composite piezoelectric materials are composite materials that include piezoelectric ceramics, crystalline, and polymers. Compared with the monophasic piezoelectric materials, composite piezoelectric materials can overcome the limitation of low energy harvesting efficiency. In particular, an obvious advantage of composite piezoelectric materials is great flexibility, which is desirable for manufacturing curved transducers [24], which will be further discussed in the following subsection.

2.1.2. Piezoelectric Transducers. Piezoelectric materials have been applied to produce transducers to detect external mechanical loadings, such as compressive deformations and low-frequency/acceleration motions. Efficiency and power density of a piezoelectric energy harvester are capable to harvest the maximum energy at its resonance frequency [26]. An energy harvester needs to be designed according to the vibration frequency of targeted motions, such as human motions and travelling vehicles [26, 27]. Depending on the installation mechanism of piezoelectric materials shown in Figure 4, piezoelectric transducers can be classified as cymbal transducers, cantilever transducers, and other transducers.

Table 2 presents the design of an example piezoelectric transducer and electric output. The cymbal transducer is usually adhesive by epoxy resin on both sides of the piezoelectric ceramic. It is wired with conductive epoxy resin that is adhesive on the metal end cap on the edge of a piezoelectric ceramic along the polarization direction. When the upper metal end begins to bear the loading, through the coupling effect of piezoelectric wafer interface, the radial vibration of a piezoelectric wafer modal superposition occurs, and then, the output alternating voltage is generated. This type of transducer had the advantage of enhanced horizontal polarization, leading to a greater density of power output.

There have been many application studies of piezoelectric cymbal transducers in pavements. Lv et al. considered a layered model of different thickness and diameter to collect the energy generated on the asphalt [31]. The conventional piezoelectric ceramic transducer is composed of PZT ceramic and hardened steel. The mechanism is that through the deformation caused by the vehicle, the impact load directly affected the PZT ceramic polarization center, and a relative displacement occurs. The positive and negative

Table 1: Features of piezoelectric materials.

Material type	Example material	Chemical composition	Advantage	Disadvantage	Reference
Inorganic piezoelectric material	Piezoelectric ceramics	Barium titanate ($BaTiO_3$)	Wide usage and high structural stiffness	Unstable dielectric constant	[20]
		PZT materials ($PbZrO_3$–$PbTiO_3$)	High electromechanical coupling factor and high efficiency of electromechanical conversion	Brittle and fragile	[18]
	Crystalline materials	Lead titanate ($PbTiO_3$)	High ratio of k_{33} to k_p with a high k_t and obtainable from the nature as mineral macedonite	Toxic	[21, 22]
Piezoelectric polymer	Polyvinylidene fluoride (PVDF)	$-(CH_2\text{-}CF_2)_n-$	High mechanical strength and toughness	Low electromechanical coupling factor	[23]
Composite piezoelectric material	Piezoelectric fiber/polymer composites	NA	Low energy density, low acoustic impedance, soft, and high flexibility	Complicate construction process	[24, 25]

Note. NA: not available.

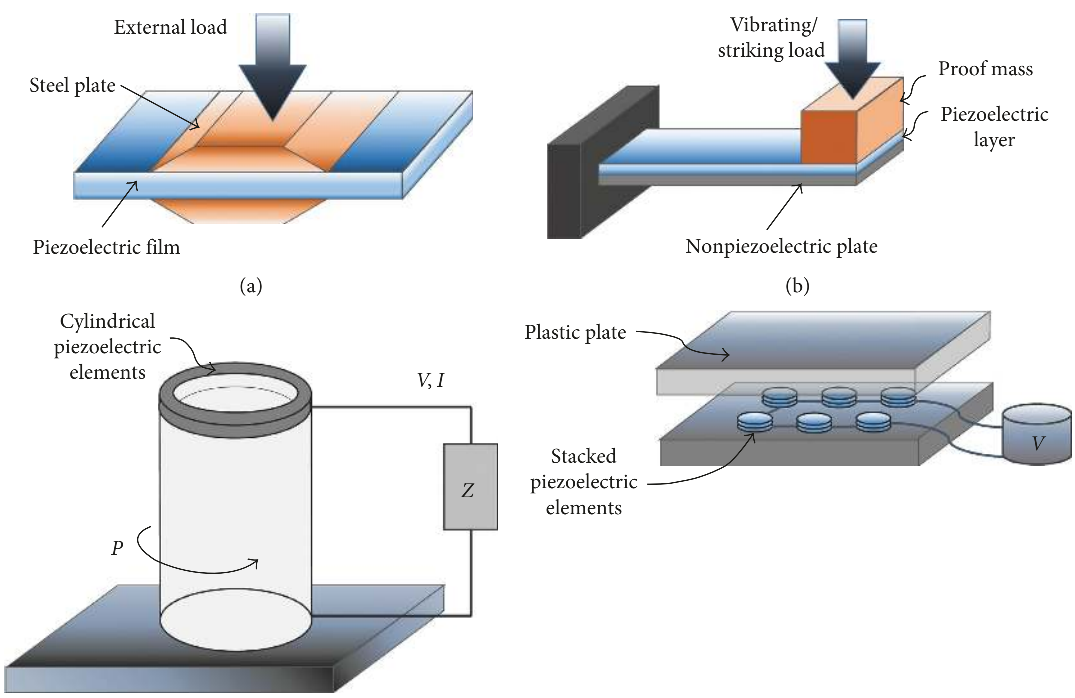


Figure 4: Piezoelectric transducer examples: (a) cymbal transducer (based on [28]); (b) cantilever transducer (based on [29]); other transducers: (c) cylindrical transducer (based on [30]) and (d) stacked piezoelectric transducers (based on [13]).

charges occur and generate loop currents. Yesner et al. developed a new type of a bridge transducer based on beryllium design to polarize piezoelectric ceramics along its length with novel electrode designs [28]. Xiong and Wang successfully collected the deformation energy of asphalt pavement, which was caused by moving vehicles, to generate electricity with the piezoelectric energy collector in order to power a stop sign. In their design, six PZT piezoelectric ceramic plates were installed in every prototype piezoelectric energy collector, which was eventually installed in the asphalt pavement in a weight station by an interstate highway [40].

Cantilever transducers represent transducers with a thin piezoelectric film attached at the free end of a cantilever beam to harvest energy from vibrations. As expected, the deformation of the piezoelectric plate is increased by adjusting the resonant frequency of the piezoelectric structure. The power output is proportional to the proof mass [27]. The cantilever beam structure can generate more power by repeatedly striking and vibrating the piezoelectric cantilever

Table 2: Physical design and electric output of piezoelectric transducers.

