Construction and Building Materials 191 (2018) 1082–1092

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

A review of eco-friendly functional road materials

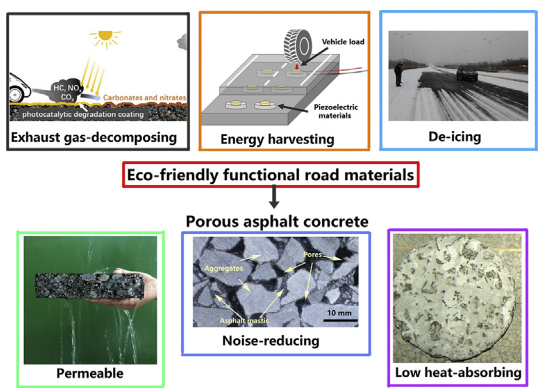
Wei Jiang [a,*], Yue Huang [b], Aimin Sha [a]

[a] *Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, South 2nd Ring Road Middle Section, Xi'an, Shaanxi 710064, China*
[b] *Institute for Transport Studies (ITS), University of Leeds, 34-40 University Road, LS2 9JT Leeds, United Kingdom*

HIGHLIGHTS

- Performance, applications and challenges of eco-friendly road materials is reviewed.
- Abundant pore structures make it possible for PAC to enable additional functions.
- More eco-friendly road materials will be expanded with development of science.
- Further studies should highlight design of road materials with multiple functions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 August 2017
Received in revised form 14 July 2018
Accepted 13 October 2018
Available online 20 October 2018

Keywords:
Road materials
Functional pavement
Eco-friendly
Sustainable construction

ABSTRACT

Extensive studies on traditional and novel engineering materials and the increasing demands by growing traffic have led to tremendous changes of the function of roads. Roads, as an important part of the human living environment, have evolved from structures that were designed and built for passing vehicles, to ecological assets with significant economic importance. In addition to structural stability and durability, functions such as noise reduction, urban heat island mitigation, de-icing and exhaust gas absorption, are also expected. This study focused on state-of-the-art research on the performance, applications and challenges of six environment-friendly functional road materials, namely the permeable asphalt concrete, noise-reducing pavement materials, low heat-absorbing pavement materials, exhaust gas-decomposing pavement materials, de-icing pavement materials, and energy harvesting pavement materials. With this study, we aim to provide references to the latest relevant literatures of the design and development of environment-friendly functional pavement, and promote innovation in materials science and pavement design principles. For this purpose, this review compiled extensive knowledge in modern road construction and related disciplines, in order to promote the development of modern pavement engineering technologies.

* Corresponding author.
E-mail address: jiangwei@chd.edu.cn (W. Jiang).

https://doi.org/10.1016/j.conbuildmat.2018.10.082
0950-0618/

Contents

1. Introduction

Road is an important infrastructure that resulted from transport activities and has promoted human civilization and development. Road construction has a long history; in the 20th century BCE, the Arab Republic of Egypt built roads to transport large amounts of rocks from quarries to sites where the rocks were used to build pyramids and the Great Sphinx [1,2]. In ancient Rome, people constructed an advanced road network centered in Rome, which played a significant role in the prosperity of the ancient Roman Empire and the proverb had it: "all roads lead to Rome" [3]. Moreover, the "Silk Road", which was in existence from the 2nd century BCE to the 13th and 14th centuries, greatly promoted the economic, cultural, and technological exchanges between the east and the west of the Asian continent, making a great contribution to the world's economic development and social progress [4]. Currently, the total mileage of roads has reached 70 million kilometers globally [5,6], which is equivalent to 1700 times the circumference of the Earth's equator.

Along with human civilization and development of civil engineering, road construction materials have also been continuously upgraded. From times before the Christ until the 19th century CE, rocks, pebbles, gravels, wood and pottery fragments were the main forms of pavement materials [3]. People also explored the use of other types of materials for road pavement. In 615s BC, asphalt was recorded as a material to build road in ancient Babylon [7]. In the 1500s, the Peruvian Incas used materials similar to modern bituminous macadam to pave their highway system [8,9]. In 1848, the first road with asphalt Macadam pavement was paved outside of Nottingham, UK, using coal tar as the binder [10]. In 1865, the first road with cement concrete was built in Inverness, Scotland [11,12]. Later in the 19th century, cement concrete and asphalt mixture became the main types of high-grade pavement materials. Continuous improvement on material performance has provided lower pavement roughness and higher skid resistance, meeting people's growing needs for fast and safe travel. The 20th century witnessed extensive studies on polymer material science and consequently, a significant boost in pavement service life and stability, with the use of various modified asphalt materials and high-performance cement.

People's requirements for ecological sustainability became increasingly high when the industrial civilization reached a certain level, and people realized that roads are not only a means for transporting people and goods but also an important component of the environment. A road is expected to play a role in infiltrating rainwater, reducing tire noise, de-icing, and purifying tailpipe exhaust gas, in addition to its basic functions (i.e. load bearing, evenness, durability and comfort). Since the beginning of the 21st century, the emergence of new functional materials and the development of interdisciplinary science have made the design and construction of environmentally friendly functional pavements possible, which

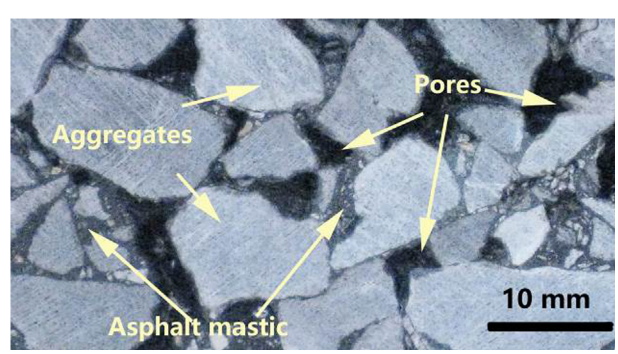


Fig. 1. Point contact between aggregates in permeable asphalt concrete.

have subsequently resulted in the expansion of research in pavement materials. To improve on ecological and environmental performance of road infrastructure, the development of environmentally friendly functional pavement materials, poses challenges as well as opportunities to road engineers and researchers.

This study focused on state-of-the-art research on the performance, applications and challenges of six environmentally friendly functional pavement materials, namely the permeable asphalt concrete (Section 2), noise-reducing pavement materials (Section 3), low heat-absorbing pavement materials (Section 4), exhaust gas-decomposing pavement materials (Section 5), de-icing pavement materials (Section 6), and energy harvesting pavement materials (Section 7). With this paper, we aim to provide an abundance of references to the design and development of environmentally friendly functional pavement materials.

2. Permeable asphalt pavement material

2.1. Functional requirements for pavement permeability

The pores on the ground surface enable rainwater to seep into the ground, which helps to restore moisture in the natural soil, regulate atmosphere humidity, facilitate plant growth, maintain surface water pressure, and replenish the groundwater. When pavement materials, such as asphalt concrete or cement concrete, are paved and compacted, rainwater is impeded from direct infiltration and the moisture cycle between the underground and aboveground spaces is blocked. These effects, together with the exploitation and excessive use of groundwater in some regions, have led to a series of problems, including considerable reduction in rainwater infiltration, ecological imbalance, and ground subsidence [13–15]. In addition, the impermeable pavement surface contributes to the formation of water films, or accumulation of water, on the pavement surface [16], which leads to vehicle drifting and water splash, thus causing traffic accidents [17,18]. Moreover, traditional impermeable pavement surfaces can cause an abrupt rise in surface runoff in the event of storms, resulting in urban inundation [19,20]. For these reasons, permeable pavement materials have attracted wide interest.

2.2. Permeable asphalt concrete

Permeable asphalt concrete is a type of gap-graded mix material with a porosity of 16% to 25%. The porosity is achieved by increasing the proportion of coarse aggregates with a nominal size of >4.75 mm and reducing the proportion of aggregates sized between 2.36 mm and 4.75 mm [21,22].

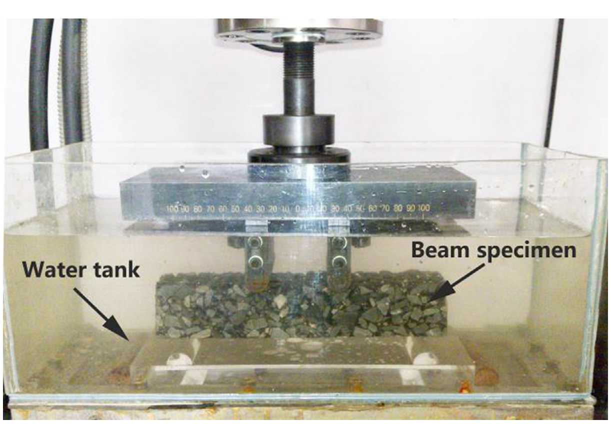


Fig. 2. Permeable asphalt concrete fatigue test under submerged condition.

