Gong et al. J Infrastruct Preserv Resil (2022) 3:9
https://doi.org/10.1186/s43065-022-00054-5

Journal of Infrastructure Preservation and Resilience

REVIEW

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Review of regulation techniques of asphalt pavement high temperature for climate change adaptation

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Abstract

Asphalt pavement is vulnerable to the temperature rising and extremely high-temperature weather caused by climate change. The regulation techniques of asphalt pavement high temperature have become a growing concern to adapt to climate change. This paper reviewed the state of the art on regulating asphalt pavement high temperature. Firstly, the influencing factors and potential regulation paths of asphalt pavement temperature were summarized. The regulation techniques were categorized into two categories. One is to regulate the heat transfer process, including enhancing reflection, increasing thermal resistance, and evaporation cooling. The other is to regulate through heat collection and transfer or conversion, including embedded heat exchange system, phase change asphalt pavement, and thermoelectric system. Then, the regulation techniques in the literature were reviewed one by one in terms of cooling effects and pavement performance. The issues that still need to be improved were also discussed. Finally, the regulation techniques were compared from the perspectives of theoretical cooling effects, construction convenience, and required maintenance. It can provide reference for understanding the development status of asphalt pavement high temperature regulation techniques and technique selection in practice.

Keywords: Climate change, Asphalt pavement, High-temperature regulation, Pavement performance, Cooling effects

Introduction

The rising global mean surface temperature (GMST) is a typical sign of climate change. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) shows a global temperature rise of 1.2°C in 2020 compared to pre-industrial levels and an increase in the frequency of extreme weather events [1]. Asphalt pavement is highly sensitive to the environment, especially the temperature conditions [2]. In the context of global warming, asphalt pavements are facing a severe challenge. Gudipudi et al. (2017) [3] assessed the impact of climate change on the pavement in the United States using the AASHTOWare Pavement ME Design™ with the climate inputs of projected climate data at different representative concentration pathways (RCPs). It was shown that climate change would increase 2% - 9% for asphalt pavement fatigue cracking and 9% - 40% for rutting in the next 20 years. Stoner et al. (2019) [4] used the projected climate data with a higher representative concentration pathway, RCP8.5, of 24 locations around the United States in evaluating the potential impact of climate change on asphalt pavement by 2100. The pavement performance was also predicted by the AASHTOWare Pavement ME Design™. The permanent deformation was highlighted as the distress with the largest increase in the given climate change scenario. Many studies have also identified high temperature-induced permanent deformation as one of the main problems for asphalt pavements in future climate change situations [5–7].

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Improving the high-temperature performance of asphalt mixtures is the main measure to cope with permanent deformation. The ability of asphalt mixtures to resist permanent deformation can be enhanced to a certain extent by using modified asphalt [8, 9], and anti-rutting additives [10, 11], or through optimizing mixture gradation [12]. The commonly used modified asphalt includes styrene-butadiene-styrene (SBS) modified asphalt, rubber asphalt, etc. [8, 13]. Various types of anti-rutting additives are also widely used [11]. The stone matrix asphalt (SMA) and open-graded friction course (OGFC) are chosen extensively because of their strong interlocking benefits rutting resistance [14]. However, the potential for further improvements in the high-temperature performance of asphalt mixtures is diminishing now. It will be increasingly difficult to cope with the effects of future climate change simply by improving the high-temperature performance of asphalt mixtures.

The problems of asphalt pavement in high-temperature conditions are mainly caused by the fact that the temperature of asphalt pavement under solar radiation is much higher than the environmental temperature. Many researchers have explored solutions to the high-temperature disease of asphalt pavement from a heat transfer perspective. It is feasible to reduce asphalt pavement temperature by certain regulation techniques, thereby alleviating the permanent deformation [15]. Regulating asphalt pavement high temperature has apparent advantages in adapting future climate change.

Regarding the high-temperature challenges of climate change on asphalt pavement, this paper reviewed the state of the practice in asphalt pavement high-temperature regulation. A comparative analysis was conducted in terms of regulation paths, cooling effects, and pavement performance. The issues that still need to be improved were also discussed. The framework of this paper is shown in Fig. 1.

Influencing factors and regulation paths of pavement temperature

Asphalt pavements are built in a natural environment. Their temperature is a dynamic parameter, which varies with the external environment [16]. The influencing factors of asphalt pavement temperature can be categorized into environmental factors and material factors. The environmental factors include air temperature [3, 17], total solar radiation [18], atmospheric counter radiation [19], wind speed [20], humidity [2], latitude [21, 22], etc. The material factors mainly include the ability to absorb and reflect solar radiation of pavement material, the heat conduction, heat convection, and heat radiation properties of pavement [23]. Many researchers have depicted the schematic diagram of the photo-thermal environment of asphalt pavement [24–26]. In this paper, the schematic diagram is further optimized and shown in Fig. 2.

Environmental factors

Among the environmental factors, air temperature has the most significant influence on asphalt pavement temperature. The asphalt pavement temperature changes with the similar trend as air temperature. Many asphalt

