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A Review of Eco-Friendly Functional Road Materials

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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.

Keywords: Road materials, Functional pavement, Eco-friendly, Sustainable construction

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 BC, 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 BC 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 1,700 times the circumference of the Earth's

36 equator.

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

51 People's requirements for ecological sustainability became increasingly high when the
52 industrial civilization reached a certain level, and people realized that roads are not only a means
53 for transporting people and goods but also an important component of the environment. A road is
54 expected to play a role in infiltrating rainwater, reducing tire noise, de-icing, and purifying tailpipe
55 exhaust gas, in addition to its basic functions (i.e. load bearing, evenness, durability and comfort).
56 Since the beginning of the 21st century, the emergence of new functional materials and the
57 development of interdisciplinary science have made the design and construction of
58 environmentally friendly functional pavements possible, which have subsequently resulted in the
59 expansion of research in pavement materials. To improve on ecological and environmental
60 performance of road infrastructure, the development of environmentally friendly functional
61 pavement materials, poses challenges as well as opportunities to road engineers and researchers.

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

69 2. Permeable asphalt pavement material

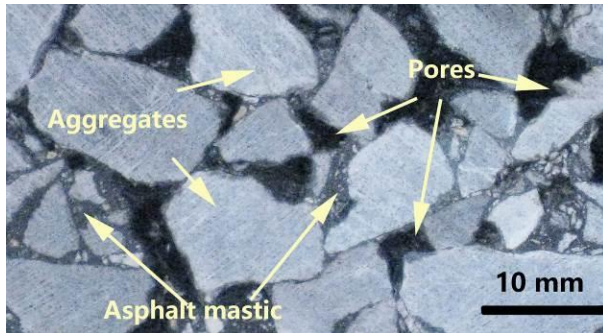
70 *2.1. Functional requirements for pavement permeability*

71 The pores on the ground surface enable rainwater to seep into the ground, which helps to
72 restore moisture in the natural soil, regulate atmosphere humidity, facilitate plant growth, maintain
73 surface water pressure, and replenish the groundwater. When pavement materials, such as asphalt
74 concrete or cement concrete, are paved and compacted, rainwater is impeded from direct
75 infiltration and the moisture cycle between the underground and aboveground spaces is blocked.
76 These effects, together with the exploitation and excessive use of groundwater in some regions,
77 have led to a series of problems, including considerable reduction in rainwater infiltration,
78 ecological imbalance, and ground subsidence [13-15]. In addition, the impermeable pavement
79 surface contributes to the formation of water films, or accumulation of water, on the pavement
80 surface [16], which leads to vehicle drifting and water splash, thus causing traffic accidents
81 [17,18]. Moreover, traditional impermeable pavement surfaces can cause an abrupt rise in surface
82 runoff in the event of storms, resulting in urban inundation [19,20]. For these reasons, permeable
83 pavement materials have attracted wide interest.

84 *2.2. Permeable asphalt concrete*

85 Permeable asphalt concrete is a type of gap-graded mix material with a porosity of 16% to
86 25%. The porosity is achieved by increasing the proportion of coarse aggregates with a nominal
87 size of > 4.75 mm and reducing the proportion of aggregates sized between 2.36 mm and 4.75 mm
88 [21, 22].

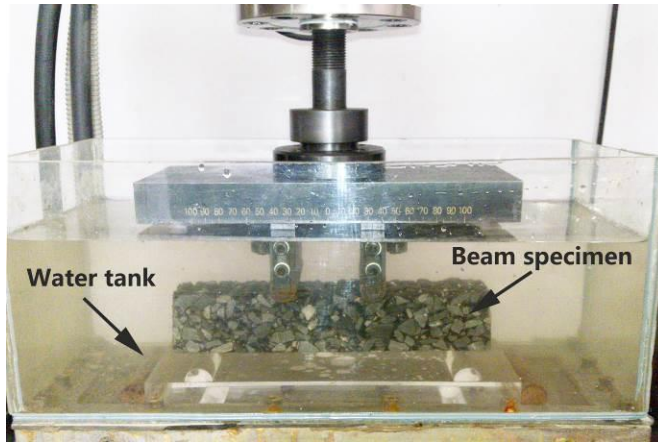
89 Unlike traditional compact pavement materials which have full-face contact between
90 aggregates, aggregates in permeable asphalt concrete form only point contact between each other
91 as shown in Fig. 1. Due to the contact area being substantially reduced, the requirements for
92 mixture design and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