Unlike traditional compact pavement materials which have full-face contact between aggregates, aggregates in permeable asphalt concrete form only point contact between each other as shown in Fig. 1. Due to the contact area being substantially reduced, the requirements for mixture design and component materials are higher, in order to maintain the strength, stability and durability of the mixture. In terms of binder selection, modified asphalt is usually used, with variations in the type and content in different regions due to varying environmental and traffic conditions [23,24]. Styrene-butadiene-styrene (SBS) modified asphalt or rubber asphalt are often used in the United States and Europe [25,26]. Hydrated lime, taking up to 1% aggregate weight and cellulose fibers, at a rate of 0.3% by total weight of the mixture [27,28], are added to reduce stripping and improve water stability [21,29]. In Asian countries, such as China, Japan, and Singapore, high-viscosity bitumen (viscosity > 20000 Pa·s) is commonly used [30–32]. Epoxy asphalt and Trinidad NAF 501 natural asphalt have also been used for permeable asphalt concretes in some studies [33,34].

To improve durability and anti-stripping property of the mix, permeable asphalt concrete is often produced with excessive asphalt binder (typically 4.5–6.0% or even more) to generate a 12 μm to 14 μm thick asphalt binder film, while the film thickness in a dense-graded asphalt concrete is about 8 μm to 10 μm [21]. In addition, a decreased inter-aggregate contact area leads to increased contact stress, calling for mixture stability and aggregate strength [35,36]; resultantly, basalt and diabase with high strength are commonly used [37]. Moreover, the content of elongated aggregate particles in permeable asphalt concrete should be strictly controlled, usually no >10% to 15%, to reduce fine grading and porosity caused by aggregate breakdown [32].

Wheel tracking test was used to evaluate the high temperature stability of permeable asphalt concrete. The evaluation index was Dynamic Stability. As a result of the use of modified asphalt and skeleton structure, permeable asphalt concrete usually shows excellent high temperature stability. The rutting dynamic stability usually reaches 5000 times/mm when the high-viscosity asphalt is used [22], far exceeding the requirements of 3000 times/mm for dense-graded modified asphalt mixture, in accordance with the standard [38]. Furthermore, the coating of thick asphalt binder film and the use of additives such as lime, have provided the concrete with adequate water stability. Freeze-thaw split test was used to evaluate the moisture susceptibility of permeable asphalt concrete. The evaluation index was Tensile Strength Ratio (TSR). Generally, the Tensile Strength Ratio (TSR) can reach 80% for dense graded modified asphalt mixtures. On the other hand, pores and limited inter-aggregate contact have adverse effects on the anti-fatigue performance and crack resistance [22]. Findings from fatigue test under submerged condition (Fig. 2) suggested that with an increase of porosity, anti-fatigue performance of the permeable asphalt concrete decreases, and the sensitivity of fatigue life to change in stress level increases; however, water immersion does not have a significant influence on the fatigue performance [39]. When permeable asphalt concrete is used in low temperature, the crack resistance can be improved in several ways, such as by reducing porosity, increasing the amount of asphalt and modifier, and adding fiber [37,40].

The rainfall intensity is considered in the design of air void for permeable asphalt concrete. Generally, an air voids content of about 20% was used, so that the permeability coefficient can reach 0.4–0.5 cm·s^{-1}, which can meet the permeability demand of roads during heavy rain. When permeable asphalt concrete is used for surface layer, the thickness is usually 40–50 mm in a single layer and 70–100 mm in a double layer. Drainage is provided by the road side of permeable asphalt pavement. As for pavement surface mixture, NCAT (National Center for Asphalt Technology) and ASTM (American Society for Testing and Materials) International (D 7064-04) suggested a minimum permeability coefficient of 100 m/day [41]. In permeable asphalt concrete, there is a good correlation between permeability and porosity, especially with interconnected pores [22]. In addition, there is a mathematical relationship between porosity and the composition of concrete. For example, for permeable asphalt concrete with a nominal maximum aggregate size (NMAS) of 13 mm, the relationship between permeability coefficients and concrete composition can be established via the constant head permeability test [22], by setting different sieve pore passing rates (4.75 mm, 2.36 mm, and 0.075 mm) and limiting the content of aggregates sized 1.18 mm to 2.36 mm, as shown in the following equation.

$$k = 0.0089e^{0.1942(33.878-0.095P_{4.75}-0.545P_{2.36}-0.090P_{1.18\sim2.36}-0.549P_{0.075})} \quad (1)$$

where k is the permeability coefficient (cm/s). $P_{4.75}$, $P_{2.36}$ and $P_{0.075}$ are the 4.75 mm, 2.36 mm and 0.075 mm sieve pore passing rates (%), respectively. $P_{1.18\sim2.36}$ is the mass percentage (%) of aggregates with particle size between 1.18 mm and 2.36 mm.

2.3. Engineering applications and challenges

Permeable asphalt concrete has been widely used in European countries in recent years, including the Netherlands, Germany, Denmark, Switzerland and Austria [37]. Over 90% of major highways in the Netherlands are paved with permeable asphalt concrete [26]. The material is known as open-graded friction course (OGFC) and used in various states of the United States, such as Texas, Virginia, Georgia, Alabama, North Carolina, New Mexico, Arizona, Tennessee, Louisiana, California and Florida [21,24,27]. Permeable asphalt concrete has also been widely used in road construction in Asian countries including China, Japan, South Korea and Singapore. In particular, Japan has requirement for the use of permeable asphalt concrete in all expressways to improve road safety since the release of "Guide for porous asphalt pavement" in November 1996 [42]. Moreover, permeable asphalt concrete is used in pavement surface in many Chinese provinces, especially in coastal (eastern) and southern regions, to improve skid resistance and reduce surface water spray in wet conditions [32].

In the long-term use, with the repeated wheel load and the aging of asphalt binder, the accumulation of particles and contaminants on the pavement surface cause the pore clogging and other main problems of permeable asphalt concrete such as raveling and spalling, which shortens the PAC's service life compared with dense-graded asphalt pavement [26]. To tackle the problem of pore clogging, some research institutions have developed a special maintenance truck for permeable asphalt pavement to maintain the permeability function of the pavement. The main principle of such maintenance truck is to use high pressure water jet with

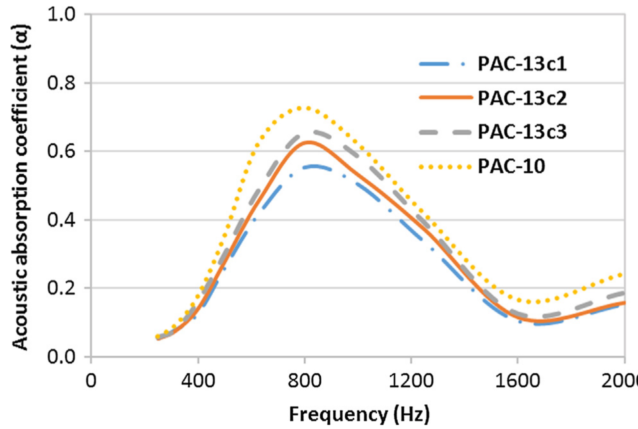


Fig. 4. Acoustic absorption coefficients for different PAC mixtures.

concurrent suction to rush out the clogging from the pore [43]. This specialized maintenance causes an increase in costs. As a result, studies on raw materials, especially on asphalt binder's properties and maintenance techniques, are of great importance for the improvement of road performance, durability, and reduction of the life-cycle cost of permeable asphalt concrete.

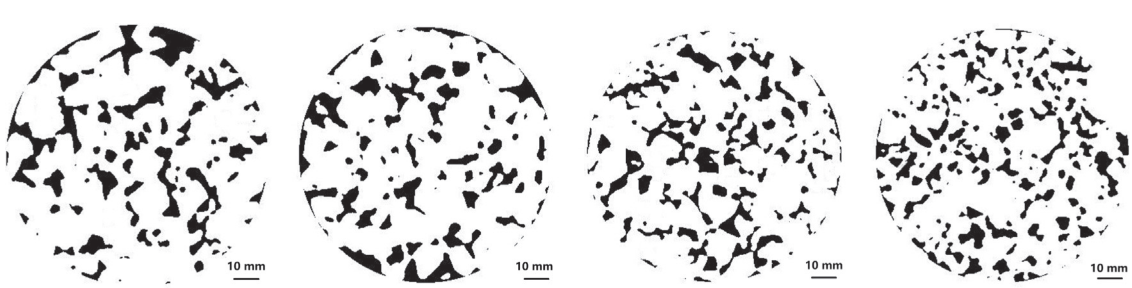
3. Noise-reducing pavement material

3.1. Functional requirements for reducing pavement noise

The growing number of vehicles has led to a serious problem of traffic noise to urban residents and roadway ecology. Traffic noise is mainly generated by the interaction between tires and road surface [44–46]. The factors affecting tyre/road noise mainly include: pavement characteristics (aggregates properties, texture depth, air voids content, etc.), tire characteristics (tread pattern and depth, tire type and pressure, etc.), environmental factors (temperature, pavement moisture, dust, etc.) and human factors of the drivers (e.g. speed) [47–51]. Research findings have suggested that the noise produced by tire/road surface contact is the predominant source of noise when the vehicle speed exceeds 40 km/h to 50 km/h [52]. Soundproof structures, such as sound barriers, can prevent noise from horizontal propagation, but are found less capable of restricting the reflection of noise; also, they take up limited urban space and affect pavement lighting [53]. As a result, reducing tire/road noise by using adequate pavement materials has become an important means to reducing traffic noise.