Piezoelectric transducer classification	Design	Frequency/frequency band (Hz)	Maximum power density (mW/cm^3)	Advantage	Disadvantage
Cymbal transducers	2 × 32 × 32 mm PZT ceramic confined between steel caps [28]	5	1.03	Enhanced horizontal polarization	Prone to polarization-induced cracks
	∅8 mm piezoelectric disk sandwiched between two nylon disks [31]	NA	NA		
	∅29 mm piezoelectric disk, 1 mm thick [29]	50~150	59.07		
	∅29 mm piezoelectric disk, 1 mm thick [32]	100~200	78.77		
	∅35 mm piezoelectric disk confined between two ∅35 mm steel discs [33]	1.19	0.31~1.37		
	∅35 mm PZT disk confined between two ∅35 mm metal endcaps [34]	5~3,000	~1,000.64		
	∅32 mm PZT disk, 2 mm thick [35]	20	0.75		
Cantilevered transducers	15 × 15 × 1.5 mm piezoelectric disk attached on a steel cantilever [36]	72	0.0003~0.0008 in the vertical direction and 0.001 in the horizontal direction	Convenient to polarize piezoelectric layers in the "31 mode"	Redundant piezoelectric materials in the nonstress zone on the cantilever
	∅1.5 mm PZT disk [37]	0.9	1.25		
	2 × 2 × 0.0047 mm piezoelectric film on 1.5 μm thick cantilever [38]	11.5~14.5	NA		
Other transducers	Multiple ∅31.60 mm PZT disks with the thickness of 14.35 mm embedded in the energy harvester device [15]	NA	0.78	Enhancing energy efficiency with improved and flexible designs	—
	Curved piezoelectric layers [30]	64	NA		
	Stacked layers with the piezoelectric film [39]	NA	360~2,400		

Note. In the "31 mode," "3" represents the polarization direction of the piezoelectric layer, and "1" represents the stress direction; NA: not available.

beam, where the vibration energy can be continuously converted into electric energy [37]. Since cantilever transducer piezoelectric energy is random and intermit, the circuit in nonworking time still consumes energy, which may cause unnecessary energy loss [36].

Cantilever transducers have been applied to harvest energy from motions of humans and vehicles [15, 17, 18]. Kuang et al.'s cantilever transducer harvested energy from human motions, with the average power output of 5.8 mW, and the dual-piezoelectric chips pulled out by the repulsive magnetic force could produce higher energy output [37]. Chen et al. presented a self-powered cantilever transducer for road speed bumps, with the basic idea to detect travelling vehicles by waking up the circuit [36]. The tire pressure of a travelling vehicle can be measured with remote monitoring systems, with the maximum power output achieved with the tire contact patch on the top of the energy harvester [41].

The other transducers, such as piezoelectric crystal pile, cylindrical piezoelectric structure and electromagnetic piezoelectric energy harvesting, have also gotten increasing attention. There have been composite forms of piezoelectric ceramic strip and steel substrate. Faisal et al. developed a piezoelectric coupling energy collector with piezoelectric films on top of a rectangular steel plate [23]. Zhao et al. developed several types of piezoelectric sensor configurations by stacking several prismatic PZT elements in circular, square, or hexagonal shapes, in order to investigate the influence of cross-sectional shape on energy output [35]. Papagiannakis et al. developed two piezoelectric prototypes with stacked cylindrical or prismatic piezoelectric elements to harvest the kinetic energy from travelling traffic

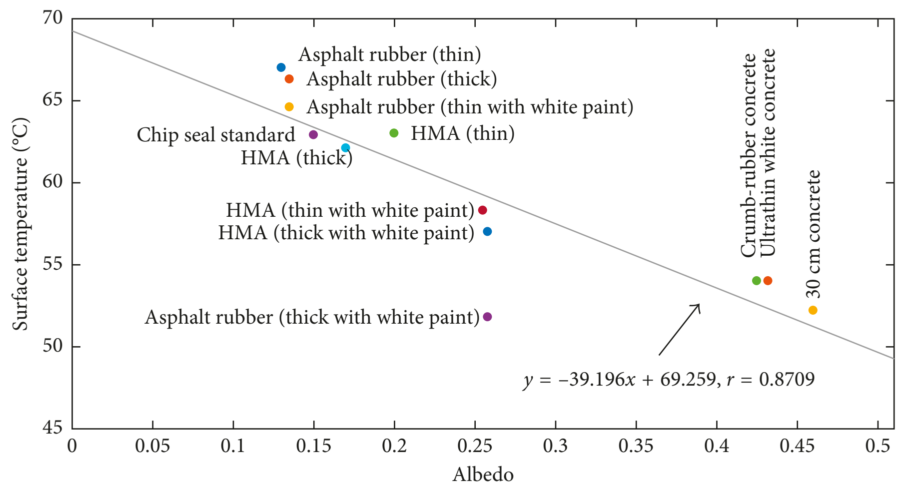


Figure 5: Albedo and surface temperature for different types of pavements (based on [10, 48]).

on roadways, with the finite element results showing the power output of 1.0~1.8 W for a single pass of a 44.48 kN truck tire load [42].

2.1.3. Application of Piezoelectric Energy Harvester in Pavements. It is effective and feasible to collect the excessive energy of pavements using piezoelectric energy harvesters [13, 43]. Moure et al. designed an energy harvesting device with piezoelectric ceramics [44]. Milani et al. designed a wireless sensor powered by a piezoelectric energy harvester [45]. Roshani et al. evaluated the performance of the piezoelectric energy harvester in asphalt pavement [46]. Energy harvested from the harvesters can be stored in batteries, which can power other electric sensors and traffic and signal lights [13, 40]. With a large-scale application of piezoelectric technology in pavements and on bridges, it is helpful to reduce the nonrenewable fossil fuel power consumption, which contributes to more resilient and sustainable pavement infrastructures.

2.2. Solar Energy Harvesting for Pavements

2.2.1. Solar Radiation. Solar energy is very attractive because solar radiation is stable and sufficient during daylight hours in the foreseeable future. Given highways in the United State with the total length of 47,856 mile and the width of 5.25 mile, considering an average incident solar radiation of 9.4 kWh per square mile per day, there are 2.36 TWh of daily solar energy incident on highway pavements. About 80~90% of these incident solar energy is absorbed as heat energy in pavements [10]. Figure 5 presents the heating effect of pavements due to the solar radiation. The horizontal axis represents albedo, which is the proportion of incident energy reflected. The solar energy coefficient increases with the increase of albedo [47]. Pavement surfaces are commonly hot in warm weather, leading to the urban heat island effect and even structural failures. In this respect, collecting solar energy from pavements and removing the excessive heat due to solar radiations could eliminate both urban heat island effect and structural failure potentials [10].