102
103 **Fig. 1** Point contact between aggregates in permeable asphalt concrete

104 To improve durability and anti-stripping property of the mix, permeable asphalt concrete is
 105 often produced with excessive asphalt binder (typically 4.5-6.0% or even more) to generate a
 106 12 μ m to 14 μ m thick asphalt binder film, while the film thickness in a dense-graded asphalt
 107 concrete is about 8 μ m to 10 μ m [21]. In addition, a decreased inter-aggregate contact area leads to
 108 increased contact stress, calling for mixture stability and aggregate strength [35,36]; resultantly,
 109 basalt and diabase with high strength are commonly used [37]. Moreover, the content of elongated
 110 aggregate particles in permeable asphalt concrete should be strictly controlled, usually no more
 111 than 10% to 15%, to reduce fine grading and porosity caused by aggregate breakdown [32].

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



130
131 **Fig. 2** Permeable asphalt concrete fatigue test under submerged condition

132
133 The rainfall intensity is considered in the design of air void for permeable asphalt concrete.
134 Generally, an air voids content of about 20% was used, so that the permeability coefficient can
135 reach $0.4\text{-}0.5\text{ cm}\cdot\text{s}^{-1}$, which can meet the permeability demand of roads during heavy rain. When
136 permeable asphalt concrete is used for surface layer, the thickness is usually 40-50 mm in a single
137 layer and 70-100 mm in a double layer. Drainage is provided by the road side of permeable asphalt
138 pavement. As for pavement surface mixture, NCAT (National Center for Asphalt Technology) and
139 ASTM (American Society for Testing and Materials) International (D 7064-04) suggested a
140 minimum permeability coefficient of 100 m/day [41]. In permeable asphalt concrete, there is a
141 good correlation between permeability and porosity, especially with interconnected pores [22]. In
142 addition, there is a mathematical relationship between porosity and the composition of concrete.
143 For example, for permeable asphalt concrete with a nominal maximum aggregate size (NMAS) of
144 13mm, the relationship between permeability coefficients and concrete composition can be
145 established via the constant head permeability test [22], by setting different sieve pore passing
146 rates (4.75 mm, 2.36 mm, and 0.075 mm) and limiting the content of aggregates sized 1.18 mm to
147 2.36 mm, as shown in the following equation.

$$148 \quad k = 0.0089e^{0.1942(33.878 - 0.095P_{4.75} - 0.545P_{2.36} - 0.090P_{1.18-2.36} - 0.549P_{0.075})} \quad (1)$$

149 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
150 0.075 mm sieve pore passing rates (%), respectively. $P_{1.18-2.36}$ is the mass percentage (%) of
151 aggregates with particle size between 1.18 mm and 2.36 mm.

152 2.3. Engineering applications and challenges

153 Permeable asphalt concrete has been widely used in European countries in recent years,
154 including the Netherlands, Germany, Denmark, Switzerland and Austria [37]. Over 90% of major
155 highways in the Netherlands are paved with permeable asphalt concrete [26]. The material is
156 known as open-graded friction course (OGFC) and used in various states of the United States,

157 such as Texas, Virginia, Georgia, Alabama, North Carolina, New Mexico, Arizona, Tennessee,
158 Louisiana, California and Florida [24,27,21]. Permeable asphalt concrete has also been widely
159 used in road construction in Asian countries including China, Japan, South Korea and Singapore.
160 In particular, Japan has requirement for the use of permeable asphalt concrete in all expressways
161 to improve road safety since the release of “Guide for porous asphalt pavement” in November
162 1996 [42]. Moreover, permeable asphalt concrete is used in pavement surface in many Chinese
163 provinces, especially in coastal (eastern) and southern regions, to improve skid resistance and
164 reduce surface water spray in wet conditions [32].