3.2. Porous noise-reducing asphalt concrete

The use of porous asphalt concrete (PAC) can reduce pavement noise thanks to the principle of noise reduction by pores. Porous



a) PAC-13c1 b) PAC-13c2 c) PAC-13c3 d) PAC-10

Fig. 3. Typical cross sections of PAC.

pavement materials contain a large number of pores that are connected. Therefore, the "air pumping action" between a tire and the pavement is significantly weakened [54]. A porous structure also enhances the acoustic impedance of pavement materials, leading to the transmission and interference of tire/pavement noise within the pavement, which helps with energy dissipation, reduction of noise generated at the source, and pavement noise impedance [55].

Similar to the water infiltration, pavement noise reduction can be achieved by using PAC. However, there is a difference in the pore structure design between low noise asphalt concrete and permeable asphalt concrete. As mentioned above, the permeability of asphalt concrete depends mainly on interconnected porosity; whereas for low noise asphalt concrete, the noise reducing ability of concrete is affected by various parameters other than porosity, such as the number, spatial distribution and dimension of the pores [56,57].

Fig. 3 shows four typical cross-sections of PAC obtained by X-ray equipment, where the black color represents air voids. While the air voids contents of the four mixtures, are similar (20% ± 0.3%), the number and dimension of pores in cross-section are significantly different. Fig. 4 shows the acoustic absorption curve of the four mixtures obtained by an impedance tube [58] at different frequencies. Among them, PAC-10 exhibits the best noise reduction effect across all frequencies, followed by PAC-13c2, PAC-13c3, and PAC-13c1. It can be concluded that the effect of noise reduction is not the same for the PAC with similar air voids content, because the spatial distribution, number and dimension of pores inside the mixtures are different, which changes the acoustic impedance of the material [22,55]. An analysis of the influence of air voids content on the noise absorbing performance of the PAC shows that the peak value of the absorption coefficient increases as the air voids content increases. With a constant air voids content, the peak absorption coefficient decreases as the dimension of pores increases [55].

As demonstrated in previous study [22], the noise reduction can be effectively improved by adopting fine gradations of the aggregates and reducing the NMAS, given the same air voids content of the PAC mixes. Therefore, when noise reduction is the primary concern in pavement design, PAC with smaller NMAS, such as PAC-10 or even PAC-8, can be used. In addition, the air voids content of PAC is generally designed to be large, often about 23%, to form a void structure that is suitable for dissipating acoustic energy.

The noise reduction effect is also related to vehicle speed. The higher the speed, the greater reduction in noise can be achieved [55,59]. In general, the noise levels of porous asphalt pavements measured by statistical pass-by method are about 3 dB to 6 dB lower than that of dense asphalt pavement [60].

3.3. Engineering applications and challenges

In Asia and the United States, porous asphalt pavements are designed for effective skid resistance and drainage; whereas in Europe noise reduction is the priority where porous asphalt pavement materials are used [61]. According to the European design experience, two-layer of PAC, which consists of a 25 mm-thick upper layer with coarse aggregates sized between 4 mm and 8 mm, and a 45 mm-thick lower layer with coarse aggregates sized between 11 mm and 16 mm, is found to have a better noise reduction effect [26]. The noise reduction measured by statistical pass-by method can be 5 dB to 6 dB [62]. Similar to permeable asphalt concrete, raveling, spalling and loss of noise reduction effect over time remain the major issues for porous noise-reducing asphalt concrete [55].

4. Low heat-absorbing pavement material

4.1. Functional requirements for low heat absorption by pavement

Currently, large cities in the world suffer from the urban heat island effect (i.e. the temperatures in downtown areas are significantly higher than in the suburbs) and the problem is becoming increasingly serious [63,64]. Heat island brings adverse effects on the urban environment in various aspects, such as an increase of energy demand for cooling, which leads to more air pollutants and greenhouse gas emissions, lowered groundwater quality, and endangerment of urban biodiversity and human health [65,66].

Urban heat island is a combined effect of human activities and local meteorological conditions during urbanization. The causes of urban heat island effect include the characteristics of urban ground surface, greenhouse gas emissions, concentration of heat sources, and air pollution. Roads are a major cause of urban heat island effect [67,68]. Pavement surface in the city, especially asphalt pavement, has changed the original thermal properties of the natural ground surface. The temperature of asphalt pavement surface rises rapidly under solar radiation to 65–70 °C, a temperature that is significantly higher than that of natural ground surface [69,70]. Furthermore, the pavement surface absorbs and stores heat during the day and releases it at night, which aggravates the urban heat island effect [69]. Thus, changing the thermal properties of pavement materials is a crucial measure of alleviating the urban heat island effect. For example, using pavement materials with a large thermal resistance coefficient, applying light-colored or heat-reflective coating materials on road surfaces, as well as using pavement materials with good capacity of absorbing and retaining

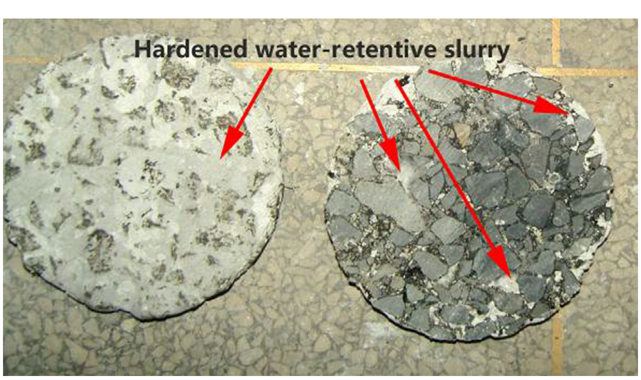


Fig. 5. Water-retentive asphalt concrete specimens, surface (left) and cut section (right).

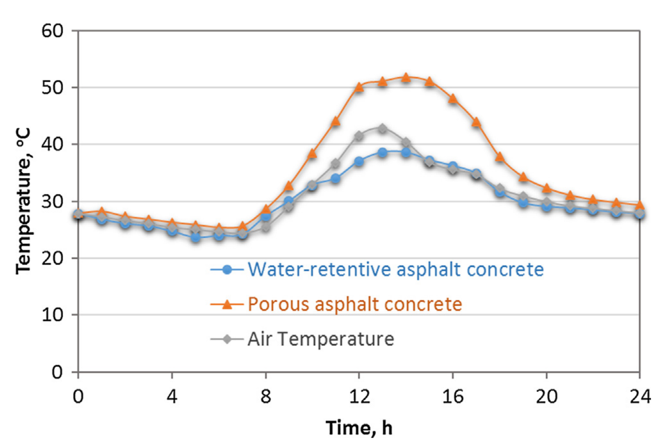


Fig. 6. Outdoor temperature test results of porous asphalt concrete and water-retentive asphalt concrete.

water are common measures [71]. By reducing the capacity of heat storage, the amount of heat released from the road can be reduced, and the comfort of pedestrians and residents nearby can be improved. Besides, this will also help to reduce permanent deformation of asphalt pavement caused by high temperatures and thus, prolong pavement service life [72,73].

4.2. Water-retentive asphalt concrete

Water-retentive asphalt concrete is derived from porous asphalt concrete in which the pores are stuffed with water-retentive slurry (Fig. 5). The slurry absorbs and stores water after curing and hardening, enabling the pavement materials to store excessive water from rainfall or artificial watering. At high temperature, the continuous moisture evaporation will help reduce the pavement temperature, relieve local heat island effect, and maintain a comfortable road environment for pedestrians and vehicles [74].

Water-retentive slurry is prepared by using ground granulated blast furnace slag powder, fly ash, alkali activator (which usually is hydrated lime) and water. Some additives, such as silica fume, cement and water reducer, can also be added to improve the asphalt concrete's freezing resistance, strength, and workability [68]. Apart from the inorganic materials that are used for slurry preparation, a certain amount of water-absorbent resin can also be added to absorb water continuously, and enhance the material's water retention capacity. However, the difficulty in dispersing the water-absorbent resin during blending needs to be addressed in practice.

To ensure that the slurry materials can be injected and retained in the pores of porous asphalt concrete, the water-retentive slurry should have excellent liquidity: a liquidity index of 8 s to 12 s is required using the method of flow grout for pre-placed aggregate concrete (ASTM C 939-02) [75]. Asphalt concrete with water-retentive slurry stuffed in the pores is considered superior to porous asphalt concrete in strength, high and low-temperature performance, and moisture susceptibility [74].

Fig. 6 shows the temperature variation of water-retentive asphalt concrete and porous asphalt concrete slabs surface by outdoor test. The slab specimens were immersed in the water outdoor for 8 h to obtain the same initial temperature (27.9 °C). It can be seen that the variation curves of the two mixtures were following the air temperature with a time delay. However, compared to porous asphalt concrete, water-retentive asphalt concrete had a much smaller temperature rise along with the air temperature variation. The maximum temperature difference between the two mixes was 13 °C at around 14:00.

The cooling effect of water-retentive asphalt concrete is closely related to pavement surface evaporation, water content, and surface reflectivity [76,77]. At high temperatures, water-retentive asphalt concrete, in its full capacity, can reduce the temperature by 10 °C to 15 °C or more compared with traditional asphalt concrete. Furthermore, water-retentive asphalt concrete can reduce the pavement surface temperature by 8 °C in the day and 3 °C at night. In addition, a layer of 10 cm water-retentive asphalt concrete can maintain the pavement's cooling ability for about one week after absorbing rainwater [78,79].