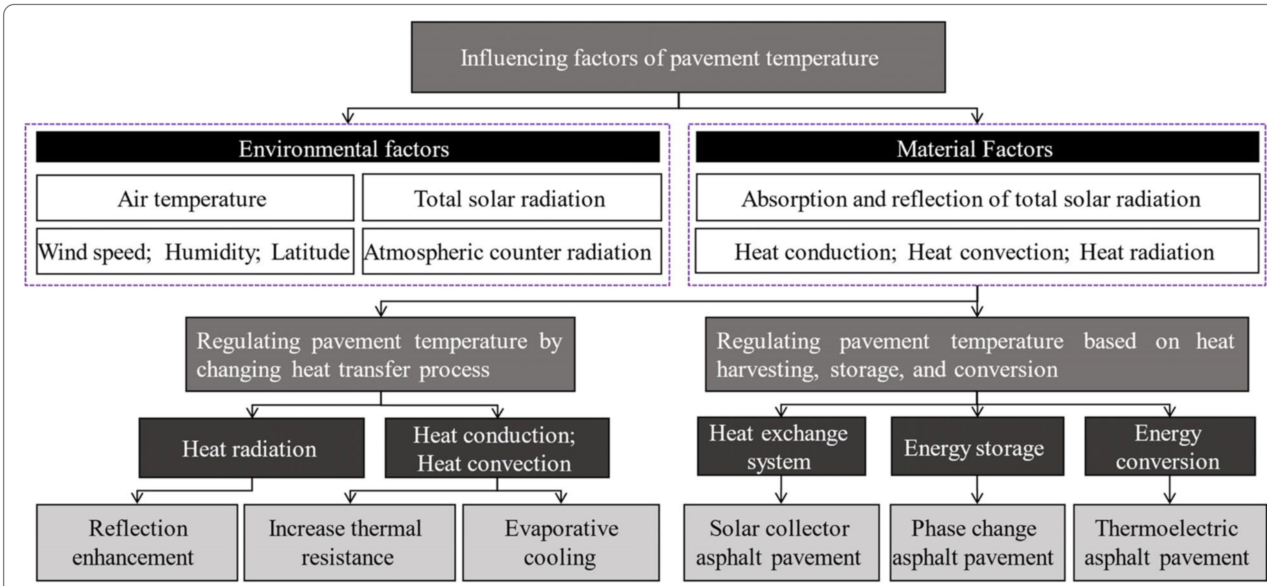

Fig. 1 Article framework

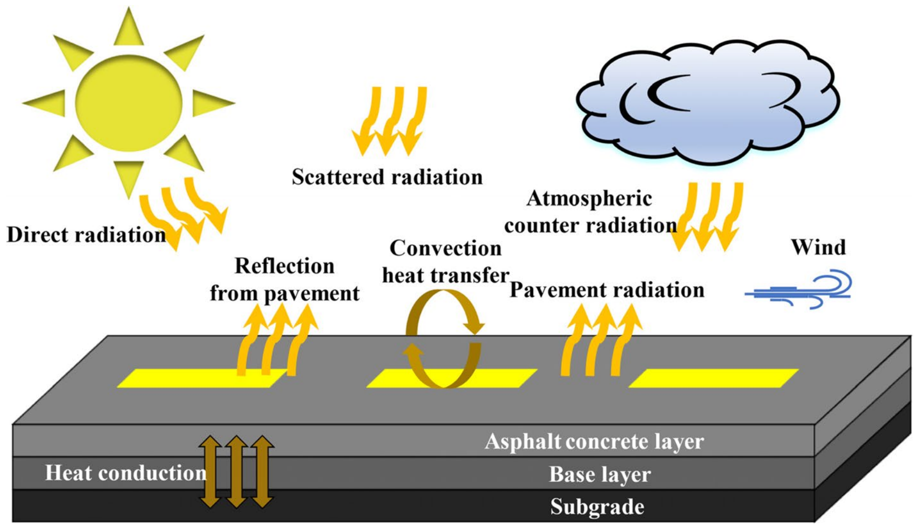

Fig. 2 The photo-thermal environment of asphalt pavement

pavement temperature models are mainly based on air temperature [27]. Asphalt pavement temperature is usually higher than the air temperature in the daytime, mainly due to solar radiation, which is the most critical environmental factor apart from air temperature. Solar radiation consists of two parts: 1) the direct radiation that the sun projects directly onto the pavement in the form of parallel rays, with wavelengths mainly concentrated between 0.3μm and 3.0μm; 2) the scattered radiation projected onto the pavement after scattering [28]. The ratio of the two parts is closely related to the weather. Direct radiation is dominant in clear weather, scattered radiation in cloudy weather [29]. Relative air humidity and wind speed also affect pavement temperature. Li et al. (2013) [30] monitored pavement temperatures where only the humidity differed. The temperature difference between wet and dry pavements ranged from 1.2 °C to 1.6 °C at surface and upped to 1.5°C to 3.4°C in the in-depth layers. Adwan et al. (2021) [25] found that the temperature difference between pavement surface and air can lead to a convection loss from the pavement to the air. The amount of lost energy is determined by wind velocity and the temperature difference between air and pavement surface. Each of these factors affects on the pavement temperature. But compared to air temperature and solar radiation, relative air humidity and wind speed have a minor effect on the pavement temperature. They are somewhat correlated with air temperature and solar radiation [31]. Therefore, air temperature and solar radiation are the major concerns in modeling asphalt pavement temperature field. Humidity, wind speed, and other factors are simplified [32]. Sun et al. (2006) [33] established a model of asphalt pavement temperature field with air temperature, solar radiation intensity, and pavement depth as the main input parameters, which can predict the temperature change in asphalt pavement with a good accuracy.

Material factors

Heat transfer pattern is generally categorized into heat conduction, heat convection, and heat radiation [26, 34]. Heat exchange between materials is a complex process, which usually involves various heat transfer patterns. And all the heat transfer patterns will be affected by the properties of materials [26, 34]. Qin [35] proposed a model to estimate the daily maximum temperature of asphalt pavement surface based on the heat transfer process (Eq (1)), in which multiple properties of asphalt pavement materials are included.

$$T_{s\,\max} = \Gamma \frac{(1-R)I_0}{\sqrt{kc\rho\omega}} + T_0 \tag{1}$$

where T_{smax} (°C) is the daily maximum temperature of asphalt pavement surface; Γ stands for the percentage of the absorption to the heat conduction; R is the albedo (or reflectivity) (Qin [35] treats albedo and reflectivity are interchangeable); I_0 (W m^{-2}) is the daily zenith solar irradiation; k (W m^{-1} K^{-1}), c (J kg^{-1} K^{-1}) and ρ (kg m^{-3}) are the thermal conductivity, the specific heat, and density of the pavement, respectively; ω (s^{-1}) is the angular frequency, $\omega=2\pi/(24\times3600)$; T_0 (°C) is a regressed constant.