165 In the long-term use, with the repeated wheel load and the aging of asphalt binder, the
166 accumulation of particles and contaminants on the pavement surface cause the pore clogging and
167 other main problems of permeable asphalt concrete such as raveling and spalling, which shortens
168 the PAC’s service life compared with dense-graded asphalt pavement [26]. To tackle the problem
169 of pore clogging, some research institutions have developed a special maintenance truck for
170 permeable asphalt pavement to maintain the permeability function of the pavement. The main
171 principle of such maintenance truck is to use high pressure water jet with concurrent suction to
172 rush out the clogging from the pore [43]. This specialized maintenance causes an increase in costs.
173 As a result, studies on raw materials, especially on asphalt binder’s properties and maintenance
174 techniques, are of great importance for the improvement of road performance, durability, and
175 reduction of the life-cycle cost of permeable asphalt concrete.

176 3. Noise-reducing pavement material

177 3.1. *Functional requirements for reducing pavement noise*

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

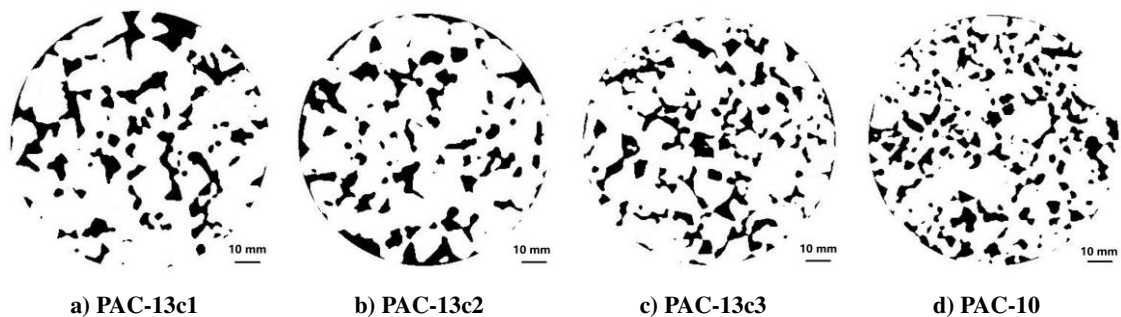
190 3.2. *Porous noise-reducing asphalt concrete*

191 The use of porous asphalt concrete (PAC) can reduce pavement noise thanks to the principle
192 of noise reduction by pores. Porous pavement materials contain a large number of pores that are
193 connected. Therefore, the “air pumping action” between a tire and the pavement is significantly
194 weakened [54]. A porous structure also enhances the acoustic impedance of pavement materials,
195 leading to the transmission and interference of tire/pavement noise within the pavement, which
196 helps with energy dissipation, reduction of noise generated at the source, and pavement noise
197 impedance [55].

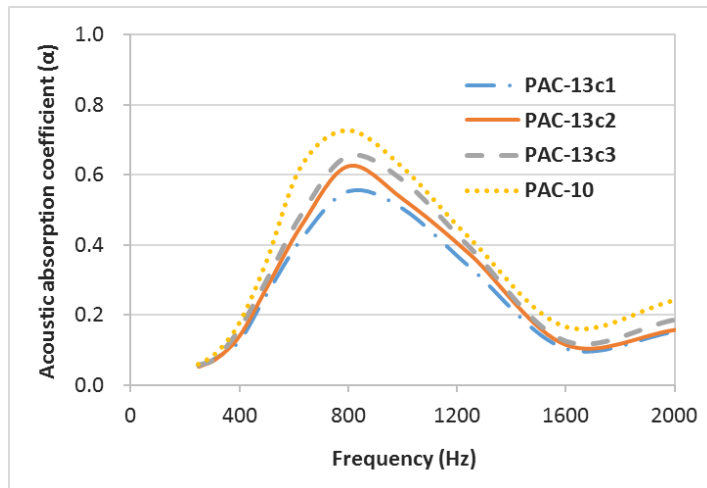
198 Similar to the water infiltration, pavement noise reduction can be achieved by using PAC.
199 However, there is a difference in the pore structure design between low noise asphalt concrete and
200 permeable asphalt concrete. As mentioned above, the permeability of asphalt concrete depends
201 mainly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