4.3. Engineering applications and challenges

Currently, the uses of water-retentive asphalt concrete are limited to laboratory tests and filed trials. Reports on use in large-scale projects are rare, which is partly attributed to the complicated construction process. The cooling effect of water-retentive asphalt concrete on the surrounding environment is achieved by evaporation of the retained water. As a result, water-retentive asphalt concrete has potential for applications in regions with periodic rainfall and seasonal high temperatures. Further research and development for water-retentive materials should focus on the performance in water absorption, water retention, strength and stability; also worth further work are the methods for high-efficiency construction, and durability of water-retentive asphalt concrete during freezing and thawing in cold regions.

5. Exhaust gas-decomposing pavement material

5.1. Demands for exhaust gas decomposition on pavement surface

Exhaust gases from automobile contain a large volume of Carbon Monoxide (CO), Hydrocarbon (HC) and Nitrogen oxides (NO_x), and are an important source of urban air pollution [80]. The pavement surface is the initial contact with the exhaust gas after tailpipe emission, which suggests that should the decomposition and purification take place on pavement surface, it can be an effective way of reducing urban air pollution.

5.2. Exhaust gas-decomposing pavement material

Exhaust gas-decomposition by pavement materials can be achieved by using photocatalysis technologies [81]. A photocatalyst is applied to the pavement surface to catalyze the oxidation (in the presence of sunlight) of CO, HC, and NO_x into carbonates and nitrates, which will be absorbed by the pavement surface and then washed away by rainwater or artificial watering (Fig. 7). The photocatalytic materials remain unchanged during this process. Materials that can be used as photocatalysts include Titanium Oxide (TiO_2), zinc oxide (ZnO), zirconium dioxide (ZrO_2) and cadmium sulfide (CdS), among which TiO_2 has attracted most attention due to its excellent photocatalytic activity, chemical stability, and recyclability [82–85]. Over the past few years, studies on

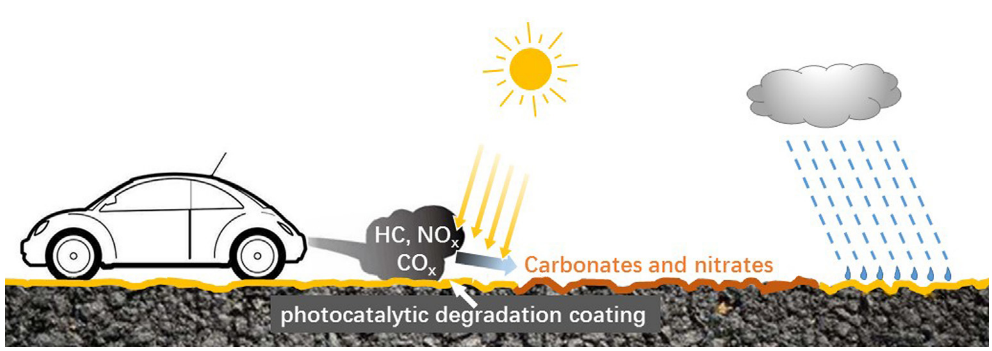


Fig. 7. Schematic of exhaust gas-decomposing pavement material.

exhaust gas decomposition using TiO_2 have focused on improving the catalytic efficiency, especially under visible light. Variations of TiO_2 in some studies include the nanometer TiO_2 [86], modified TiO_2 by adding metal ions to prepare materials such as Fe-TiO_2 [87], and modified TiO_2 by adding non-metal ions to prepare materials with high catalytic efficiency, such as $TiO_{2-x}N_x$ which has lattice oxygen in TiO_2 partially replaced by non-metal nitrogen [88]. All those materials have been found to enhance the photocatalytic activity and exhaust gas-decomposing efficiency of TiO_2 [89].

There are two ways of using TiO_2 in exhaust gas-decomposing pavement materials [84,90]: (1) TiO_2 is used in the preparation of water-based coating, which is directly coated on the surface of asphalt concrete; (2) TiO_2 is used as a filler and added to asphalt concrete during the blending process. TiO_2 is likely to be wrapped by the asphalt binder, therefore the distribution of TiO_2 particles is limited when added to the mixture during the blending; thus, direct coating of TiO_2 has a higher photocatalytic efficiency compared with the blending method.

The efficiency of TiO_2 can be affected by environmental conditions, such as temperature, humidity, illumination intensity, and presence of contaminants on the pavement surface such as dust and oil [91,92]. Exhaust gas-decomposing materials prepared by different researchers also vary from one to another due to the use of different photocatalysts materials, experiment conditions, and evaluation methods. By testing the photocatalytic efficiency of nanometer TiO_2 coated onto the surface of asphalt concrete, Hassan et al. found that the degradation rate of NO_x in the air could reach 31% to 55% [84]. A report by Venturini and Bacchi found that the decomposition efficiency of different types of TiO_2 ranged from 20.4% to 57.4%, and that anatase TiO_2 showed the best degradation effect [83]. Field tests on road sections conducted by Folli Andrea et al. indicated that with ideal climate and light conditions, the daily average density of NO within a road area can be reduced by 22% compared with the normal pavement [80].

5.3. Engineering applications and challenges

Tests on road sections paved with exhaust gas-decomposing material are seen in various regions, including Milan (Italy), Copenhagen (Denmark), and Nanjing (China) [80,83,93]. However, exhaust gas-decomposing pavement materials have been used mainly in laboratory studies and there is a lack of applications in large projects for the following reasons: 1) Exhaust gas-decomposition efficiency is less satisfactory on actual pavement surface owing to the low light intensity, environmental temperature, humidity, and wind. 2) TiO_2-coating on the pavement surface is found less durable due to abrasion by tires [80,83,92]. 3) Exhaust gas-decomposing coating is usually applied at the cost of a decreased pavement texture depth, which reduces its skid resistance. As a result, further studies on exhaust gas-decomposing pavement materials should focus on improving the durability of the purification effect, and balance with skid resistance of the pavement surface. Furthermore, the development of standard test methods, and equipment for construction and maintenance are also necessary.

It is worth noting that although titanium dioxide is odorless, and considered to be non-toxic, non-irritating, chemically and mechanically stable [94], it still poses potential health hazards. According to the preliminary collated list of carcinogens released by the International Agency for Research on Cancer (IAC) of the World Health Organization, titanium dioxide is listed as a category 2B carcinogen [95]. Potential pollution of road surface runoff water, including threshold value, concentration measurement and pathway modelling, should be considered in future research.

6. De-icing pavement material

6.1. Demands for de-icing pavement surface

Snowy weather can lead to reduction in vehicle speed, which affects journey time and results in an increase of fuel consumption and emissions. Snow and ice on the pavement surface also result in a low friction coefficient and thus, a higher likelihood of traffic accidents [96]. Snow and ice can be removed by hand sweeping, mechanical sweeping or applying a melting agent [97]. However, these methods present the following disadvantages: hand sweeping has a low operation speed and causes delays; mechanical sweeping is costly, and some machines may damage the pavement surface during operation; snow/ice-melting agents lead to pollution (of water, soil, and air) and erosion of pavement materials, vehicles, and ancillary facilities [98]. In the event of extremely low temperature or excessive snowfall, snow/ice-melting agents may not be effective in a timely manner [99]. The aforementioned approaches are known as passive de-icing techniques as they are applied externally in response to adverse climate incidents.

6.2. Active de-icing pavement materials

Researchers have conducted studies on the active de-icing pavement. The de-icing pavement materials are roughly divided into three types, namely the anti-freezing pavement materials, energy-converting pavement materials, and salt de-icing pavement materials.

Anti-freezing pavement materials include elastic pavement materials and rough pavement materials. The elastic is made by adding a certain amount of highly elastic materials to the pavement surface to change the contact between the pavement and tire, and the deformation characteristics of the pavement surface. By this method, ice and snow can be broken by the stress on the pavement surface generated from traffic load, thus effectively preventing the accumulation of snow and ice [100,101]. The most commonly used elastic materials are rubber particles that can be obtained from recycled tires [102].

Open-graded asphalt concrete, such as porous asphalt concrete, is often used to enhance the pavement's texture depth and roughness [103]. When the pavement is covered with ice, non-uniform stress on the snow/ice layer makes it difficult to form ice under the traffic load. With this method, broken ice will be removed by horizontal force of the vehicles, a larger texture depth is also benefitial to the skid resistance of the pavement surface.

Examples of energy-converting de-icing methods include the heating cable, solar heating, terrestrial heat tube, heating wire, and infrared lamp heating. Energy storage and conversion devices, such as pipes and cables, are laid within the pavement which enable the increase of temperature by the heat generated from electricity, solar panels, thermal energy or natural gas, for melting or preventing ice [104–106].

Apart from the two active de-icing technologies, salt de-icing methods, such as adding rock salts (NaCl or $CaCl_2$) to the asphalt concrete are used to reduce the freezing point and prevent icing formed on the pavement surface [107,108].