Regulation paths of asphalt pavement temperature

Changes in each influencing factor will result in changes in the asphalt pavement temperature. So the asphalt pavement temperature can be regulated by adjusting any influencing factors. Some environmental factors such as air temperature and solar radiation in the photo-thermal environment of asphalt pavement can be adjusted by the shade of trees. However, this measure is challenged in high-grade roads due to their large width [36–38]. Adjusting the properties of pavement materials and changing the heat transfer process of pavement are good options for regulating asphalt pavement temperature. Researchers have tried thermal reflective asphalt pavement, thermal resistant asphalt pavement, and evaporative cooling pavement to regulate the high temperature of asphalt pavement. In addition, the heat in asphalt pavement can be harvested and transferred outside or converted into other energy forms by appropriate methods, thereby reducing the temperature. Solar collector asphalt pavement, phase change asphalt pavement, and thermoelectric asphalt pavement are solutions along this path [39].

Heat transfer process regulation

Reflection enhancement

The response of an object to thermal radiation can be divided into reflection, absorption, and transmission. For asphalt pavements, its transmittance is not easily adjusted, but its reflectivity is possible [40]. Heat-reflective coating was developed to enhance the reflectivity of asphalt pavement [41]. In 1945, Schwartz [42] introduced a reflection enhancement technique into buildings as a measure for saving energy. At late 1990's, the Japanese Nagashima Coating Company developed a pavement coating based on reflection enhancement technique. The application showed that the white coating could significantly improve pavement reflectivity and reduce the temperature [43]. Many researchers have conducted extensive research on the heat-reflective materials, coating performance, and cooling effects [44–46]. Heat-reflective pavements have been used in Japan, the United States and some other countries. It can be prepared by simply paving a heat reflective coating on the original pavement, as shown in Fig. 3.

Fig. 3 Conventional and heat-reflective pavements [47]

Heat-reflective materials

Heat-reflective materials for asphalt pavement coating are generally composed of base polymer, additives, and pigment. The reflectivity is closely related to the performance of the pigment and base polymer [39]. Xie et al. (2019) [48, 49] analyzed the effect of color on reflectance and found that the visible reflectance (wavelength: 0.40-0.72μm, Rvisi) is sensitive to color brightness but the near-infrared reflectance (wavelength: 0.72-2.50μm, Rnir), on which the thermal properties mainly depend, isn't. Table 1 lists the pigments reported and the reflectance of coated and uncoated asphalt pavements, in which the total solar reflectance (wavelength: 0.2-2.5μm) is noted as Rtotal. It can been seen from the table, TiO_2 and Iron oxide yellow have a good reflection effect, which are widely used. The reflectance of the coatings prepared by TiO_2 and Iron oxide yellow can reach 40.5%. Compared with the traditional asphalt pavement, the total solar reflectance of the coating increases significantly. The near-infrared reflectance improved even more.

Table 1 Reflectance of different pigments and asphalt mixtures [48, 49]

Pigment type	Rtotal (%)	Rvisi (%)	Rnir(%)
Iron oxide blue	37.5	23.09	51.86
Iron oxide green	43.53	20.33	65.35
Iron oxide grey	24.87	25.15	25.66
Iron oxide red	34.89	13.57	54.72
Iron oxide yellow	61.98	35.97	88.52
Fe_3O_4 (Brown)	11.25	11.40	10.99
Ni_2O_3 (Black)	10.48	10.03	10.83
TiO_2 (White)	86.64	83.65	94.71
Asphalt concrete (control group)	4.49	3.84	3.37
Asphalt concrete (TiO_2 and Fe_2O_3)	40.5	20.7	60.11

The base polymer is used to bond other materials together and attach them to asphalt pavement. Commonly used base polymers include acrylic resin, epoxy resin, polyamide resin, polyphthalamine resins, etc. [50–54]. Wang et al. (2013) [53] used infrared spectroscopy and other optical means to study the base polymer and found that the base polymer has negligible reflectivity and cooling function. It should focus on the pigment to improve the coating reflectivity. Yi et al. (2019) [55]

investigated the effect of the ratio of pigment to base polymer on the cooling effect. It was found that the best cooling effect was achieved when the ratio of pigment to base polymer is 1:1. The optimal ratio may vary with different pigment and base polymer types, but the differences are minor [49–52].

There are also many kinds of additives are included in the coating materials, such as diluents, wetting dispersants, defoamers, flow agents. They are mainly used to improve the storage stability and construction workability of the coating materials. Moreover, some additives can enhance the performance and extend the life of the coating [50]. Researchers found that the adhesion promoter additives can significantly increase the adhesion strength of the coating, thereby improving the service life of the coating [55].

The cooling effect of heat-reflective coating

Table 2 lists the cooling effect of typical heat-reflective coating in the literature. The Rtotal of heat-reflective coatings is significantly higher than that of the ordinary asphalt pavements (about 4.49%, listed in Table 1) to various extents. The maximum temperature reduction of the pavement in summer can reach nearly 20°C. The cooling effect is related to the composition of the coating material, the coating thickness, and the surface cleanliness. It also can be seen from Table 2 that different pigments and base polymers will result in different cooling effects [45, 56]. Zheng et al. (2015) [56] found that the cooling effect increases linearly with the increase of coating thickness, but the pavement skid resistance will be compromised. Jiang et al. (2019) [57] found that the increasing cooling effect mainly comes from the increase of pigment in thicker coating. So, increasing the pigment percent in coating materials also can improve the cooling effect. Tang et al. (2012) [58] found that the cooling effect tends to decrease with the accumulation of dust and other pollutants on the coating surface. Hence, it is necessary to clean the coating surface regularly to retain the cooling effect.