2.2.2. Solar Energy Harvester. To harvest solar energy for a sufficient period of time during daylight hours, many energy harvesting technologies have been developed. The discovery of high-purity silicon photovoltaic cells accelerates the development of solar energy harvesting. This innovation allows us to create a pavement surface that remains clean and absorbs solar radiations in the meantime. As shown in Figure 6, prevalent methods to harvesting solar energy include installing solar panels along roadways, installing solar panels underneath a transparent top layer as photovoltaic pavements, and pavement solar collectors with embedding pipe systems to extract heat. In Figure 6(a), solar panels are installed along roadways to harvest solar radiations, contributing to reduction in external energy usage and greenhouse gas emissions [49]. This design has been widely utilized in practice for powering traffic lights and signal lights along roadways. Previous research found that photovoltaic technology has the greatest peak productivity than the other green technologies for energy harvesting, but the productivity is limited by illumination conditions [50].

Photovoltaic pavement surfaces consist of a high-strength transparent layer on the top, with solar panels installed underneath. The top layer serves as a water proof layer, which allows sunlight to pass through. The solar panel layer converts solar energy into electric energy. A 100 ft^2 solar walkway at the George Washington University generates the average peak capacity of 400 Watt, which is capable to power 450 LED pathway lights below the panel [51]. Fouad et al. evaluated the cost-benefit of photoelectric pavements by considering the environmental, photovoltaic, installation, and cost. Through continuous research, the negative effects are expected to be eliminated and the performance of photovoltaic conversion is expected to be improved [52]. Photovoltaic pavements are made of tempered glass, to be installed on roads, parking lots, and bike lanes, and sometimes solar cells are installed between two

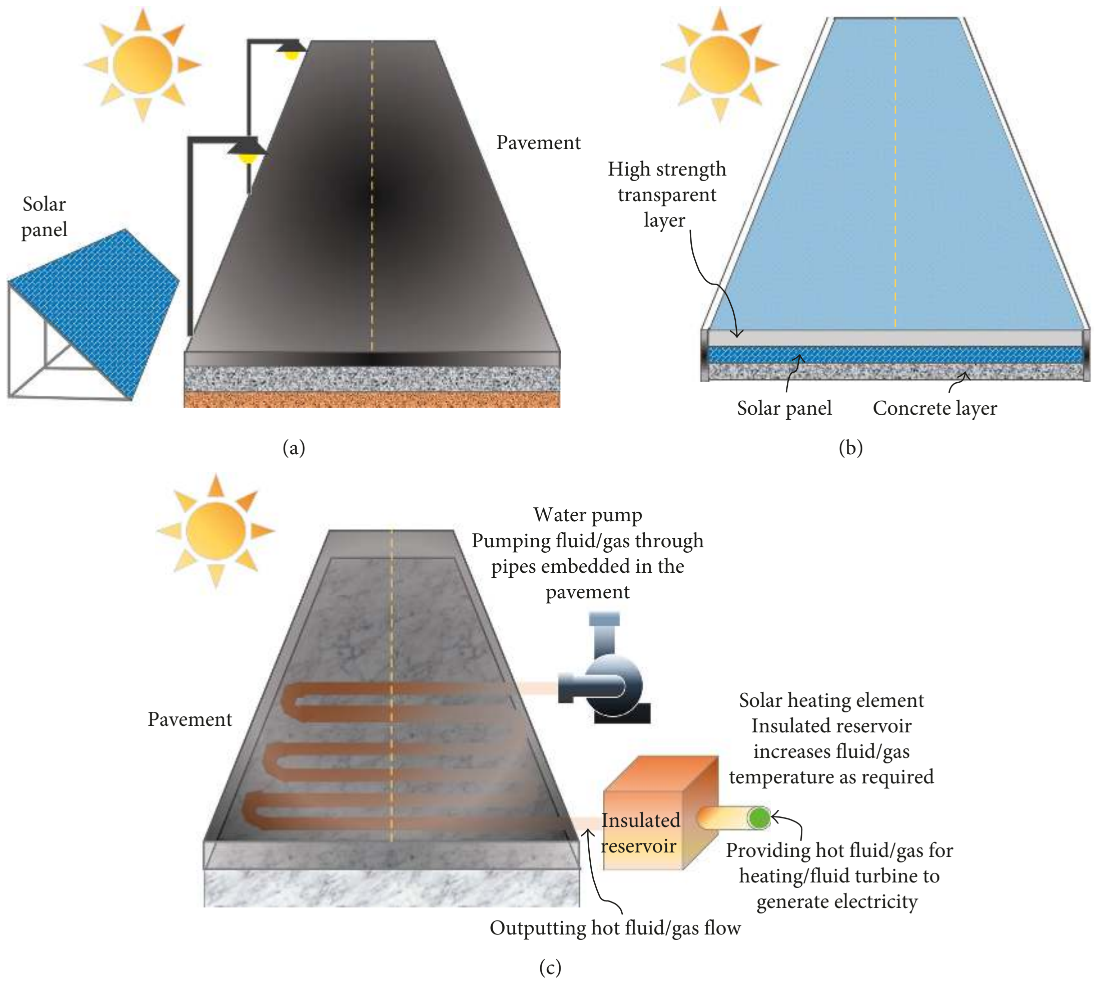


FIGURE 6: Solar energy harvesting technologies for pavements: (a) solar panel (based on [56]), (b) photovoltaic pavement (based on [57, 58]), and (c) heat extraction with the piping system (fluid/gas) in pavements (based on [10, 59]).

porous rubber layers [53]. Northmore and Tighe studied the performance of a pavement with a transparent surface with an embedded solar cell through a finite element model of various structure designs. They believed that a solar pavement can be designed to withstand the traffic load [54]. Qin et al. established a small-scale pilot project on the use of pavement solar energy with an automatic data-acquisition system and evaluated the effectiveness of pavement solar systems in energy conversion [55]. Despite the aforementioned exploratory studies, photoelectric roads are still not ready for practical applications yet due to high installation costs and concerns about potential short service life.