6.3. Engineering applications and challenges

Elastic pavement materials have not yet shown promising results in durability, evenness, and de-icing efficiency; therefore, it is currently used only in laboratory and road trial tests. As the de-icing effect is influenced by various factors, including environment temperature and traffic flow, the elastic pavement material

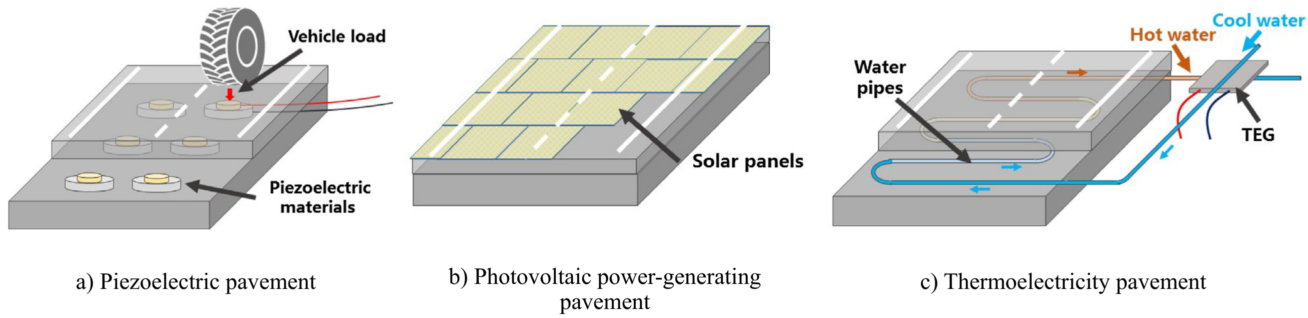


Fig. 8. Schematic of energy harvesting pavements.

performs less effectively in breaking ice when the temperature is lower than minus 12 °C and the ice thickness exceeds 9 mm [109].

Energy-converting pavement materials have undergone long-term research and tests in various countries, such as the United States, Japan, China and Europe including Switzerland, Iceland, Norway and Poland. Example road projects include the Goleniow airport in Poland [110], the A8 Express road in Switzerland [111,112], the Gardermoen parking apron in Norway [113], and the Gaia system for highway and ramp in Japan [114,115]. Energy-converting de-icing pavement is known for its cleanliness, being environmentally friendly, and high de-icing efficiency [116,117]; however, construction of this type of pavement is very difficult, it requires great initial investment and on-going maintenance during use [118-121]. As a result, this method is more applicable to road sections for airports, bridges, bends and large-gradient longitudinal slopes.

Salt de-icing pavement materials have been applied and tested on road sections in Switzerland, Germany, Japan, China and the United States [107,108]. With a small amount of salt added, the long-term de-icing effect on the pavement remains doubtful as the salt is released gradually. In addition, the effect of salts on pavement materials and the surrounding environment, such as corrosion, needs further investigation.

7. Energy harvesting pavement material

7.1. Demands for energy harvesting from pavement surface

A large amount of thermal energy and mechanical energy is generated within the pavement when the road serves the traffic. For example, dark (i.e. asphalt) pavement absorbs solar radiation and the thermal energy accumulates within the pavement; furthermore, mechanical energy is generated from the dynamic load on the pavement when the vehicle tire passes [122–124]. In recent years, energy harvesting from road pavement has become a research focus in the context of global energy shortage, environmental pollution, and climate change [125–127].

7.2. Energy harvesting pavement materials

Studies on the use of kinetic energy focus on the following aspects: 1) Piezoelectric pavement technology (Fig. 8a), i.e. embedding piezoelectric materials in the pavement and converting part of the mechanical energy generated by the vehicle load into electric energy [128,129]. 2) Photovoltaic (PV) power-generating pavement (Fig. 8b), i.e. paving the road using solar panels instead of traditional asphalt concrete or cement concrete to convert solar energy absorbed by the PV panels into electric energy [130,131]. 3) Thermoelectric pavement technology (Fig. 8c), i.e. converting the heat absorbed by the pavement, especially asphalt pavement, into electric energy using the thermoelectric module (TEG) embedded in pavement structure [124]. Fig. 8 presents the schematic of the three types of energy harvesting pavements.

A good number of laboratory tests and simulation studies have been carried out on the piezoelectric pavement technology. For example, Bowen and Near have patented a piezoelectric actuator for road pavements [132], which was developed recently [133]. The system developed by Abramovich et al. was tested in a real road environment by Innowattech using a product called Innowattech Piezo Electric Generator (IPEG) [134,135].

For the photovoltaic power-generating pavement technology, TNO in the Netherlands has paved a solar energy powered bicycle lane using a 10 mm–thick glass as the top layer of the pavement, underneath which crystalline silicon solar panels are laid [136]. Julie and Scott Brusaw proposed a solar collector system to replace the upper layer of the road pavement, called Solar Roadway, which consisted of a series of structurally engineered solar panels [137].

The principle of the thermoelectric pavement technology is that the temperature difference between the two ends of the thermoelectric module is used to generate a voltage. The greater the temperature difference, the higher voltage is generated. However, making full use of the temperature gradient within the pavement structure or between the pavement and the surroundings remains a key challenge for this technology. Wu et al. improved the power generating efficiency by connecting high thermal conducting materials to the subgrade and taking advantage of the temperature difference between subgrade and pavement [138,139]. Hasebe et al. managed to improve the thermoelectric efficiency of pavement by embedding water pipes in the pavement to collect heat, i.e. cool water from a river nearby was introduced to increase the temperature difference of the thermoelectric module [140].

7.3. Engineering applications and challenges

The above pavement energy-harvesting technologies are mostly at a stage of laboratory testing or field trial, because the many technical difficulties remain unsolved for practical use. The main barriers to using piezoelectric pavement include the inadequate durability of piezoelectric materials due to repeated load on the pavement, low compatibility with traditional pavement materials, and the necessity of a second energy conversion because of the electric power that generate instant high voltage and low current cannot be used directly [129,141,142]. The challenges for photovoltaic pavement include: 1) Development of new solar panels is needed to replace traditional pavement materials. 2) The durability and stability of a photovoltaic panel must be adequate to resist the effect of external factors, such as vehicle load, rainwater, snow and ice. 3) The decreasing efficiency of solar panels after abrasion by vehicles and accumulation of dust should be addressed, along with riding comfort, skid resistance, and reparability [122]. Currently, the use of temperature gradient-based thermoelectric pavement technology is limited by its low power-generating efficiency [124,143,144].

8. Summary and conclusions

(1) With the growing traffic and demand for sustainability, the road that serves as a critical transport infrastructure is also changing its intrinsic functions, i.e. from structures that were designed and built for passing vehicles to ecological assets with significant economic importance to the built environment. In addition to basic load bearing functions and durability, people now have more expectations of the road, such as noise reduction, alleviation of urban heat island effect, de-icing, and exhaust gas absorption, to provide road users and the public with a better transport environment and travel experience.

(2) The above-mentioned pavement functions can be obtained in multiple ways. This paper only exemplified a few engineering measures. For instance, in addition to the porous asphalt concrete, rubber asphalt (containing elastic rubber particles) pavement is also found to have a positive effect on noise reduction. Apart from water-retentive asphalt concrete, light-colored pavement is also effective in reducing the pavement temperature and thus alleviating the urban heat island effect, by means of sunlight reflection.

(3) Abundant pore structures make porous asphalt concrete effective in water permeation and noise reduction. Porous asphalt is also in favor of additional functions, such as low heat absorption (water-retentive pavement), de-icing, and exhaust gas decomposition. The material also provides large texture depths and coating areas, which provide skid resistance and facilitate the application of coating materials. Porous asphalt concrete pavements have attracted increasing attention; however, there are fundamental differences between porous and conventional pavement materials with regard to their composition, structure, and performance. As a result, further studies are needed on the construction methods, maintenance techniques, mechanical models, testing and evaluation methods.

(4) The different functions and performance requirements often contradict each other in terms of material composition and behavior, and pavement design criteria. For instance, exhaust gas-decomposing and de-icing functions can be achieved by applying coatings on the pavement surface, at a cost of reduction in texture depth, which reduces its skid resistance. Water permeation and noise reduction of porous asphalt concrete is achieved by increasing porosity, at a cost of low temperature performance, anti-stripping and durability. Therefore, keeping an adequate balance between the functions fit for a specific use is a crucial challenge for engineers and researchers when designing functional pavement.

(5) Researchers have carried out a considerable number of studies on different pavement functions, but the majority of studies focused on achieving a single function. Further studies should highlight the design of pavement materials with multiple function requirements by traffic demand and environmental protection, i.e. de-icing with an energy harvesting ability and meanwhile permeable, noise-reducing pavement.

(6) The functions of environmentally friendly pavement can be achieved generally in two ways. One is to obtain the pavement function by means of structural design or performance enhancement using traditional engineering materials, e.g. porous asphalt concrete and water-retentive asphalt concrete. The other way is to add novel materials to the asphalt concrete mix, apply them onto the pavement surface, or embed them underneath a pavement structural layer. It is foreseeable that, with the rapid development of material science and sensor technology, findings from research on existing civil engineering materials will further extend and enrich other environment-friendly functions of road pavement.

(7) Apart from pavement design and construction technologies, maintenance and recycling techniques for existing asphalt concrete are also growing increasingly robust, which is an important supplement to studies of material composition and structural design.

Conflict of interest

No potential conflict of interest was reported by the authors.

Acknowledgements

This project was jointly supported by the National Natural Science Foundation of China (Grant No. 51608043), the Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2015KJXX-23), the Fundamental Research Funds for the Central Universities (Grant No. 310821172001), and the Construction Science and Technology Plan in Shaanxi Province of China (Grant No. 2015-K99).