The surface function of heat-reflective coating

The heat-reflective coating is a thin functional layer coated on the asphalt pavement surface, which does not affect the structural performance of asphalt pavement but reduces the texture depth of pavement surface, thereby affecting the surface function. Qin et al. (2015) [35] indicated that reflecting too much visible light will cause glare and aesthetic problems. Therefore, in practice, the heat-reflective coating is primarily gray, black, or other colors rather than white [57, 62, 63]. Li et al. (2020) [18] developed a thermochromic coating to balance the cooling effect and the pavement color, which can turn light at high temperature and dark as temperature decreases. The skid resistance of asphalt pavement is usually compromised by heat-reflective coatings, which can be compensated by adding machine-made sands, glass microspheres, wear-resisting agents, and ceramic particles to the coating [50, 55, 64]. Anti-aging and durability are also challenges for heat-reflective coatings. Xie et al. (2020) [31] compared the decay of reflectivity of heat-reflective coatings in different colors with consideration of temperature, humidity, and ultraviolet light conditions. It was found that the reflectivity of white coating is more likely to decline than that of coatings in other colors. Chen et al. (2018) [52] found that heat-reflective

Table 2 Cooling effects of different heat-reflective coatings

Coating types		Rtotal (%)	Testing environment	Cooling effect
Grey thermal reflective materials [59]		About 50	Air temperature: 23-34°C	Reduce T_{smax} about 10°C in the heat of the day; Drops 3°C in the morning3°C
PerfectCool [60]		82.8	Singapore; A day of 23 hot days	Onsite measurements: reduce T_{smax} about 17°C; Laboratory tests: reduce T_{smax} by up to 5°C
Coatings based on titanium dioxide [56]	Cool off-white	66	Italy; Summer; August	Maximum:19.3°C; Mean values:8.2°C
	Cool grey	40	Italy; Summer; August	Maximum:8-10°C; Mean values:1.8-3.8°C
	Cool blue	25		
	Cool green	36		
Cool colored thin layer asphalt [45]		27-55	Athens; July ; Air temperature: 20.5-39.3°C; mean air temperature: 28.7°C; humidity: 44%; Wind speed: 3.7m/sec; Daily average radiation: 6536W/m^2	T_{smax} is reduced by 7%-20%; an average air temperature decrease of 5°C
Epoxy-based heat reflective coating for the pavement [54]			The highest temperature is 35°C	Laboratory tests: reduce 12-14°C Onsite measurements: 7.8°C
Solar heating reflective coating layers [61]			Indoor test of the pavement cooling effect	10 ± 2.5°C on the top; 10 ± 3°C on the bottom

coating can significantly improve the durability of asphalt pavement, but the durability of the coating can't match that of asphalt pavement.

Increasing thermal resistance

Cooling mechanism and cooling effect test method

The thermal resistance of a material is proportional to its thickness and inversely proportional to its thermal conductivity, as shown in Eq (2). For asphalt pavement, the thermal resistance can be characterized by the thermal conductivity when the thickness is constant. The thermal resistance of asphalt pavement can be increased by using materials with low thermal conductivity or changing the mixture gradation to obtain a small thermal conductivity [65–67]. Chen et al. (2012) [68–70] proposed a model of concrete thermal conductivity based on the Campbell-Allen and Throne model and the Harmathy model, as shown in Eq (3). According to the model, the smaller aggregate thermal conductivity and the larger the void ratio, the smaller the concrete thermal conductivity.

$$\mathrm{R} = \frac{\delta}{\lambda} \tag{2}$$

where δ is the material thickness; λ is the thermal conductivity; R is material thermal resistance.

$$\lambda = \frac{K}{\frac{V_a}{K\lambda_a} + \frac{K-V_a}{K\lambda_m}} + \frac{1-K}{\frac{1-K-\Phi}{(1-K)\lambda_m} + \frac{\Phi}{(1-K)\lambda_\Phi}} \tag{3}$$

where λ_a, λ_m, λ_Φ are the thermal conductivity of aggregate, mortar, and voids, respectively; V_a: is the volume fraction of mortar; Φ is the concrete void ratio.

Table 3 lists the commonly used four kinds of methods for assessing the temperature regulation effect of thermal resistant asphalt pavement. The simulation test (indoor or outdoor) is the most used method, which can directly show the cooling effect [71, 72]. The temperature field of asphalt pavement can be analyzed by the finite element method, which can support a cooling effect evaluation in more detail [73]. The cooling effect also can be assessed by the thermophysical properties of the pavement materials [66, 74]. In practice, all the four kinds of methods have their own limitations. Incorporating multiple methods is a better way to ensure the reliability of the assessment.

The cooling effect through increasing thermal resistance

A usual approach to improve the thermal resistance of asphalt pavement is to replace the coarse aggregate, fine aggregate, or mineral powder in asphalt mixture by alternatives with low thermal conductivity. In addition, changing the air void content of asphalt mixture is a feasible way to improve the pavement thermal resistance value. Regardless of the way, the cooling effect depends on the thermophysical properties and amounts of the alternatives and the air void content of asphalt mixture. The cooling effect of the thermal resistant pavement in the literature is summarized in Fig. 4 [66, 73, 75], where the coarse aggregate is shale ceramic (CE), the fine aggregate is floating beads (FB), the mineral powder is fly ash cenosphere (FAC), and the temperature is measured at a depth of 4 cm or 5 cm inside the pavement. It can be seen from Fig. 4 that the cooling effect increases with the increase of the amounts of alternatives with low thermal conductivity and the increase of the air void content of asphalt mixture. However, the cooling effect is not so good when all the fine aggregate is replaced. Wang et al. (2018) [74] attributed this to the high porosity of the thermal resistance fine aggregate, too much of which will result in a loose structure due to the insufficient asphalt binder. As shown in Fig. 4, using coarse alternative aggregate can achieve the best cooling effect. Using fine alternative aggregate also can obtain some effect when the substitution rate is appropriate. Moreover, because it has less impact on asphalt pavement performance, the fine alternative aggregate has many applications. Che et al. (2018) [69] investigated the cooling effect of thermal resistant asphalt pavement with fine ceramsite. A 2.6 °C reduction and a 2.8 °C were observed in the indoor and

Table 3 Test method of cooling effect [66, 71–74]

Test methods		Temperature measurement position	Disadvantage	Advantage
Determination of thermal parameters	Thermal conductivity Specific heat capacity	Entirety	Cannot directly explain the cooling effect	Rapid; Simple; Reproducible
Indoor irradiation test		Upper and lower surfaces and representative positions	Difference from real road light thermal environment	Reproducible
Outdoor irradiation test		Upper and lower surfaces and representative positions	Non-repeatable; Affected by weather	Closest to reality
Finite element simulation		Optional position	Low credibility	The temperature change at any time at any position can be measured.