Pavement solar collectors with the embedding pipe system collect heat due to solar radiations with the pipe system in the asphalt pavement structure and store as electric energy, depicted in Figure 6(c). The design uses similar pipe systems as in the design of geothermal energy harvesting, with the harvested thermal energy generated from solar radiations rather than from a geothermal source. The first pavement solar collector with embedded pipe systems was implemented by Sedgwick and Patrick with a grid of plastic pipes 20 mm underneath the asphalt surface in a tennis court, demonstrating a relatively constant temperature [60]. Wu et al. proposed the use of black asphalt pavements as solar collectors for direct cooling and heating in snow removal in the winter [61]. Major problems are to maintain temperature in the pipe system and to eliminate pipe clogging over time. There are many factors affecting the heat collecting effect, including the latitude of pavement, the albedo of the surface layer, the diameter, distance, and burial depth of pips, and the emissivity and thermal conductivity of the surface layer [62]. Pavements at a low latitude are usually exposed to greater solar radiations; therefore, the benefit of solar pavements increases with a decrease of latitude [63]. On the contrary, albedo has a great influence on the performance of the solar energy harvester, as the temperature of pavement surface increases with albedo [64]. In addition, to maximize the energy harvesting efficiency, the pipe diameter and burial depth need to be carefully selected, with the fluid velocity setting in an optimal range [59]. It is worth mentioning that solar energy projects along roadways raise some new concerns, such as safety concerns due to the reflection and glint effects [65].

Table 3: Advantages and disadvantages of thermoelectric materials.

Thermoelectric material	Advantage	Disadvantage	Reference
Carbon fiber-reinforced cement composites	Great output power	High cost and complex preparation process	[68, 69]
Pyroelectric crystals	Best thermoelectric performance	Low power generation	[70]
New cement-based materials	Low cost and rich raw materials	Low thermoelectric performances	[71, 72]

2.3. Thermoelectric Pavements. Collecting the heat from pavements is capable to generate electricity and provide heat to the surrounding building and eliminates the UHI effect [63, 66]. Thermoelectric materials can be used as energy collectors in pavement applications. Table 3 shows three common thermoelectric materials. At present, the most widely used thermoelectric materials are carbon fiber-reinforced cement composite materials, cement-based composite materials, pyroelectric materials, and so on. Wei et al. carried out an energy harvesting experiment based on the thermoelectric behavior of carbon fiber-reinforced cement composites (CFRC). The collected outdoor heat energy was converted into electrical energy [67]. Rew et al. studied the effects of powdery carbon-based additives on asphalt composites, including graphite and carbon black. The electrical conductivity was evaluated by experiments, which provided a basic foundation for the application of carbon-based powder conductive additives to the multi-functional application of asphalt composites [68].

Cement-based materials are based on the carbonate cement, with a variety of ceramic fiber, carbon, wire, or mineral fiber as a reinforcement by adding filler, chemical additives constitute, and composite materials. New cement-based materials have increased the functional conductivity. Ghahari et al. added ZnO nanoparticles in cement paste to improve the thermal properties of cement paste and systematically studied the possibility to harvest heat storage in concrete structure. The thermoelectric properties of ZnO-cement composite surface showed its thermal energy recovery potential on concrete structure and pavement [69, 72].

Pyroelectric materials are materials that generate electricity at an elevated temperature. In the case of mechanical loading condition, the pyroelectric coefficient of pyroelectric materials is measured as the sum of the primary pyroelectric coefficient at constant strain and the secondary pyroelectric coefficient due to piezoelectric contribution from thermal expansion. Pyroelectric materials can be broadly classified into three categories: single crystals, polycrystalline ceramics, and polymers [73]. Bhattacharjee et al. conducted research on the pyroelectric material consisting of lithium tantalate ($LiTaO_3$), ordinary Portland cement, and carbon nanofiber. Their results showed that lithium titanate crystals have excellent thermoelectric properties and are excellent candidates for pyroelectric energy harvesters, to produce electricity for other sensing devices [70]. Batra et al. theoretically studied the energy harvesting capacity of existing pyroelectric elements and transducers by capturing thermal energy from pavement heat. With temperature data from the MEPDG climate database, they discovered that the energy collected by thermoelectric power was a viable technique for the automatic power supply of low-power demand devices [74]. The thermoelectric generator (TEG) for waste heat harvesting can also be controlled by thermoelectric effects, also known as Seebeck effects. The energy harvester system with the thermal module device can capture the energy from the pavement temperature gradient according to the Seebeck effect [20].

Commercially, thermoelectric materials have a great energy productivity at the great heat flux condition (over 180°C) [75]. In pavements, the temperature gradient may be lower, resulting in a smaller heat flux. As a result, for wide pavement applications, the thermoelectric energy harvester should be optimized in terms of both material design and device design to yield a better energy conversion efficiency.

2.4. Geothermal Pavements. On the contrary, natural geothermal resources refer to thermal energy-stored underground soils. The natural geothermal resources are mainly caused by the high-temperature melts in shallow crust and the decay of some radioactive elements. As shown in Figure 7, geothermal energy is collected with pipe networks to generate electricity in many countries, such as Mexico [76] and Turkey [77]; geothermal energy is also applicable to heat pavements for deicing [78]. In the pipe networks, fluid operation parameters, such as temperature and flow rate, have a great influence on the thermal exchange [61]. Therefore, the pipe networks should be carefully designed, in terms of pipe diameter and installation depth, among others, to achieve the optimal fluid operation parameters and the maximal energy conversion efficiency.

Harvested geothermal energy has many applications, and ore advanced techniques for geothermal energy harvesting are still under development. Geothermal energy harvesting for melting snow begins from 1940s at Oregon in the United States, and its iron piping system failed due to external corrosions and serious leakages after 50 years' service. Later on, plastic pipes are frequently used as the replacement of metal pipes to avoid corrosion. Wang et al. proposed a small-scale geothermal system to melt ice on concrete pavements, and experimental results showed that the melting process of ice and snow consists of a staring period, a linear period, and an accelerated period [78]. Zhou et al. verified the applicability for storing thermal energy and deicing in winter [61]. Liu et al. analyzed the heat transfer and snow melting of asphalt concrete pavement and paved the pavement with electric heating pipes [79, 80]. Mauro and Grossman proposed a low-enthalpy geothermal energy harvester. The geothermal temperature gradient was generated by materials with a great thermal conductivity to eliminate annual street temperature fluctuations [81].