204 Fig. 3 shows four typical cross-sections of PAC obtained by X-ray equipment, where the
205 black color represents air voids. While the air voids contents of the four mixtures, are similar
206 ($20\% \pm 0.3\%$), the number and dimension of pores in cross-section are significantly different. Fig.
207 4 shows the acoustic absorption curve of the four mixtures obtained by an impedance tube [58] at
208 different frequencies. Among them, PAC-10 exhibits the best noise reduction effect across all
209 frequencies, followed by PAC-13c2, PAC-13c3, and PAC-13c1. It can be concluded that the effect
210 of noise reduction is not the same for the PAC with similar air voids content, because the spatial
211 distribution, number and dimension of pores inside the mixtures are different, which changes the
212 acoustic impedance of the material [22,55]. An analysis of the influence of air voids content on the
213 noise absorbing performance of the PAC shows that the peak value of the absorption coefficient
214 increases as the air voids content increases. With a constant air voids content, the peak absorption
215 coefficient decreases as the dimension of pores increases [55].

216



217 **Fig. 3** Typical cross sections of PAC



218

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

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

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

230 3.3. Engineering Applications and Challenges

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

240 4. Low heat-absorbing pavement material

241 4.1. Functional requirements for low heat absorption by pavement

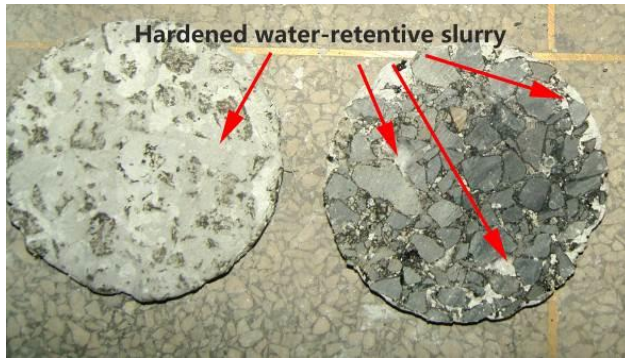
242 Currently, large cities in the world suffer from the urban heat island effect (i.e. the
 243 temperatures in downtown areas are significantly higher than in the suburbs) and the problem is

244 becoming increasingly serious [63,64]. Heat island brings adverse effects on the urban
245 environment in various aspects, such as an increase of energy demand for cooling, which leads to
246 more air pollutants and greenhouse gas emissions, lowered groundwater quality, and
247 endangerment of urban biodiversity and human health [65,66].

248 Urban heat island is a combined effect of human activities and local meteorological
249 conditions during urbanization. The causes of urban heat island effect include the characteristics
250 of urban ground surface, greenhouse gas emissions, concentration of heat sources, and air
251 pollution. Roads are a major cause of urban heat island effect [67,68]. Pavement surface in the city,
252 especially asphalt pavement, has changed the original thermal properties of the natural ground
253 surface. The temperature of asphalt pavement surface rises rapidly under solar radiation to
254 65–70°C, a temperature that is significantly higher than that of natural ground surface [69,70].
255 Furthermore, the pavement surface absorbs and stores heat during the day and releases it at night,
256 which aggravates the urban heat island effect [69]. Thus, changing the thermal properties of
257 pavement materials is a crucial measure of alleviating the urban heat island effect. For example,
258 using pavement materials with a large thermal resistance coefficient, applying light-colored or
259 heat-reflective coating materials on road surfaces, as well as using pavement materials with good
260 capacity of absorbing and retaining water are common measures [71]. By reducing the capacity of
261 heat storage, the amount of heat released from the road can be reduced, and the comfort of
262 pedestrians and residents nearby can be improved. Besides, this will also help to reduce permanent
263 deformation of asphalt pavement caused by high temperatures and thus, prolong pavement service
264 life [72,73].

265 *4.2. Water-retentive asphalt concrete*

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



272

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

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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 [75]. 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.

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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) [76]. 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].

287

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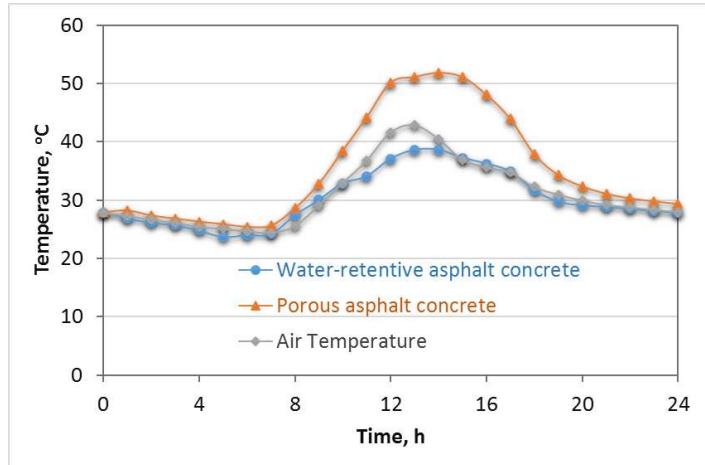
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Fig. 6 shows the temperature variation of water-retentive asphalt concrete and porous asphalt concrete slabs surface by outdoor test. The slab specimens were immersed in the water outdoor for 8 hours to obtain the same initial temperature (27.9 °C). 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.