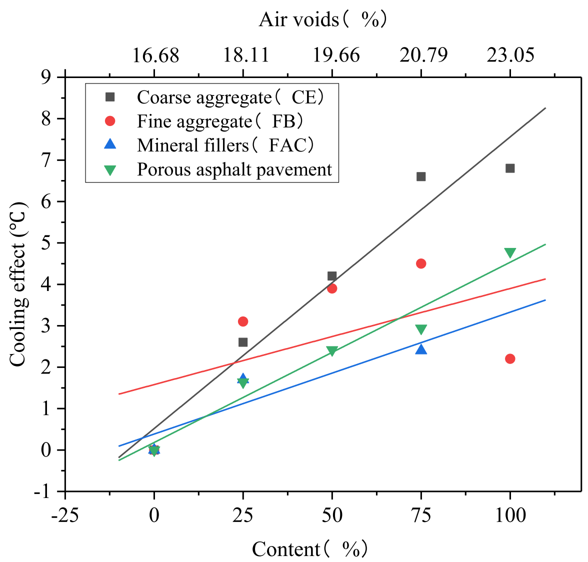

Fig. 4 Cooling effect of different thermal resistant pavements

outdoor tests respectively when the ceramsite substitution rate was 60%. The porous asphalt pavement can obtain a similar cooling effect with the thermal resistant pavement with fine alternative aggregate when the air void content reaches about 23%.

Thermal resistant coarse aggregate is the guarantee of high cooling effect. Wang et al. (2018) [75] investigated the cooling effect of asphalt pavement with shale ceramic coarse aggregate. It was shown that the pavement thermal conductivity gradually decreases with the increase of the amount of shale ceramic particles. The bottom of the pavement was cooled down by 6.6 °C in the test when the substitution rate reached 75%. Chen et al. (2017) [76] chose calcined bauxite coarse aggregate to prepare thermal resistant asphalt pavement. It was found from the indoor simulation test that the temperature of the upper and lower surface of the specimen decreased with the increase of the used amount of bauxite, the temperature difference between upper and lower surfaces became larger. When substitution rate reached 100%, the temperature at the specimen upper and lower surfaces was reduced by 10.30% and 18.51% respectively. It was indicated that calcined bauxite particles can reduce the absorption of heat radiation and hinder the heat diffusion in the pavement, thereby effectively reducing the internal temperature of asphalt pavement. Huang et al. (2020) [77] analyzed the cooling effect of asphalt pavement with ceramic waste as coarse aggregate using numerical simulation. It was shown that the maximum temperature inside the asphalt pavement gradually decreases with the increase of ceramic waste content, which was attributed to the decrease of the thermal conductivity brought by the ceramic waste aggregate. However, more heat will be accumulated at the pavement surface when the downward approach of heat transferring is resisted. An increase of the maximum temperature of pavement surface was observed from the pavement model with a 50% replacement of coarse aggregate by ceramic waste when the temperature at 4 cm depth decreased by 5.5 °C.

The performance of thermal resistant asphalt mixture

Aggregates with lower thermal conductivity tend to have poorer mechanical properties, which usually damage asphalt mixture performance [49, 78, 79]. Table 4 lists the basic properties of commonly used thermal resistant aggregates. Thermal resistant aggregates have relatively small apparent density, high water absorption, and high crushing and wear values. So the asphalt mixture performance and the thermal conductivity should be balanced in practice. Che et al. (2018) [71] investigated the high-temperature performance of thermal resistant asphalt mixture with fine ceramic aggregate by laboratory tests.

Table 4 Basic properties of thermal resistant aggregate

Thermal resistant aggregate	Apparent density (g/cm^3)	Water absorption (%)	Crushing value (%)	Wear value (%)	Thermal conductivity (W m^{-1} k^{-1})
Refractory gravel [80, 81]	2.562-2.799	6.158-6.294	26.4-28.9	16.6-26.9	0.4-0.7
Shale ceramsite [71, 75, 82, 83]	1.378-1.517	5.3-8.7	21.0-30.1	14-21	0.836-1.045
Ceramic waste [77, 84]	2.34-2.4	0.86-1.04	22.7	20-20.5	0.57-1.045
Calcined bauxite [76]	2.841-2.857	1.71-1.77	21.7-22.9		-
Porous volcanic rock (untreated) [85, 86]	2.12	10.39	42.6	36.24	remained unchanged
Silicone resin modification [85, 86]	1.75	1.78	33.2	25.89	
Silicone–acrylic emulsion modification [85, 86]	1.91	5.91	36.1	27.32	
Technical requirement	≥2.60	≤2.00	≤26.0	≤28.0	-

The results showed that the dynamic stability of the mixture first increases with the increase of ceramic particle amount and then decreases with that. An about 60% replacement of fine aggregate by ceramic aggregate can result in the largest dynamic stability. It was mainly attributed to the balance between the advantages from lowed internal temperature and the disadvantages from the compromised mechanical properties by ceramic aggregate. Many researchers have studied the low-temperature performance of the thermal resistant asphalt mixtures using low-temperature bending test. Only slight reductions of low-temperature performance were observed in the thermal resistant asphalt mixture with ceramic, floating beads, or calcined bauxite aggregates [71, 75, 76].