References

[1] S. Shirley, A Brief History of Road Building, < http://www.triplenine.org/Vidya/OtherArticles/ABriefHistoryofRoadBuilding.aspx>; [Accessed July 2, 2018].
[2] Road, Word concept (in Chinese), <https://baike.baidu.com/item/%E9%81%93%E8%B7%AF/18791?fr=aladdin>.
[3] K. Jenkins, Introduction to Road Pavements. In: Hitchhiker's Guide to Pavement Engineering, <http://www.citg.tudelft.nl/fileadmin/Faculteit/CiTG/Over_de_faculteit/Afdelingen/Afdeling_Bouw/-_Secties/Sectie_Weg_en_Railbouwkunde/-_Leerstoelen/Leerstoel_Wegbouwkunde/-_Onderwijs/-_College_Dictaten/doc/Introduction_to_Roads_KJJ.pdf>; [Accessed February 20, 2017].
[4] Silk Road, About the Silk Road, <http:// http://en.unesco.org/silkroad/about-silk-road>; [Accessed February 20, 2017].
[5] R. Chattaraj, History of Road Development in India, < http://www.academia.edu/18195464/History_of_Road_development_in_India>; [Accessed March 15, 2017].
[6] Introduction: World, < http://teacherlink.ed.usu.edu/tlresources/reference/factbook/geos/countrytemplate_xx.html>; [Accessed March 15, 2017].
[7] History of Asphalt, <http://www.asphaltpavement.org/index.php?option=com_ content&view=article&id=21&Itemid=41>; [Accessed March 15, 2017].
[8] F.J. Benson, M.G. Lay, Roads and highways, <https://global.britannica.com/technology/road>; [Accessed March 15, 2017].
[9] A. Folli, M. Strom, T.P. Madsen, T. Henriksen, J. Lang, J. Emenius, T. Klevebrant, A. Nilsson, Field study of air purifying paving elements containg TiO2, Atomspheric Environ. 107 (2015) 44–51.
[10] Asphalt, Paving & Construction-The History of Asphalt, <http://www.lafarge-na.com/wps/portal/na/en/3_C_2_2-History>; [Accessed March 15, 2017].
[11] First Concrete Pavement, <http://www.asce.org/project/first-concrete-pavement/>; [Accessed March 15, 2017].
[12] Concrete Pavement Facts, <http://www.concreteconstruction.net/projects/infrastructure/concrete-pavement-facts_o>; [Accessed March 15, 2017].
[13] M. Scholz, P. Grabowiecki, Review of permeable pavement systems, Build. Environ. 42 (2007) 3830–3836.
[14] B.J. Wardynski, R.J. Winston, W.F. Hunt, Internal Water Storage Enhances Exfiltration and Thermal Load Reduction from Permeable Pavement in the North Carolina Mountains, J. Environ. Eng. 139 (2013) 187–195.
[15] T. Asaeda, V.T. Ca, Characteristics of permeable pavement during hot summer weather and impact on the thermal environment, Build. Environ. 35 (2000) 363–375.
[16] C.J. Pratt, J.D.G. Mantle, P.A. Schofield, UK research into the performance of permeable pavement, reservoir structures in controlling storm-water discharge quantity and quality, Water Sci. Technol. 32 (1995) 63–69.
[17] K.A. Collins, W.F. Hunt, J.M. Hathaway, Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina, J. Hydrol. Eng. 13 (2008) 1146–1157.
[18] K.A. Collins, W.F. Hunt, J.M. Hathaway, Evaluation of various types of permeable pavement with respect to water quality improvement and flood control, in: 8th International Conference on Concrete Block Paving, San Francisco, California USA, 2006.
[19] M.E. Barrett, Effects of a Permeable Friction Course on Highway Runoff, J. Irrig. Drain. Eng. 134 (2008) 646–651.