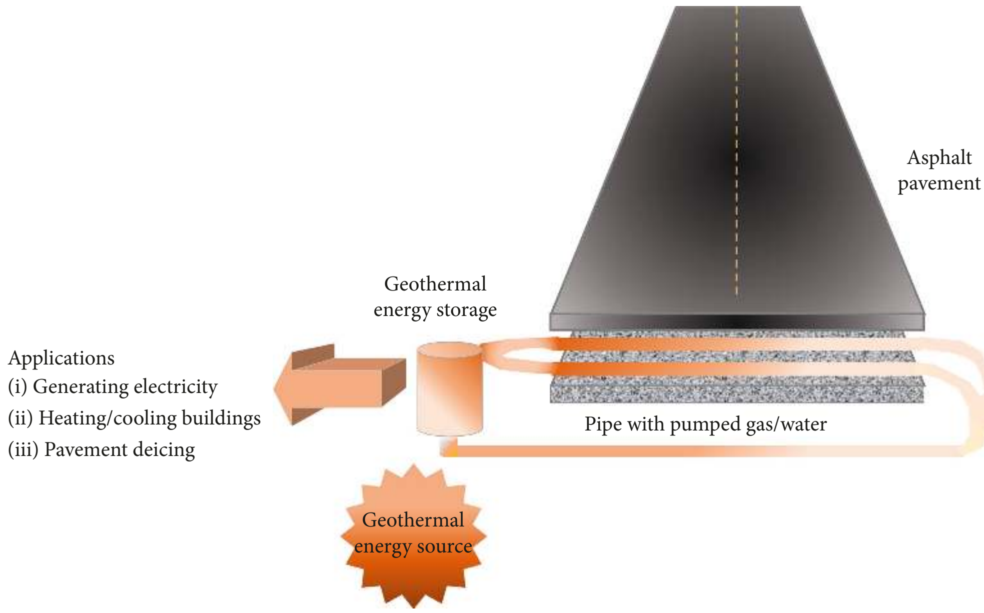


Figure 7: Geothermal pavement (based on [78]).

Successful applications of geothermal energy harvesting to heat airport pavements demonstrated that geothermal energy harvesting has safety and environmental benefits, despite a higher initial investment than the traditional snow removal methods [82–85]. Although geothermal energy is an attractive renewable energy source, it may have an inherent limitation of geographically and geologically limited availability. Popular applications are for surface deicing and snow removal in airports, bridges, and sidewalks.

2.5. Composite Energy Harvesting Technology. Some other studies try to incorporate multiple energy harvesting technologies together. Figure 8 depicts three example designs of composite energy harvesters. It is found that piezoelectric materials usually have the thermoelectric effect. Tao and Hu investigated the electrical response of the PVDF with both mechanical and thermal stimulations, finding that PVDF microsensors are very effective in energy conversion [86]. Meanwhile, several other studies have demonstrated that harvesting energy through the hybrid piezo-pyroelectric effect from pavements with PVDF is likely to generate a greater electric output compared to only harvesting mechanical energy from the piezoelectric effect [17, 87]. However, current research on the hybrid piezoelectric-thermal energy system remains in laboratory tests, seldom applied to pavement structures in field applications yet.

Similarly, electric power output can also be significantly increased by combining solar concentrators with piezoelectric energy harvesting circuits [89, 90]. In order to improve the efficiency of energy harvesting to provide more power for street lights, Arnab et al. combined piezoelectric materials with solar panels, as shown in Figure 8(b), to improve energy harvesting efficiency [90]. Sathiyamoorthy and Bharathi designed a hybrid energy harvester with solar panels, piezoelectric devices, and wind turbines, aiming at harvesting renewable energy from pavements as much as possible to power traffic lights and houses [91].

As shown in Figure 8(c), the solar-geothermal energy harvesting system is to harvest both solar and geothermal energies. In such a system, solar energy is collected by solar panels, and the pavement heat is collected by a water circulation system. All the harvested energy is stored as hot water in the energy storage tank, to heat up the surrounding buildings or generate electricity to power the nearby electric devices. Then, the energy storage tank releases cold water into the system, and a new circulation begins. Zhu and Turchi proposed such a harvesting system named centralized solar power (CSP) generation, which uses the harvested solar energy to provide additional thermal energy for the power generation of a geothermal plant [92]. Harvesting both solar and geothermal energy can lead to an increase of 11.6% in the electric output, based on the thermodynamic simulations [93].

In addition, there are some other hybrid energy systems that make full use of at least one of the aforementioned energy harvesting techniques. For instance, Liu et al. analyzed a hybrid geothermal-fossil power system, by using geothermal energy to preheat the feed water before the power generation in a coal-fired power plant [94]. Buonomano et al. simulated a trigeneration system with a turbine, making use of solar and geothermal energies [95]. Such a great variety of composite energy harvester designs are intensively studied via pilot studies and numerical simulations, with a great potential for future practical applications.

3. Permeable Pavement

Permeable pavements can recover the natural hydrological cycle and relief the urban flood risk and the urban heat island effect. In general, permeable pavements are implemented by using porous materials with large voids to directly allow the

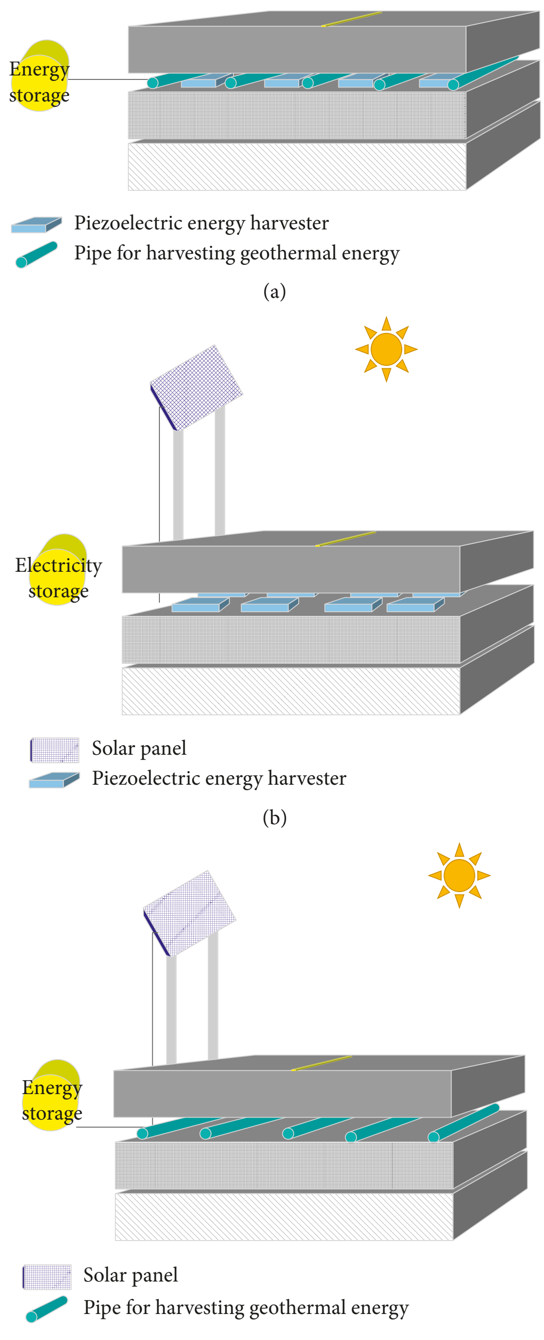
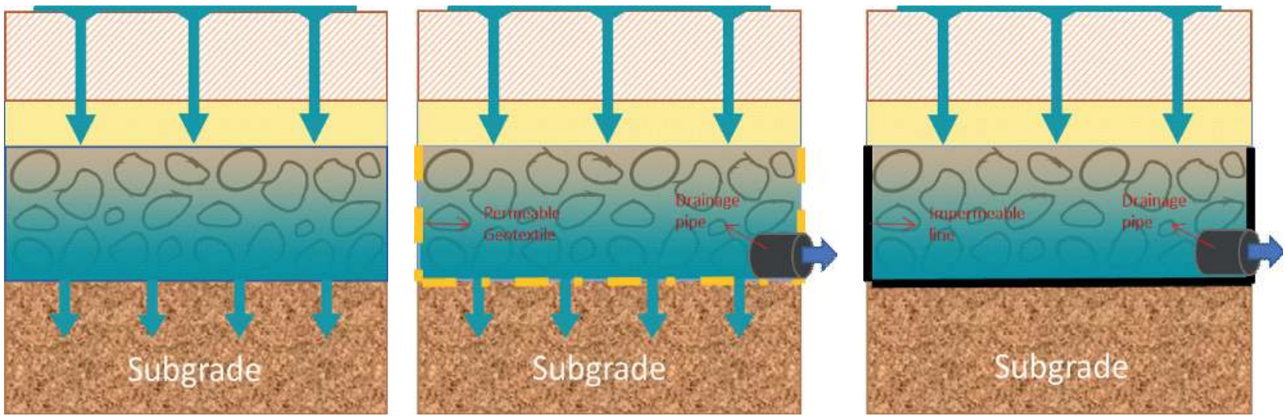