294

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

296 The cooling effect of water-retentive asphalt concrete is closely related to pavement surface
 297 evaporation, water content, and surface reflectivity [77,78]. At high temperatures, water-retentive
 298 asphalt concrete, in its full capacity, can reduce the temperature by 10°C to 15°C or more
 299 compared with traditional asphalt concrete. Furthermore, water-retentive asphalt concrete can
 300 reduce the pavement surface temperature by 8°C in the day and 3°C at night. In addition, a layer
 301 of 10 cm water-retentive asphalt concrete can maintain the pavement’s cooling ability for about
 302 one week after absorbing rainwater [79,80].

303 *4.3. Engineering applications and challenges*

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

313 **5. Exhaust gas-decomposing pavement material**

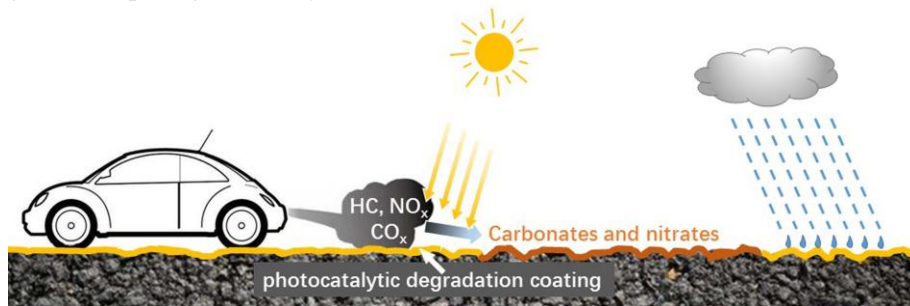
314 *5.1. Demands for exhaust gas decomposition on pavement surface*

315 Exhaust gases from automobile contain a large volume of Carbon Monoxide (CO),
 316 Hydrocarbon (HC) and Nitrogen oxides (NO_x), and are an important source of urban air pollution
 317 [81]. The pavement surface is the initial contact with the exhaust gas after tailpipe emission,
 318 which suggests that should the decomposition and purification take place on pavement surface, it

319 can be an effective way of reducing urban air pollution.

320 5.2. Exhaust gas-decomposing pavement material

321 Exhaust gas-decomposition by pavement materials can be achieved by using photocatalysis
322 technologies [82]. A photocatalyst is applied to the pavement surface to catalyze the oxidation (in
323 the presence of sunlight) of CO, HC, and NO_x into carbonates and nitrates, which will be absorbed
324 by the pavement surface and then washed away by rainwater or artificial watering (Fig. 7). The
325 photocatalytic materials remain unchanged during this process. Materials that can be used as
326 photocatalysts include Titanium Oxide (TiO₂), zinc oxide (ZnO), zirconium dioxide (ZrO₂) and
327 cadmium sulfide (CdS), among which TiO₂ has attracted most attention due to its excellent
328 photocatalytic activity, chemical stability, and recyclability [83-86]. Over the past few years,
329 studies on exhaust gas decomposition using TiO₂ have focused on improving the catalytic
330 efficiency, especially under visible light. Variations of TiO₂ in some studies include the nanometer
331 TiO₂ [87], modified TiO₂ by adding metal ions to prepare materials such as Fe-TiO₂ [88], and
332 modified TiO₂ by adding non-metal ions to prepare materials with high catalytic efficiency, such
333 as TiO_{2-x}N_x which has lattice oxygen in TiO₂ partially replaced by non-metal nitrogen [89]. All
334 those materials have been found to enhance the photocatalytic activity and exhaust
335 gas-decomposing efficiency of TiO₂ [90].