[20] M.A. Rahman, M.A. Imteaz, A. Arulrajah, J. Piratheepan, M.M. Disfani, Recycled construction and demolition materials in permeable pavement systems: geotechnical and hydraulic characteristics, J. Cleaner Prod. 90 (2015) 183–194.
[21] A.E. Alvarez, A.E. Martin, C. Estakhri, A review of mix design and evaluation research for permeable friction course mixtures, Constr. Build. Mater. 25 (2011) 1159–1166.
[22] W. Jiang, A. Sha, J. Xiao, Experimental study on relationships among composition, microscopic void features, and performance of porous asphalt concrete, J. Mater. Civ. Eng. 27 (2015) 04015028.
[23] A.M. Al-Rubaei, A.L. Stenglein, M. Viklander, G. Blecken, Long-Term hydraulic performance of porous asphalt pavements in Northern Sweden, Irrigation and Drainage Engineering. 139 (2013) 499–505.
[24] A.E. Alvarez, A.E. Martin, C. Estakhri, Drainability of permeable friction course mixtures, J. Mater. Civ. Eng. 22 (2010) 556–564.
[25] F. Frigio, E. Pasquini, M.N. Partl, F. Canestrari, Use of reclaimed asphalt in porous asphalt mixtures: Laboratory and Field Evaluations, J. Mater. Civ. Eng. 27 (2014) 04014211.
[26] Y. Zhang, M.V.D. Ven, A. Molenaar, S. Wu, Preventive maintenance of porous asphalt concrete using surface treatment technology, Mater. Des. 99 (2016) 262–272.
[27] W.D. Martin, B.J. Putman, A.I. Neptune, Influence of aggregate gradation on clogging characteristics of porous asphalt mixtures, J. Mater. Civ. Eng. 26 (2014).
[28] M.L. Afonso, M. Dinis-Almeida, C.S. Fael, Study of the porous asphalt performance with cellulosic fibres, Constr. Build. Mater. 135 (2017) 104–111.
[29] F. Frigio, S. Raschia, D. Steiner, B. Hofko, F. Canestrari, Aging effects on recycled WMA porous asphalt mixtures, Constr. Build. Mater. 123 (2016) 712–718.
[30] A. Moriyoshi, T. Jin, T. Nakai, H. Ishikawa, Evaluation methods for porous asphalt pavement in service for fourteen years, Constr. Build. Mater. 42 (2013) 190–195.
[31] A. Moriyoshi, T. Jin, T. Nakai, H. Ishikawa, K. Tokumitsu, A. Kasahara, Construction and pavement properties after seven years in porous asphalt with long life, Constr. Build. Mater. 50 (2014) 401–413.
[32] Q.Q. Liu, D.W. Cao, Research on material composition and performance of porous asphalt pavement, J. Mater. Civ. Eng. 21 (2009) 135–140.
[33] L.D. Poulikakos, M.N. Partl, A multi-scale fundamental investigation of moisture induced deterioration of porous asphalt concrete, Constr. Build. Mater. 36 (2012) 1025–1035.
[34] P. Herrington, D. Alabaster, Epoxy Modified Open graded Porous Asphalt, Road Mater. Pavement Des. 9 (2008) 481–498.
[35] G.D. Airey, A.E. Hunter, A.C. Collop, The effect of asphalt mixture gradation and compaction energy on aggregate degradation, Constr. Build. Mater. 22 (2008) 972–980.
[36] E. Mahmoud, E. Masad, S. Nazarian, Discrete element analysis of the influences of aggregate properties and internal structure on fracture in asphalt mixtures, J. Mater. Civ. Eng. 22 (2010) 10–20.
[37] D. Wang, M. Oeser, Interface treatment of longitudinal joints for porous asphalt pavement, Int. J. Pavement Eng. 17 (2015) 741–752.
[38] Ministry of Transport, Technical specification for construction of highway asphalt pavements, JTG F40-2004, P.R. China (in Chinese) (2005a)
[39] W. Jiang, A. Sha, J. Pei, S. Chen, H. Zhou, Study on the fatigue characteristic of porous asphalt concrete, J. Build. Mater. 15 (2012) 513–517 (in Chinese with English summary).
[40] L. Poulikakos, S. Takahashi, M.N. Partl, Coaxial Shear Test and Wheel Tracking Tests for Determining Porous Asphalt Mechanical Properties, Road Mater. Pavement Des. 8 (2007) 579–594.
[41] R.B. Mallick, P. Kandhal, J.L. Cooley, D.E. Watson, Design construction, and performance of new generation open-graded friction courses, Auburn, AL: National Center for Asphalt Technology, NCAT Report, USA, 2000.
[42] Association of Japan Highway, Guide for porous asphalt pavement, Maruzen Corporation, Tokyo, 1996.
[43] J.D. Baladès, M. Legret, H. Madiec, Permeable pavements: Pollution Management Tools, Water Sci. Technol. 32 (1995) 49–56.
[44] J. Nelson, E. Kohler, A. Öngel, B. Rymer, Acoustical absorption of porous pavement, J. Transp. Res. Board. 2058 (2008) 125–132.
[45] S.N. Suresha, V. George, A.U.R. Shankar, Effect of aggregate gradations on properties porous friction course mixes, Mater. Struct. 43 (2010) 789–801.
[46] R.K. Mishra, M. Parida, S. Rangnekar, Evaluation and analysis of traffic noise along bus rapid transit system corridor, Int. J. Environ. Sci. Technol. 7 (2010) 737–750.
[47] T. Beckenbauer, Road Traffic Noise, in: G. Müller, M. Möser (Eds.), Handbook of Engineering Acoustics, Springer, Berlin, Heidelberg, 2013.
[48] M.C. Berengier, M.R. Stinson, G.A. Daigle, J.F. Hamet, Porous road pavements: acoustical characterization and propagation effects, J. Acoust. Soc. Am. 101 (1997) 155–162.
[49] M. Bueno, J. Luong, U. Vinuela, F. Teran, S.E. Paje, Pavement temperature influence on close proximity tire/road noise, Appl. Acoust. 72 (2011) 829–835.
[50] T. Fujikawa, H. Koike, Y. Oshino, H. Tachibana, Definition of road roughness parameters for tire vibration noise control, Appl. Acoust. 66 (2005) 501–512.
[51] R. Goleblewski, R. Makarewicz, M. Nowak, A. Preis, Traffic noise reduction due to the porous road surface, Appl. Acoust. 64 (2003) 481–494.
[52] H. Bendtsen, B. Andersen, Noise-Reducing Pavements for Highways and Urban Roads – State of the Art in Denmark, J. Assoc. Asphalt Paving Technol. 74 (2005) 1085–1106.
[53] K. Choi, J.H. Kim, K. Shin, Economic Feasibility Analysis of Roadway Capacity Expansion with Accounting Traffic Noise Barrier Cost, KSCE J. Civil Eng. 8 (2004) 117–127.
[54] L. Mo, M. Huurman, S. Wu, Mortar fatigue model for meso-mechanistic mixture design of raveling resistant porous asphalt concrete, Mater. Struct. 47 (2014) 947–961.
[55] R. Tonin, Quiet Road Pavements: Design and Measurement—State of the Art, Acoust. Australia 44 (2016) 235–247.
[56] M. Losa, P. Leandri, A comprehensive model to predict acoustic absorption factor of porous mixes, Mater. Struct. 45 (2012) 923–940.
[57] W. Jiang, A.M. Sha, Evaluation of Anti-clogging Property of Porous Asphalt Concrete Using Microscopic Voids Analysis, Multi-Scale Modeling and Characterization of Infrastructure Materials, RILEM Bookseries 8 (2012) 159–172.
[58] ASTM International, Standard test method for impedance and absorption of acoustical materials Using a tube, two microphones and a digital frequency analysis system, E1050, Philadelphia, 1998.
[59] L. Chu, T.F. Fwa, K.H. Tan, Evaluation of wearing course mix designs on sound absorption improvement of porous asphalt pavement, Constr. Build. Mater. 141 (2017) 402–409.
[60] Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 1: Statistical pass-by method, ISO 11819-1, 1997.
[61] M. Miradi, A.A.A. Molenaar, M.F.C. van de Ven, Performance Modelling of Porous Asphalt Concrete using Artificial Intelligence, Road Mater. Pavement Des. 10 (2012) 263–280.
[62] M. Liu, X.M. Huang, G.Q. Xue, Effects of double layer porous asphalt pavement of urban streets on noise reduction, Int. J. Sustain. Built Environ. 5 (2016) 183–196.
[63] W.Q. Zhou, Y.G. Qian, X.M. Li, W.F. Li, L.J. Han, Relationships between land cover and the surface urban heat island: seasonal variability and effects of spatial and thematic resolution of land cover on predicting land surface temperatures, Landscape Ecol. 29 (2014) 153–167.
[64] T. Karlessi, M. Santamouris, A. Synnefa, D. Assimakopoulos, P. Didaskalopoulos, K. Apostolakis, Development and testing of PCM doped cool colored coatings to mitigate urban heat island and cool buildings, Build. Environ. 46 (2011) 570–576.
[65] C. Wamsler, E. Brink, C. Rivera, Planning for climate change in urban areas: from theory to practice, J. Cleaner Prod. 50 (2013) 68–81.
[66] M. Hendel, M. Colombert, Y. Diab, L. Royon, Improving a pavement-watering method on the basis of pavement surface temperature measurements, Urban Clim. 10 (2014) 189–200.
[67] N. Anting, M.F. Din, K. Lwao, M. Ponraj, K. Jungan, L.Y. Yong, A.J.L.M. Siang, Experimental evaluation of thermal performance of cool pavement material using waste tiles in tropical climate, Energy Build. 142 (2017) 211–219.
[68] M. Santamouris, A. Synnefa, T. Karlessi, Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions, Sol. Energy 85 (2011) 3085–3102.
[69] J.Q. Chen, H. Wang, H.Z. Zhu, Analytical approach for evaluating temperature field of thermal modified asphalt pavement and urban heat island effect, Appl. Therm. Eng. 113 (2017) 739–748.
[70] B. Teltayev, K. Aitbayev, Modeling of Temperature Field in Flexible Pavement, Indian Geotech. 45 (2015) 371–377.
[71] M. Santamouris, N. Gaitani, A. Spanou, Using cool paving materials to improve microclimate of urban areas - Design realization and results of the flisvos project, Build. Environ. 53 (2012) 128–136.
[72] R.B. Mallick, D. Singh, A. Veeeraragavan, Extension of Asphalt Pavement Life by Reduction of Temperature, Transp. Dev. Econ. (2016) 2–7.
[73] A. Motamed, H.U. Bahia, Incorporating temperature into the constitutive equation for plastic deformation in asphalt binders, Constr. Build. Mater. 29 (2012) 647–658.
[74] W. Jiang, A.M. Sha, J.J. Xiao, Z.J. Wang, Alex Apeagyei, Experimental study on materials composition design and mixture performance of water-retentive asphalt concrete, Constr. Build. Mater. 111 (2016) 128–138.
[75] ASTM C 939-02, Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method), American Society for Testing and Materials, Philadelphia, 2002.
[76] K. Ishimaru, K. Mssai, Effects of Thermal Mitigation on a Water-retentive Pavement, Memoirs of Akashi National College of Technology (2007).
[77] H. Yamagata, M. Nasu, M. Yoshizawa, A. Miyamoto, M. Minamiyama, Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater, Water Sci. Technol. 57 (2008) 763–771.
[78] K. Takahashi, K. Yabuta, Road Temperature Mitigation Effect of "Road Cool", a Water-Retentive Material Using Blast Furnace Slag, JFE Technical Report (2009).
[79] T. Nakayamaa, T. Fujita, Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas, Landscape Urban Plann. 96 (2010) 57–67.
[80] A. Folli, M. Strom, T.P. Madsen, T. Henriksen, J. Lang, J. Emenius, T. Klevebrant, A. Nilsson, Field study of air purifying paving elements containing TiO_2, Atmos. Environ. 107 (2015) 44–51.
[81] A. Fujishima, X. Zhang, D.A. Tryk, TiO2 photocatalysis and related surface phenomena. Surface Sci. Rep. 63 (2008) 515–582. <https://doi.org/10.1016/j.surfrep.2008.10.001>; [Accessed May 20, 2017].