Qian et al. (2020) [77, 87] found all the rutting resistance, moisture stability, and low-temperature performance were damaged when replacing coarse aggregate by ceramic particles by volume. The moisture stability is the most sensitive. The moisture stability will be unable to meet the requirements of related specifications of China when the replaced amount is higher than 40%. So the critical issue is how to reduce the pavement temperature with no or little compromise of asphalt mixture performance. Some researchers have explored the solutions by aggregate surface treatment. Wang et al. (2020) [85, 86] tried to modify shale ceramsite aggregates, porous volcanic rock aggregates, and refractory gravel aggregates using silicone resin and silicone–acrylic emulsion. The modified aggregates can bring significant improvements to asphalt mixture performance (as shown in Table 4). Andrzejuk et al. (2018) [88] tried to control the used amount of thermal resistant aggregate to ensure the asphalt mixture performance can meet the basic requirements. The thermal conductivity of the pavement also can be reduced by using porous asphalt mixture. However, too large air void content will also affect the pavement performance [73]. So it is needed to balance the thermal resistance and asphalt mixture performance.

Evaporative cooling

There are two kinds of asphalt pavement that can support evaporative cooling relatively well: permeable asphalt pavement and water retaining asphalt pavement [89, 90]. Wang et al. (2021) [91] compared the structures of traditional asphalt pavement and permeable asphalt pavement, and analyzed the cooling mechanism of them. The structure diagrams in reference [91] were optimized in this paper with combining the photo-thermal environment of the pavement, as shown in Fig. 5. Compared with conventional pavements, permeable pavements provide approaches for water to penetrate into the pavement, which make it possible to take the heat away from the interior of pavements through water evaporation. In addition, the porous nature of permeable pavement can reduce the thermal conductivity and heat diffusion rate, which is helpful to reduce the pavement temperature. However, the porous structure will also reduce the pavement reflectivity and weaken the cooling effect [73, 92]. Water retaining pavement can absorb water during raining or watering, and prolong the time with water [93–95]. In addition, water-retaining materials are generally in light color, which can improve the reflectivity of the pavement to a certain extent, thereby improving the cooling effect [92].

The reported cooling effects of permeable pavements and water retaining pavements were summarized in Table 5. It can be seen that water evaporation can reduce the surface and internal temperature of asphalt pavement. The cooling effect is significant when water is sufficient. The short-time temperature reduction can be more than 10 °C, but the cooling effect will be weakened with the dissipation of water. Water retaining pavement can reduce the temperature by up to 10 °C, and has a relatively stable cooling effect compared to permeable pavement. Wang et al. (2018) [96] measured the water absorption rate of pavement using the partial immersion test, and analyzed the effect of water absorption capacity on cooling effect. It was shown that a high water

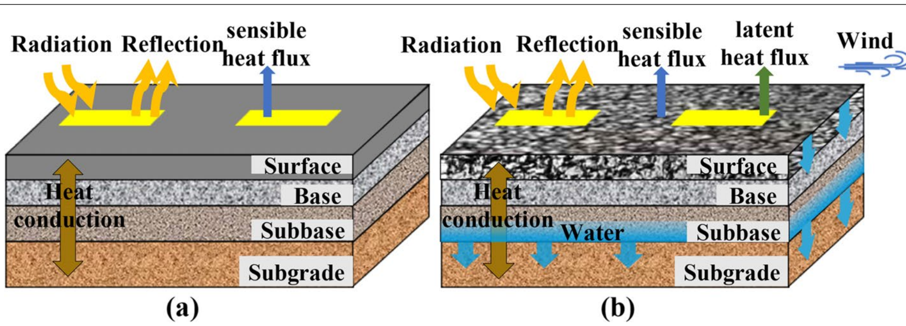

Fig. 5 **a** Conventional pavement, **b** Permeable pavement [91]

Table 5 Cooling effect of different permeable pavements and water retaining pavements

Pavement types	Cooling effect (°C)
Permeable asphalt pavement	1.2-1.6 (Air temperature: 0.2-0.45, bottom temperature: 1.5-3.4) [30], 2-2.5 (Bottom temperature: 3-3.5) [101], 15-35 (The peak cooling effect of watering for the test sections) [102], 2-7(25h after watering) [102],
Water-retentive asphalt pavement	8.1-9.4 [103], 5-10 [104]
Permeable concrete pavement	1-3 [105]
Permeable interlocking concrete pavement	6.6 [106], 15.3 [89]

absorption is beneficial to reduce the pavement temperature. The temperature reduction can reach 10 °C after watering. However, the cooling effect heavily depends on the water content of pavement. Buyung et al. (2017) [97] studied the temperature of permeable asphalt pavements with severe water shortage and found that the temperature of permeable pavements tends to be higher than that of conventional pavements during the dry season. So permeable pavements are not recommended in dry regions. Watering is the major measure to maintain the water content of pavement, which will also increase the consumption of water resources. Some researchers have analyzed the relationship between watering amount and cooling effect, which is helpful to achieve a balance between cooling effect and cost [98–100].

The permeable asphalt pavement has been widely used because it has multiple functions, such as noise mitigation [106] and safety enhancement in the rain [107]. It doesn't need any adjustment to the structure and materials of permeable pavement for evaporative cooling in practice, which will not damage the original pavement performance. For water retaining asphalt pavements, researchers mainly focused on the water-retaining materials and pavement performance [107]. Jiang et al. (2016) [90] obtained a water retaining asphalt pavement through grouting a water-retaining slurry, prepared using fly ash and calcium hydroxide, into porous asphalt pavement. The water-retaining slurry can bring not only the water-retaining capacity but also the improvements of pavement rutting resistance and moisture stability. Lee et al. (2009) [108] prepared a water-retaining slurry with a water absorption rate up to 70% using cellulose fiber and high absorption polymer. These typical studies show that water retaining pavement has cooling function without affecting the pavement performance, even can directly improve it.