336
337 **Fig. 7** Schematic of exhaust gas-decomposing pavement material

338 There are two ways of using TiO₂ in exhaust gas-decomposing pavement materials [85,91]:
339 (1) TiO₂ is used in the preparation of water-based coating, which is directly coated on the surface
340 of asphalt concrete; (2) TiO₂ is used as a filler and added to asphalt concrete during the blending
341 process. TiO₂ is likely to be wrapped by the asphalt binder, therefore the distribution of TiO₂
342 particles is limited when added to the mixture during the blending; thus, direct coating of TiO₂ has
343 a higher photocatalytic efficiency compared with the blending method.

344 The efficiency of TiO₂ can be affected by environmental conditions, such as temperature,
345 humidity, illumination intensity, and presence of contaminants on the pavement surface such as
346 dust and oil [92,93]. Exhaust gas-decomposing materials prepared by different researchers also
347 vary from one to another due to the use of different photocatalysts materials, experiment
348 conditions, and evaluation methods. By testing the photocatalytic efficiency of nanometer TiO₂

349 coated onto the surface of asphalt concrete, Hassan et al. found that the degradation rate of NO_x in
350 the air could reach 31% to 55% [85]. A report by Venturini and Bacchi found that the
351 decomposition efficiency of different types of TiO₂ ranged from 20.4% to 57.4%, and that anatase
352 TiO₂ showed the best degradation effect [84]. Field tests on road sections conducted by Folli
353 Andrea et al. indicated that with ideal climate and light conditions, the daily average density of
354 NO within a road area can be reduced by 22% compared with the normal pavement [81].

355 *5.3. Engineering Applications and Challenges*

356 Tests on road sections paved with exhaust gas-decomposing material are seen in various
357 regions, including Milan (Italy), Copenhagen (Denmark), and Nanjing (China) [81,84,94].
358 However, exhaust gas-decomposing pavement materials have been used mainly in laboratory
359 studies and there is a lack of applications in large projects for the following reasons: 1) Exhaust
360 gas-decomposition efficiency is less satisfactory on actual pavement surface owing to the low
361 light intensity, environmental temperature, humidity, and wind. 2) TiO₂-coating on the pavement
362 surface is found less durable due to abrasion by tires [81,84,93]. 3) Exhaust gas-decomposing
363 coating is usually applied at the cost of a decreased pavement texture depth, which reduces its skid
364 resistance. As a result, further studies on exhaust gas-decomposing pavement materials should
365 focus on improving the durability of the purification effect, and balance with skid resistance of the
366 pavement surface. Furthermore, the development of standard test methods, and equipment for
367 construction and maintenance are also necessary.

368 It is worth noting that although titanium dioxide is odorless, and considered to be non-toxic,
369 non-irritating, chemically and mechanically stable [95], it still poses potential health hazards.
370 According to the preliminary collated list of carcinogens released by the International Agency for
371 Research on Cancer (IAC) of the World Health Organization, titanium dioxide is listed as a
372 category 2B carcinogen [96]. Potential pollution of road surface runoff water, including threshold
373 value, concentration measurement and pathway modelling, should be considered in future
374 research.

375 **6. De-icing pavement material**

376 *6.1. Demands for de-icing pavement surface*

377 Snowy weather can lead to reduction in vehicle speed, which affects journey time and results
378 in an increase of fuel consumption and emissions. Snow and ice on the pavement surface also
379 result in a low friction coefficient and thus, a higher likelihood of traffic accidents [97]. Snow and
380 ice can be removed by hand sweeping, mechanical sweeping or applying a melting agent [98].
381 However, these methods present the following disadvantages: hand sweeping has a low operation
382 speed and causes delays; mechanical sweeping is costly, and some machines may damage the

383 pavement surface during operation; snow/ice-melting agents lead to pollution (of water, soil, and
384 air) and erosion of pavement materials, vehicles, and ancillary facilities [99]. In the event of
385 extremely low temperature or excessive snowfall, snow/ice-melting agents may not be effective in
386 a timely manner [100]. The aforementioned approaches are known as passive de-icing techniques
387 as they are applied externally in response to adverse climate incidents..