[82] J.K. Sikkema, J.E. Alleman, T. Cackler, P.C. Taylor, B. Bai, S.K. Ong, K. Gopalakrishnan, Photocatalytic Pavements, Climate Change, Energy, Sustainability and Pavements Part of the series Green Energy and Technology 26 (2014) 275–307.
[83] L. Venturini, M. Bacchi, Research, Design and Development of a Photocatalytic Asphalt Pavement, Venturini Loretta: Photocatalytic Asphalt Pavements, RNVIROAD, 2009, Research Institute of Roads and Bridges, Poland, 2009.
[84] M. Hassan, H. Dylla, S. Asadi, L.N. Mohammad, S. Cooper, Laboratory Evaluation of Environmental Performance of Photocatalytic Titanium Dioxide Warm-Mix Asphalt Pavements, J. Mater. Civ. Eng. 24 (2012) 599–605.
[85] H. Dylla, M.M. Hassan, Characterization of nanoparticles released during construction of photocatalytic pavements using engineered nanoparticles, J. Nanopart. Res. 14 (2012). 825 825.
[86] B. Zielińska, A.W. Morawski, TiO2 photocatalysts promoted by alkali metals, Appl. Catal. B 55 (2005) 221–226.
[87] M. Chen, J.W. Chu, NOx photocatalytic degradation on active concrete road surface-from experiment to real-scale application, J. Cleaner Prod. 19 (2011) 1266–1272.
[88] R. Asahi, T. Morikawa, T. Ohwaki, Visible-Light photocatalysis in nitrogen-doped titanium oxides, Science 293 (2001) 269–271.
[89] Y.Y. Jimmy, H. Wingkei, Y. Jiaguo, Efficient visible-light-induced photocatalytic disinfection on sulfur-doped nanocrystalline titania, Environ. Sci. Technol. 39 (2005) 1175–1179.
[90] M. Hassan, L.N. Mohammad, S. Asadi, H. Dylla, S. Cooper, Sustainable photocatalytic asphalt pavements for mitigation of nitrogen oxide and sulfur dioxide vehicle emissions, J. Mater. Civ. Eng. 25 (2013) 365–371.
[91] S. Asadi, M. Hassan, A. Nadiri, H. Dylla, Artificial intelligence modeling to evaluate field performance of photocatalytic asphalt pavement for ambient air purification, Environ. Sci. Pollut. Res. 21 (2014) 8847–8857.
[92] C. Brovelli, M. Crispino, Photocatalytic Suspension for Road Pavements: Investigation on Wearing and Contaminant Effects, J. Mater. Civ. Eng. 25 (2013) 548–554.
[93] E. Boonen, A. Beeldens, Photocatalytic roads: from lab tests to real scale applications, Eur. Transp. Res. Rev. 5 (2013) 79–89.
[94] Wikipedia, Titanium dioxide, <https://en.wikipedia.org/wiki/Titanium_dioxide>; [Accessed July 1, 2018].
[95] Agents Classified by the IARC Monographs, Volumes 1–122, < https://monographs.iarc.fr/ENG/Classification/ClassificationsGroupOrder.pdf>; [Accessed July 1, 2018].
[96] D.M. Gray, D.H. Male, Handbook of snow: Principles, processes, management & use, Second Ed., The Blackburn Press, New Jersey, USA, 1981.
[97] M. Viklander, K. Reinosdotter, Road salt infuence on pollutant releases from melting urban snow, Water Qual. Res. J. Can. 42 (2007) 153–161.
[98] L. Fay, X. Shi, Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge, Water Air Soil Pollut. 223 (2012) 2751–2770.
[99] M. Esen, A. Balbay, Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks, Scientific Res. Essays 5 (2010) 3955–3966.
[100] D.L. Presti, Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: a literature review, Constr. Build. Mater. 49 (2013) 863–881.
[101] Epps Uses of recycled rubber tyres in highways, DC: Synthesis of Highway Practice No.198, TRB National Research Council, NCHRP Report, Washington, 1994.
[102] H. Wei, Q.Q. He, Y.B. Jiao, J.F. Chen, M.X. Hu, Evaluation of anti-icing performance for crumb rubber and diatomite compound modified asphalt mixture, Constr. Build. Mater. 107 (2016) 109–116.
[103] S. Macdonald, Porous asphalt shows advantages for trail surfacing, <https://americantrails.org/resources/trailbuilding/Porous-asphalt-Middleton-Wisconsin.html>; [Accessed January 5, 2017].
[104] K. Mensah, J.M. Choi, Review of technologies for snow melting systems, J. Mech. Sci. Technol. 29 (2015) 5507–5521.
[105] A.D.W. Nuijten, K.V. Høyland, Comparison of melting processes of dry uncompressed and compressed snow on heated pavements, Cold Reg. Sci. Technol. 129 (2016) 69–76.
[106] H.N. Xu, Y.Q. Tan, Modeling and operation strategy of pavement snow melting systems utilizing low-temperature heating fluids, Energy. 80 (2015) 666–676.
[107] Z.Z. Liu, A.M. Sha, R. He, M.L. Xing, Antifreeze asphalt mixtures design and antifreeze performances prediction based on the phase equilibrium of natural solution, Cold Reg. Sci. Technol. 129 (2016) 104–113.
[108] M.L. Zheng, C.T. Wang, L.L. Han, Y.Q. Sun, Y.F. Li, Z.H. Ma, Laboratory evaluation of long-term anti-icing performance and moisture susceptibility of chloride-based asphalt mixture, Int. J. Pavement Res. Technol. 9 (2016) 140–148.
[109] C.X. Zhou, Y.Q. Tan, Study of De-icing Performance of Crumb Rubber Granular Asphalt Mixture, J. Build. Mater. 12 (2009) 672–675 (in Chinese with English summary).
[110] K. Zwarycz, Snow melting and heating systems based on geothermal heat pumps at Goleniow airport, Geothermal Training Programme, The United Nations University Report, Poland, 2002.
[111] W.J. Eugster, J. Schatzmann, Harnessing solar energy for winter road clearing on heavily loaded expressways, in: Proceedings of the new challenges for winter road service XIth international winter road congress, 2002.
[112] J. Walter, Eugster, Road and bridge heating using geothermal energy, Overview and Examples, in: Proceedings European Geothermal Congress, Unterhaching, Germany, 2007.
[113] G. Eggen, G. Vangsnes, Heat pump for district cooling and heating at Oslo Airport, Gardermoen, in: Proceedings of the eighth IEA heat pump conference, Las Vegas, USA, 2005.
[114] K. Morita, M. Tago, Operational characteristics of the Gaia snow-melting system in Ninohe, in: Proceedings of the World Geothermal Congress, Iwate, Japan, 2000.
[115] K. Morita, M. Tago, Snow-melting on sidewalks with ground-coupled heat pumps in a heavy snowfall city, Proc. in World Geothermal Congress, Antalya, 2005.
[116] V.B. Jesus, P.P. Muñoz, D.C. Fresno, J.R. Hernandez, Asphalt solar collectors: a literature review, Appl. Energy 102 (2013) 962–970.
[117] W.J. Eugster, J. Schatzmann, Harnessing solar energy for winter road clearing on heavily loaded expressways, in: Proceedings of the New Challenges for Winter Road Service XIth International Winter Road Congress, 2002.
[118] R.B. Mallick, B. Chen, S. Bhowmick, Harvesting energy from asphalt pavements and reducing the heat island effect, Int. J. Sustainable Eng. 2 (2009) 214–228.
[119] L.D. Minsk, Heated Bridge Technology, Report on Istea, Publication No. FHWARD-99-158, U.S. Department of Transportation, 1999.
[120] J. Spitler, M. Ramamoorthy, Bridge deck deicing using geothermal heat pumps, in: Proceedings of the 4th, International Heat Pumps in Cold Climated Conference, Aylmer, Quebec, 2000.
[121] J. Zhao, H. Wang, Z. Chen, H. Qu, Seasonal behavior of pavement in geothermal snow-melting system with solar energy storage, Trans. Tianjin Univ. 12 (2006) 319–324.
[122] S.A. Andriopoulou, Review on Energy Harvesting from Roads, KTH, Stockholm, Sweden, 2012.
[123] A. Dawson, R. Mallick, A.G. Hernandez, P.K. Dehdezi, Energy Harvesting from Pavements, Green Energy and Technology, Springer Press, 2014.
[124] F. Duarte, A. Ferreira, Energy harvesting on road pavements: state of the art, in: Proceedings of the ICE-Energy. 169 (2016) 79–90
[125] J. Webb, D. Hawkey, M. Tingey, Governing cities for sustainable energy: the UK case, Cities 54 (2016) 28–35.
[126] Intergovernmental Panel on Climate Change (IPCC). Summary for policymakers. Climate Change 2014, Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, pp. 1–32.
[127] A. Khaligh, O.C. Onar, Solar, Wind, and Ocean Energy Conversion Systems, Energy Harvesting (2010).
[128] J. Tao, J. Hu, Energy harvesting from pavement via polyvinylidene fluoride: hybrid piezo-pyroelectric effects, J. Zhejiang Univ.-Sci. A (Appl. Phys. Eng.) 17 (2016) 502–511.
[129] H.D. Zhao, Y.J. Tao, Y.L. Niu, J.M. Ling, Harvesting energy from asphalt pavement by piezoelectric generator, Journal of Wuhan University of Technology-Mater, Sci. Ed. 10 (2014) 933–937.
[130] W.K. Won, A.J. Correia, A Pilot Study for Investigation of Novel Methods to Harvest Solar Energy from Asphalt Pavements, Korea Institute of Construction Technology (KICT), Goyang City, South Korea, 2010.
[131] Z. Zhou, X. Wang, X. Zhang, G. Chen, J. Zuo, S. Pullen, Effectiveness of pavement solar energy system – an experimental study, Appl. Energy 138 (2015) 1–10.
[132] L. Bowen, C. Near, Low Voltage Piezoelectric Actuator, US Patent 6,111,818, 2000.
[133] C. Near, Power Generator. US Patent US20130207520 A1, 2013.
[134] H. Abramovich, C. Milgrom, E. Harash, L. Azulay, U. Amit, Multi-Layer Modular Energy Harvesting Apparatus, System And Method, US Patent US20100045111 A1, 2010.
[135] Innowattech, <http://www.innowattech.co.il/>; [Accessed April 21, 2017].
[136] TNO. SolaRoad: paving the way to the roads of the future. < https://www.tno.nl/media/4574/solaroadtechnology.pdf>; [Accessed February 6, 2017].
[137] SR (Solar Roadways). <http://www.solarroadways.com>; [Accessed February 6, 2017].
[138] G. Wu, X. Yu, Thermal energy harvesting across pavement structures, Proceedings of the Transportation Research Board (TRB) 91st Annual Meeting, Transportation Research Board, Washington, DC, USA, 2012.
[139] G. Wu, X. Yu, Computer-aided design of thermal energy harvesting system across pavement structure, Int. J. Pavement Res. Technol. 6 (2013) 73–79.
[140] M. Hasebe, Y. Kamikawa, S. Meiarashi, Thermoelectric generators using solar thermal energy in heated road pavement, In Proceedings ICT '06 – 25th International Conference on Thermoelectrics (ICT), Vienna, Austria. IEEE – Institute of Electrical and Electronics Engineers, New York, NY, USA, 2006.
[141] L. Guo, Q. Lu, Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements, Renew. Sustain. Energy Rev. 72 (2017) 761–773.
[142] H. Roshani, S. Dessouky, A. Montoya, A.T. Papagiannakis, Energy harvesting from asphalt pavement roadways vehicle-induced stresses: a feasibility study, Appl. Energy 182 (2016) 210–218.
[143] W. Jiang, D. Yuan, S. Xu, H. Hu, J. Xiao, A. Sha, Y. Huang, Energy harvesting from asphalt pavement using thermoelectric technology, Appl. Energy 205 (2017) 941–950.
[144] W. Jiang, J. Xiao, D. Yuan, H. Lu, S. Xu, Y. Huang, Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions, Energy Build. 169 (2018) 39–47.