Regulation based on heat harvesting, storage, and conversion

If the heat in asphalt pavement can be harvested and transferred outside or converted into other energy forms, the pavement temperature will be reduced. Along this technical route, researchers have developed heat exchange systems [109], phase change materials (PCMs) [110], and thermoelectric systems [111] for asphalt pavement to regulate its temperature. The heat exchange system regulates the pavement temperature through heat exchange between pavement and fluid flowing through the pipes embedded in pavement [109, 112]. The addition of PCMs can make asphalt pavement store the absorbed energy in latent heat at a specific temperature range to retain pavement temperature [113, 114]. The temperature difference between different layers of pavement can be used by a thermoelectric generator to convert heat into electrical energy, so that the pavement temperature can be reduced [115].

Heat exchange system

Heat exchange system in pavement was originally developed for using geothermal water to melt ice and snow in winter [116]. It also can use cold fluid to extract the heat in pavement. Wendel et al. (1979) [117] proposed a system to collect the solar energy by pavement and roof, and use the energy for pavement temperature regulation. In many countries, the heat exchange system has been used to regulate asphalt pavement temperature. In winter, the system is used to melt ice and snow by piping warm water in pavement. In summer, it is used to cool down pavement temperature by piping cool water in pavement, as shown in Fig. 6 [118, 119]. Researchers have carried out a lot of research on pipe materials, laying methods, and temperature regulation capacity [109, 120]. The Ooms Avenhorn Holding developed a Road Energy System, which showed good effects in cooling pavement in summer and melting ice and snow in winter in a test application in Netherlands [121]. An energy collection capacity of about 140MW·h per year and an energy output capacity of 30 - 100MW·h per year were observed in the test of an integrated system for melting snow and storing energy at A8 expressway in Switzerland [122]. The peak temperature of the pavement was reduced by 15 °C - 20 °C in summer. In 2009, a test road with a system coupling solar and geothermal energy for melting ice and snow was built in Daqing, Heilongjiang Province, China. It was observed that the pavement temperature retained above 0 °C when the air temperature reached -30 °C [119]. These reported

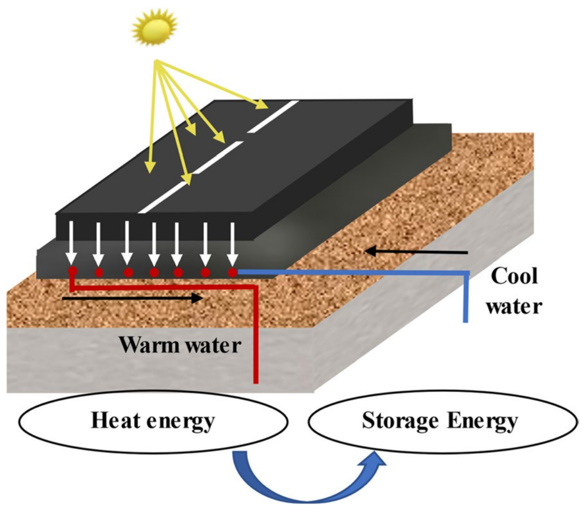

Fig. 6 Diagram of heat exchange system

applications showed that the heat exchange-based systems have good effects in melting ice and snow and reducing pavement temperature. However, these systems need to embed a pipe system in asphalt pavement, which is costly and challenging to maintain. So they were only applied in some airport pavement, and critical sections of high-grade urban roads and highways.

Energy storage

PCM asphalt pavement

PCMs can absorb or release a large amount of heat with retaining a specific temperature through changing its phase, which can significantly reduce the magnitude of temperature change [123, 124]. PCMs have relatively wide applications in construction, such as PCM trombe walls, PCM wallboards, PCM shutters, PCM building blocks, PCM pavement. PCMs are usually embedded by a distributed or layered structure [125]. Athukorallage et al. (2018) [126] studied the distributed and layered PCM asphalt pavement and found that for the layered has certain problems whether the PCM is embedded inside the pavement or at the surface. The PCM will be prone to vehicle wearing when at the surface and will change the heat distribution to a bad pattern when inside. In practice, PCM asphalt pavement mainly adopts the distributed structure. The PCMs can be added in asphalt pavement directly, or through packaged in a carrier or microcapsule.

The methods of PCMs incorporation

Adding directly is a straightforward method. Wei et al. (2019) [127] prepared a PCM modified asphalt by adding polyurethane solid-solid PCM into the asphalt. It was found that the specific heat capacity and thermal conductivity of the modified asphalt increased with the increase of the amount of PCM, but the thermal conductivity was always smaller than that of the base asphalt. Wei et al. (2019) [110] prepared a phase change asphalt mixture by using NiTi alloy phase change energy-storage particles (NiTi APCEP) as fine aggregate. The test results showed that The NiTi APCEP asphalt pavement with the substitution rate of 12 wt% has a 3.5 °C daily maximum temperature difference from the ordinary asphalt mixture specimen pavement. But, too much addition will damage the low-temperature crack resistance of asphalt mixture. Bian et al. (2012) [128] found that the addition of PCMs will compromise the cohesion and toughness of the asphalt.

It is more common to form phase change composite by introducing appropriate carrier materials to carry the PCMs. Solid-liquid PCMs and porous high absorption materials are usually selected for preparing phase change composite, in which the flow of PCMs can be confined due to the capillary and surface tension forces [113, 129]. Table 6 lists the typical carriers, PCMs, and the properties of the composites. Kuai et al. (2021) [130] prepared a modifier by using the polyethylene glycol-400 (PEG-4000) as the PCM and silica as the carrier, which was used in porous asphalt pavement. It was shown that the pavement temperature can be reduced by 3 °C and the mechanical properties and moisture stability of the mixture can meet the relevant requirements. Jin et al. (2019) [131] prepared fine aggregate and filler with binary fatty acids as a PCM and diatomite as a carrier and made asphalt mixtures with an addition of 3.5%. The test results showed that the maximum temperature at the upper and lower asphalt pavement surfaces decreased by 8.11 °C and 6.36 °C respectively. The low-temperature performance of pavement is almost unchanged, and the moisture stability decreased slightly. Jin et al. (2018) [132] prepared coarse aggregate using ceramsite as a carrier, poly (ethylene glycol) and ethylene glycol distearate (EGD) as PCMs. Then the particles were sealed by epoxy resin and used to mix asphalt mixture. The laboratory simulation tests showed that the asphalt pavement temperature can be reduced by 9.1°C through the usage of the prepared coarse aggregate.