388 *6.2. Active de-icing pavement materials*

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

392 Anti-freezing pavement materials include elastic pavement materials and rough pavement
393 materials. The elastic is made by adding a certain amount of highly elastic materials to the
394 pavement surface to change the contact between the pavement and tire, and the deformation
395 characteristics of the pavement surface. By this method, ice and snow can be broken by the stress
396 on the pavement surface generated from traffic load, thus effectively preventing the accumulation
397 of snow and ice [101,102]. The most commonly used elastic materials are rubber particles that can
398 be obtained from recycled tires [103].

399 Open-graded asphalt concrete, such as porous asphalt concrete, is often used to enhance the
400 pavement's texture depth and roughness [104]. When the pavement is covered with ice,
401 non-uniform stress on the snow/ice layer makes it difficult to form ice under the traffic load. With
402 this method, broken ice will be removed by horizontal force of the vehicles, a larger texture depth
403 is also beneficial to the skid resistance of the pavement surface.

404 Examples of energy-converting de-icing methods include the heating cable, solar heating,
405 terrestrial heat tube, heating wire, and infrared lamp heating. Energy storage and conversion
406 devices, such as pipes and cables, are laid within the pavement which enable the increase of
407 temperature by the heat generated from electricity, solar panels, thermal energy or natural gas, for
408 melting or preventing ice [105-107].

409 Apart from the two active de-icing technologies, salt de-icing methods, such as adding rock
410 salts (NaCl or CaCl₂) to the asphalt concrete are used to reduce the freezing point and prevent
411 icing formed on the pavement surface [108,109].

412 *6.3. Engineering applications and challenges*

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

417 is lower than minus 12°C and the ice thickness exceeds 9 mm [110].

418 Energy-converting pavement materials have undergone long-term research and tests in
419 various countries, such as the United States, Japan, China and Europe including Switzerland,
420 Iceland, Norway and Poland. Example road projects include the Goleniow airport in Poland [111],
421 the A8 Express road in Switzerland [112,113], the Gardermoen parking apron in Norway [114],
422 and the Gaia system for highway and ramp in Japan [115,116]. Energy-converting de-icing
423 pavement is known for its cleanliness, being environmentally friendly, and high de-icing
424 efficiency [117,118]; however, construction of this type of pavement is very difficult, it requires
425 great initial investment and on-going maintenance during use [119-122]. As a result, this method
426 is more applicable to road sections for airports, bridges, bends and large-gradient longitudinal
427 slopes.

428 Salt de-icing pavement materials have been applied and tested on road sections in
429 Switzerland, Germany, Japan, China and the United States [108,109]. With a small amount of salt
430 added, the long-term de-icing effect on the pavement remains doubtful as the salt is released
431 gradually. In addition, the effect of salts on pavement materials and the surrounding environment,
432 such as corrosion, needs further investigation.

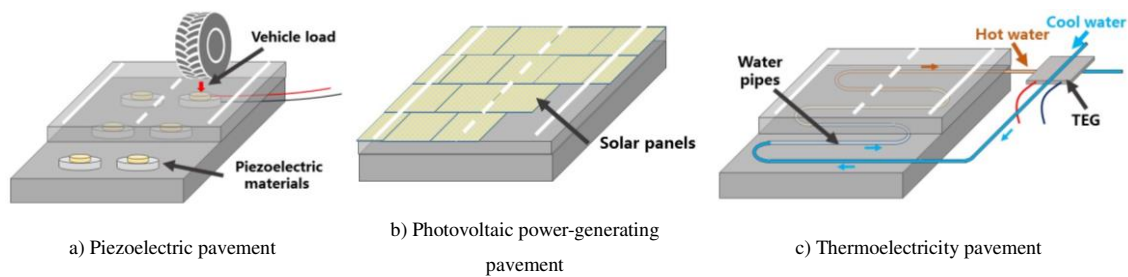
433 7. Energy harvesting pavement material

434 7.1. Demands for energy harvesting from pavement surface

435 A large amount of thermal energy and mechanical energy is generated within the pavement
436 when the road serves the traffic. For example, dark (i.e. asphalt) pavement absorbs solar radiation
437 and the thermal energy accumulates within the pavement; furthermore, mechanical energy is
438 generated from the dynamic load on the pavement when the vehicle tire passes [123-125]. In
439 recent years, energy harvesting from road pavement has become a research focus in the context of
440 global energy shortage, environmental pollution, and climate change [126-128].