Figure 8: Hybrid energy harvesting systems: (a) hybrid piezoelectric-thermoelectric energy harvester, (b) solar-piezoelectric composite energy harvester, and (c) solar-geothermal energy harvester (based on [88]).

rainwater seeping through the pavement surface (Figure 9). In case of rain event, water can quickly infiltrate through the pavement structure into subsoil, which consequently reduces the pressure of urban drainage system and facilitates the water supply of natural cycle [7]. In the meantime, the evaporation of water can bring away excessive heat within the pavement structure, reducing the urban heat island effect [96, 97]. Because of these superior environmental-friendly features, permeable pavement systems are particularly suitable for applications in residential, commercial, and industrial areas under light traffic loads [97, 98].

To achieve the high permeability, a void-rich pavement structure is currently recognized as the most feasible and effective way, such as porous asphalt (PA), porous concrete (PC), and permeable interlocking concrete pavement (PICP) [7, 102]. In this case, an open-graded grain size distribution ensures the expected void contents and pore structures of pavement. Different models and design methods were proposed by considering the grain size distribution to analyze the effect on the hydraulics property [103–105]. Furthermore, the water-purifying evaluation of three types of permeable pavement structure was also investigated especially for cold regions [106, 107]. To optimize the hydraulic conductivity of permeable pavement, a combined scheme was created by enhancing surface runoff controlling results of bioretention ponds, infiltration galleries, and permeable pavement [108]. To fundamentally understand the void distribution in the open-graded asphalt concrete, X-ray computer tomography (XCT) was performed, where the effect of void diameter, void tortuosity, and minimum sectional dimension on the hydraulics property was analyzed [109–111]. Based on XCT measurements, a permeability numerical model was proposed for the open-graded asphalt concrete. In addition to the high hydraulic conductivity, the porous structure can also reduce the air-pumping effect between tire and pavement interactions, which is the major cause of traffic noises (above 1,000 Hz) [112, 113]. The absorption properties of porous pavement structure also contribute to noise reduction, following the same absorption principle as acoustical wall treatment [98, 105, 112, 114].

Apart from the functionality, mechanical properties of permeable pavement were also widely investigated to evaluate the durability. To make life-cycle maintenance strategy for permeability deterioration, an artificial soiling test to simulate the soiling process during life-time of porous asphalt was developed [112]. To clarify the mechanical response of permeable pavement, wide fatigue behaviors were performed in comparison with the conventional rigid pavement [102, 113]. Most of the studies have been performed at the individual sites. However, in a complex serving environment, various moisture levels might be captured in the porous pavement structure, resulting in various possible combinations of air, liquid, and solid. Moreover, with the filtration and the upward movement of sublayer and soil, the porous pavement structures are mostly in an unsaturated state, where multiphysical processes occurred such as freezing and spalling, drying and shrinkage, hydrodiffusion and subsidence, and capillarity and cracking [115]. Each one of these processes, involving more than two physical phases, can cause a complex mechanical distribution, which exerts a significant influence on the pavement behavior [116]. To address this problem, several coupled-phase models have been established, with experimental validations. Results from numerical models and experimentations reveal the mechanism of porous pavement under partial saturated conditions [102, 117].



(a) (b) (c)

Figure 9: Typical permeable pavement sections (based on [99–101]): (a) fully permeable pavement, where water can infiltrate to subgrade; (b) half permeable pavement, with some water infiltrating to the subgrade, most is stored in the pavement structure; (c) permeable pavement with no water infiltrating to the subgrade but is stored in the pavement structures.

It can be concluded from the literatures of urban permeable pavements, including hydraulic characteristics and other functional performances, that using permeable pavement is promising and feasible to resolve the city flooding problem and eliminate the urban heat island effect. However, these researches are mostly based on the phenomenological analysis at the macroscopic level. The microscopic performances such as the inner water permeation, storage and evaporation, pollutant distribution, storage and migration are not clear, which hinders the understanding of degradation mechanisms. As a result, a systematic investigation of the permeable pavement system has to be carried out at multiple spatial scales.

4. Discussion

4.1. Comparison of Green Technologies in Pavement Applications. Green technology applications can contribute to sustainable and resilient pavements from many aspects. Applying energy harvesting techniques in pavements can continuously generate the self-contained and clean power to activate in situ monitoring sensors and illuminate traffic lights and signals. By contrast, permeable pavements can rapidly drain storm water runoff to alleviate the risk of urban flooding and enhance travel safety, especially for walkways and parking lots. Typically, permeable pavements have the interconnected voids of 15%~35% by volume [118], with a significant hydraulic benefit of reducing 90% of the peak runoff volume [119–121]. These applications contribute to enhancing water sustainability management by reusing the urban runoff but also in improving the energy conservation by collecting wasted energy from pavements [84, 122–124]. The green technology applications in pavements lead to safe, sustainable, and resilient transportation infrastructures with a reduced cost of maintenance and emergence response, enhanced travel safety, and improved environmental benefit, allowing transportation infrastructures independent of external power grids in the case of the large-scale power outage in a disruptive event [46, 123, 125].