441 7.2. Energy harvesting pavement materials

442 Studies on the use of kinetic energy focus on the following aspects: 1) Piezoelectric
443 pavement technology (Fig. 8 a), i.e. embedding piezoelectric materials in the pavement and
444 converting part of the mechanical energy generated by the vehicle load into electric energy
445 [129,130]. 2) Photovoltaic (PV) power-generating pavement (Fig. 8 b), i.e. paving the road using
446 solar panels instead of traditional asphalt concrete or cement concrete to convert solar energy
447 absorbed by the PV panels into electric energy [131,132]. 3) Thermoelectric pavement technology
448 (Fig. 8 c), i.e. converting the heat absorbed by the pavement, especially asphalt pavement, into
449 electric energy using the thermoelectric module (TEG) embedded in pavement structure [125]. Fig.
450 8 presents the schematic of the three types of energy harvesting pavements.



451 **Fig. 8** Schematic of energy harvesting pavements

452 A good number of laboratory tests and simulation studies have been carried out on the
 453 piezoelectric pavement technology. For example, Bowen and Near have patented a piezoelectric
 454 actuator for road pavements [133], which was developed recently [134]. The system developed by
 455 Abramovich et al. was tested in a real road environment by Innovattech using a product called
 456 Innovattech Piezo Electric Generator (IPEG) [135,136].

457 For the photovoltaic power-generating pavement technology, TNO in the Netherlands has
 458 paved a solar energy powered bicycle lane using a 10 mm-thick glass as the top layer of the
 459 pavement, underneath which crystalline silicon solar panels are laid [137]. Julie and Scott Brusaw
 460 proposed a solar collector system to replace the upper layer of the road pavement, called Solar
 461 Roadway, which consisted of a series of structurally engineered solar panels [138].

462 The principle of the thermoelectric pavement technology is that the temperature difference
 463 between the two ends of the thermoelectric module is used to generate a voltage. The greater the
 464 temperature difference, the higher voltage is generated. However, making full use of the
 465 temperature gradient within the pavement structure or between the pavement and the surroundings
 466 remains a key challenge for this technology. Wu et al. improved the power generating efficiency
 467 by connecting high thermal conducting materials to the subgrade and taking advantage of the
 468 temperature difference between subgrade and pavement [139,140]. Hasebe et al. managed to
 469 improve the thermoelectric efficiency of pavement by embedding water pipes in the pavement to
 470 collect heat, i.e. cool water from a river nearby was introduced to increase the temperature
 471 difference of the thermoelectric module [141].

472 *7.3. Engineering applications and challenges*

473 The above pavement energy-harvesting technologies are mostly at a stage of laboratory
 474 testing or field trial, because the many technical difficulties remain unsolved for practical use. The
 475 main barriers to using piezoelectric pavement include the inadequate durability of piezoelectric
 476 materials due to repeated load on the pavement, low compatibility with traditional pavement
 477 materials, and the necessity of a second energy conversion because of the electric power that
 478 generate instant high voltage and low current cannot be used directly [130,142,143]. The
 479 challenges for photovoltaic pavement include: 1) Development of new solar panels is needed to

480 replace traditional pavement materials. 2) The durability and stability of a photovoltaic panel must
481 be adequate to resist the effect of external factors, such as vehicle load, rainwater, snow and ice. 3)
482 The decreasing efficiency of solar panels after abrasion by vehicles and accumulation of dust
483 should be addressed, along with riding comfort, skid resistance, and reparability [123]. Currently,
484 the use of temperature gradient-based thermoelectric pavement technology is limited by its low
485 power-generating efficiency [125,144,145].

486 **8. Summary and conclusions**

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

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

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

509 (4) The different functions and performance requirements often contradict each other in
510 terms of material composition and behavior, and pavement design criteria. For instance, exhaust
511 gas-decomposing and de-icing functions can be achieved by applying coatings on the pavement
512 surface, at a cost of reduction in texture depth, which reduces its skid resistance. Water permeation
513 and noise reduction of porous asphalt concrete is achieved by increasing porosity, at a cost of low

514 temperature performance, anti-stripping and durability. Therefore, keeping an adequate balance
515 between the functions fit for a specific use is a crucial challenge for engineers and researchers
516 when designing functional pavement.

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

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

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

533

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