Table 4 compares different energy harvesting technologies in pavement applications, in terms of the energy conversion method and efficiency, and advantage and disadvantage, as well as example applications and technology development maturity. Solar energy harvesting has the highest conversion efficiency to harvest the energy from solar radiations into electric energy. The major advantage of solar energy harvesting is that solar radiations are available worldwide. An obvious disadvantage is that sun radiations are maximized at the direct sunlight, and they are limited at nights or rainy days. Depending on the design scheme, piezoelectric energy harvesting converges mechanical energy into electric energy at a low–medium convergence efficiency. Previous research considered that piezoelectric energy harvesting may be one of the most encouraging technologies with the widest power density versus voltage envelope [126]. Conversely, geothermal energy harvesting converges geothermal energy into electric energy or thermal energy at a medium convergence efficiency. The harvested renewable energy from these technologies can be applied to power electric devices associated with pavements, such as traffic lights and signal lights, or to monitor pavement health, such as temperature, deflection, and moisture content, or to deice pavement in cold weather. Many pilot studies have demonstrated the feasibility of energy harvesting from pavements. Both solar energy harvesting and geothermal energy harvesting techniques are relatively matured, whereas thermoelectric energy harvesting techniques are the least matured, with a low energy conversion level.

4.2. Application Challenges and Recommendations. For more practical applications, there are some challenging issues remaining, such as how to properly install the devices in construction, efficiently maintain the devices during the service life, and timely replace damaged components. Compared to the traditional pavement system, the presence of energy harvesting devices may have a negative influence

Table 4: Comparison of green technologies to harvest energy from pavements.

Energy harvesting technology for pavements	Energy conversion method	Energy conversion efficiency	Advantage	Disadvantage	Application to pavements	Technology development maturity
Solar energy harvesting	Solar energy to electric/thermal energy	Medium–high	(i) High energy conversion rate (ii) Abundant resources	(i) Weather limited	(i) Pavement health monitoring (ii) Powering traffic lights and signals (iii) Pavement deicing	High
Piezoelectric energy harvesting	Mechanical energy to electric energy	Low–medium	(i) Energy harvesting in many designs	(i) Relatively low energy conversion efficiency	(i) Pavement health monitoring (ii) Power traffic lights and signals	Medium
Thermoelectric energy harvesting	Thermal energy to electric energy	Low	(i) Flexible applicability	(i) Low efficiency (ii) High unit cost	(i) Power traffic lights and signals	Low
Geothermal energy harvesting	Geothermal energy to electric energy	High	(i) High energy conversion rate (ii) Abundant resources	(i) Geologically limited (ii) Technical challenging	(i) Pavement deicing (ii) Cooling pavement (iii) Geothermal electricity production	High

on the structural integrity, leading to weak mechanical properties and crack developments, which may cause internal moisture damages in operations. On the contrary, there are concerns of their weak mechanical performances and clogging-prone nature of permeable pavements. Many studies have shown that there is a negative correlation between the porosity and compressive strength of permeable cement concrete [121, 127–129], which is commonly used in permeable pavement systems. For instance, the compressive strength of permeable concrete is usually less than 25 MPa [118]. Such weak mechanical properties are likely to lead to crack failures in permeable pavements, which significantly reduce the service life. Moreover, previous studies have demonstrated that the clogging issue in permeable pavements significantly reduces the porosity, reducing the service life [121, 129, 130]. Therefore, we should optimize the design with the best efficiency, conduct the safe construction to eliminate initial damages, and determine an optimal time to perform regular maintenance in the following aspects.

First, we need to pay special attention on optimal designs, proper location selections, and careful installations. In the case of energy harvester devices, the effect of energy harvesting throughout the service life is related to many factors, such as material type, device dimension, installation depth, physical and mechanical properties of pavement structure, weather condition, and geographical location, among others [11, 37, 40, 64, 75, 131]. By selecting appropriate materials and careful device designs, the stiffness of an energy harvester should be at a level similar to the overall pavement stiffness to avoid reflective cracks [46], and sharp edges should be eliminated to prevent cracks around the device and to minimize the differential deflection on the device-pavement interface [132]. External tempered protectors are suggested to implement to improve the durability performance, by preventing future water infiltrations and chloride penetrations [132]. Energy harvesting devices should be carefully installed by experienced workers to eliminate damages in the installation process. For piezoelectric energy harvesters, they are more suitable to be installed on the wheel path (1.5~2 feet away from the lane edge) of asphalt pavements at a depth of 2 inch from the surface to allow for regular pavement maintenances (such as milling and overlaying) [46]. For solar pavements, solar panels should be installed at a certain location range of the maximal solar exposure with the minimal reflection and glint effect to ensure the road safety. To the best knowledge of the authors, there is no publicly reported study on the replacement cost of energy harvesters in pavements yet. In the case of permeable pavement systems, hydraulic feature of permeable pavements depends on the grain size and mineralogy of sediments [133, 134], and the clogging characteristics mainly depends on the filter media aggregate size [135]. Coustumer et al. suggested to use the performance period when the effective hydraulic conductivity reduces to 50% of its design value due to clogging as the relevant specification [136]. Recent researches have investigated different ways to eliminate the clogging effect through periodic cleaning [134, 137, 138] and to improve mix design for bearing heavier loads by using advanced porous materials [139, 140].

Second, we should assess the life-cycle performance of green technologies in pavement applications in both socioeconomic and environmental aspects through both numerical simulations and laboratorial experiments, as well as field measurements. To improve the life-cycle performance of sustainable pavements, future research should be conducted to promote better designs and efficient applications. For example, the harvested energy could be used for powering sensors and data loggers for health monitoring [141]. To understand the mechanical properties of energy harvesters and permeable pavements at multiple spatial scales, advanced testing and characterization methods could be used to evaluate the expected service life and identify the best timing for regular maintenance [142–148]. From the economic point of view, we should also assess the life-cycle cost-benefit of green technology applications. The life-cycle cost includes not only the initial construction cost but also operation, maintenance, and repair costs, as well as replacement cost, and so on. Even though the initial installation cost of energy harvesting devices and permeable pavement systems is greater than conventional pavement structures, their life-cycle costs are likely to be smaller. The harnessed energy may significantly contribute to the energy saving and greenhouse gas emission reduction. In the pavement cooling applications, geothermal pavements can not only eliminate the risk of thermal cracking but also mitigate the UHI effect. In snow/ice melting applications, thermal electric and geothermal pavements can enhance the travel safety by eliminating surface snow and ice and reduce the environmental pollution due to a less usage of road salt. The collected runoff from permeable pavement systems can be reused to improve water sustainability in urban areas.

Last but not least, as scientific technology advances, more studies and applications of green technology in pavements are anticipated. At some point, we will need standardized guidelines and evaluation tools to facilitate engineers, researchers, and decision makers to design, construct, and assess the field performance of these pavements from different aspects. By establishing a database in a consistent format to continuously collect data about the materials, designs, methods, and costs for maintenance and replacement, researchers and engineers can utilize these data for allowing the objective assessment of life-cycle performance and cost-benefit analysis. In this way, sustainable pavements using different materials, of different designs, at different locations can be easily compared with each other. These analyses can provide informative suggestions to decision makers for developing efficient plans of sustainable and resilient transportation infrastructures with the implementation of different green technologies.

5. Summary

In recent decades, there have been many studies focusing on the development of green technologies for sustainable pavements by generating renewable energy and eliminating adverse environmental impacts. This paper starts with a comprehensive summary of energy harvesting technologies, including piezoelectric energy harvesting, solar energy harvesting, thermoelectric energy harvesting, and geothermal energy harvesting, as well as composite energy harvesting. After that, permeable pavement systems are critically reviewed. Major findings are as follows:

(1) Energy harvesting technologies have been developed in laboratory and/or applied in prototype studies. Results from both laboratories and prototype studies have demonstrated the feasibility of energy generation from pavements and the adaptability of energy harvesting techniques to different pavement conditions. Among these energy harvesting technologies, solar energy harvesting has the greatest energy conversion efficiency in practice, with the most mature technologies and the widest application. Even though piezoelectric technologies become increasingly popular in research, the actual application is limited in laboratory and at a prototype stage due to a lower energy conversion efficiency and brittle properties of piezoelectric materials. In addition, geothermal energy harvesting technologies also have a similar energy conversion efficiency. These energy harvesting technologies have not been well validated in practice yet; therefore, they are not ready for practical applications in field at the current stage. However, they provide us a promising future for building more sustainable pavements by harvesting renewable energy, once the challenging issues are properly addressed.

(2) Permeable pavement systems, on the contrary, are an important part of sustainable pavements. The implementation of permeable pavements helps us to eliminate surface runoffs in rainy days and to enhance water sustainability. Future research should be conducted to develop new designs or to use advanced materials for improving the mechanical strength and durability of permeability pavements with the least clogging effect. Moreover, an emerging trend for building sustainable pavements is to implement energy harvesting technologies in permeable pavements to improve both energy conservation efficiency and water sustainability.

(3) Future research should focus on solving the following urgent issues involved in the implementation of green technologies for sustainable pavements: construction technology, maintenance technology, and life-cycle performance. Solving these issues can strengthen theoretical understanding in technical, economical, and sustainable perspectives, and eventually, they would facilitate extensive applications of green technologies for building sustainable pavements in practice.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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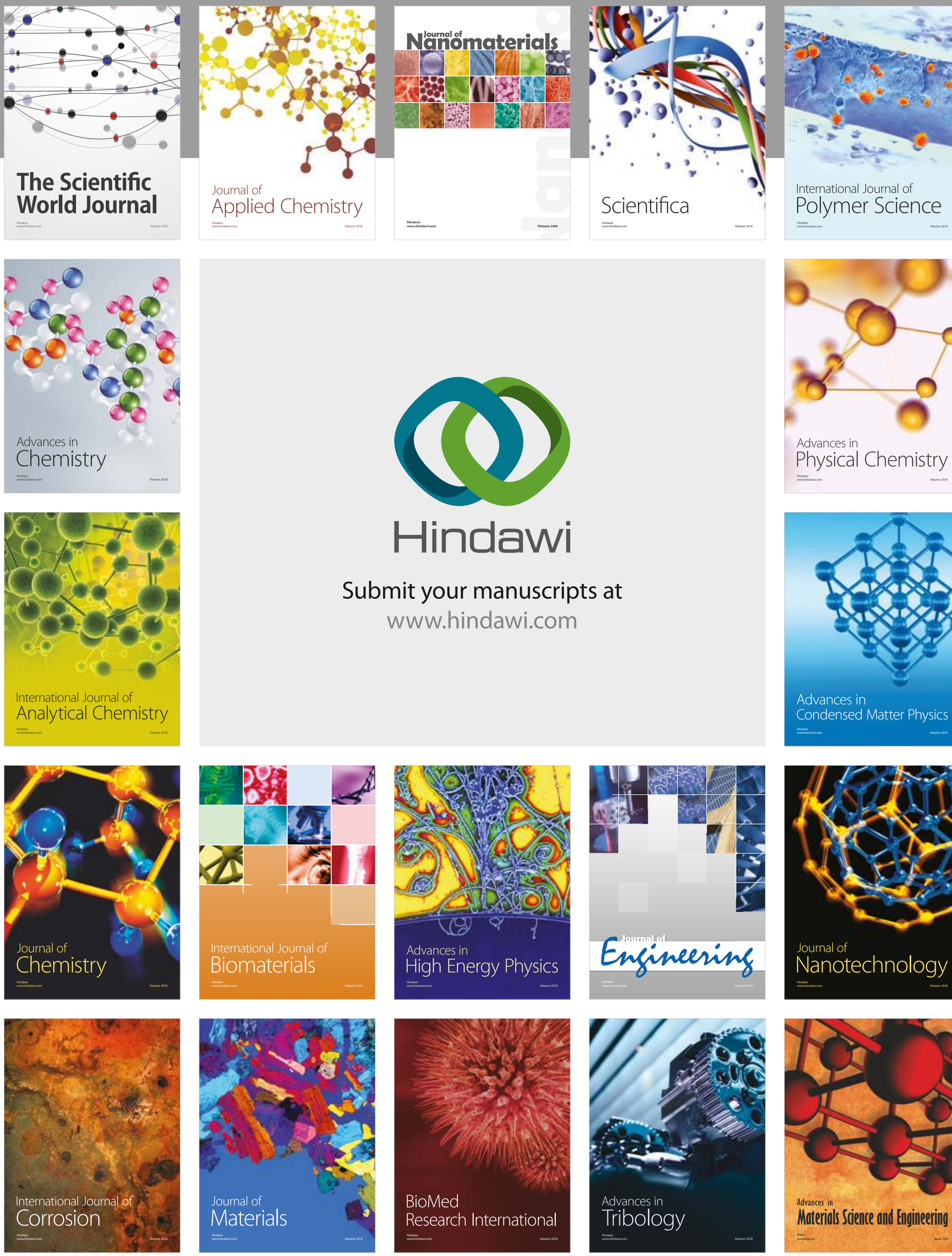

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