Encapsulating the PCMs into microcapsules can avoid the loss of PCMs in use. The structure stability, mechanical properties, and thermal conductivity of the microcapsule shell are the major concerns in development. Wei et al. (2017) [140] synthesized a microcapsule material with *n*-tetradecane and dimethylbenzene as phase change core materials and epoxy polymer as shell by interfacial polymerization, which showed good stability. Guo et al. (2019) [141] developed a microcapsule material with

Table 6 Basic properties of different PCMs

Carrier matrix	Working substance	Phase change temperature(°C)	Phase change enthalpy(J/g)
SiO_2	PEG-4000 [130]	47.6-60.5	-
	Hydrocarbons PCM [133]	-1.5-24	80.98
	N-tetradecane-type paraffin waxes [134]	2-5	107-118
Diatomite	Stearic acid (SA) and palmitic acid (PA) [131]	52.93	106.70
	Polyethylene glycol (PEG) [135]	-	9.0332
	SA [129]	67.13	143.7
	PA [128]	59.1	97.74
Ceramsite	PEG and EGD [132]	54-60	29-50
	PEG-4000 [136]	53.8	125.1
ZnMgAl-mixed metal oxides	PEG [137]	50.9	108.1
Expanded graphite	Paraffin [138]	40-50	150
polypropylene	Unsaturated organic acid [133, 139]	0.5-26	46.97

silicone rubber/paraffin@silicon dioxide compound, of which the mechanical properties were enhanced. Zhang et al. (2017) [142] prepared a microcapsule material using paraffin and melamine-formaldehyde resin as the phase change core and shell, respectively, with graphene oxide nanosheets embedded in the middle. Test results show the material has good stability, mechanical properties, and thermal conductivity.

PCM asphalt pavement has active temperature regulation function, of which the maximum and minimum temperature can be regulated by properly selecting PCMs. However, it still has some problems need to be improved and optimized by now. The high cost is also a factor limiting its wide application.

Energy conversion

Thermoelectric principle and cooling mechanism

Thermoelectric pavement can convert heat into electrical energy using the temperature difference between different layers of asphalt pavement or between road and the surrounding environment, thereby reducing the pavement temperature [111, 115]. The thermoelectric effect manifests itself as a voltage difference between the hot and cold sides of a semiconductor in response to a thermal gradient [115]. The voltage can be expressed by Eq (4). For a thermoelectric system, the current, power, and the total amount of heat can be obtained by Eq (5) through Eq (7) [143, 144].

$$V = \alpha(T_h - T_c) \tag{4}$$

$$I = V/(R - R_l) \tag{5}$$

$$P = Q_h - Q_c = I^2 R_l \tag{6}$$

$$Q = \alpha I T_c + K(T_h - T_c) - 1/2 I^2 R_L \tag{7}$$

where V is the voltage of the thermoelectric generator (TEG); T_h is the hot side temperature of the

TEG; T_c is the cold side temperature of the TEG; α is the Seebeck coefficient of the TEG. I is the current; R is the internal resistance of TEG, R_L is the load resistance; $(Q_h - Q_c)$ is the heat flux due to temperature gradient; Q is the total amount of heat, and K is the heat transfer coefficient.

The methods for improving thermoelectric efficiency

An enough temperature difference is critical to the thermoelectric system. Thermoelectric pavement initially only relies on the natural temperature difference between different pavement layers or between the road and the surrounding environment to generate electricity. In order to increase the power generation efficiency and cooling effect, researchers have tried many improvement measures, such as increasing the temperature difference, enhancing the heat collection efficiency, and improving the thermal conductivity of the pavement. Jiang et al. (2018) [111] introduced vapor chambers and water tanks in the system, to improve heat collection and increase the temperature difference, respectively, so as to increase the voltage difference and achieve more efficient energy conversion. The introduction of water tank also can improve the cooling effect. The reduction of pavement temperature can reach about 9 °C. Hu et al. (2014) [145] proposed a thermoelectric system for asphalt pavement using aluminum plates as heat carriers, which improves heat collection efficiency and makes construction easier. Mallick et al. (2009) [146] constructed test pavement using aggregates with good thermal conductivity. It was found that suitable aggregates could improve the efficiency of thermoelectric conversion. Wu et al. (2005) [109, 147] suggested adding graphite and thermal conductive fibers to asphalt mixture, so as to enhance the pavement thermal conductivity. Although this approach can improve the power generation efficiency, the increased thermal conductivity will promote the pavement to absorb more heat from the environment, which is not unbeneficial to the regulation of asphalt pavement temperature. Hasebe et al. (2006) [148] employed the nearby river water as coolant to widen the temperature difference, thereby increasing the power generation of the thermoelectric system. It was found that both the power generation and the cooling effect can be improved when the cold end of the thermoelectric system has an enough low temperature.

Currently, the conversion efficiency of thermoelectric pavement is relatively low. The highest conversion efficiency found in this review is only 7.4% and the power generation of the systems is far from the theoretical value [149, 150]. Moreover, the thermoelectric system will increase the complexity of pavement structure, which brings some issues to be solved.

Comparison of different regulation techniques

Each regulation technique has its own advantages and disadvantages. The choice should be determined based on comparison of different regulation techniques with considering the environmental conditions. From the perspective of cooling effect, although many studies have quantified the cooling effect of different regulation techniques, there are still significant differences between the studies. In this paper, the theoretical cooling effects of different high-temperature regulation techniques were assessed according to Eq (1). In the assessment, the parameters of common asphalt pavement and the photo-thermal environment of a typical region in China were taken into account. Γ takes 0.8, R takes 0.15, I_0 takes 810.99 W/m^2, k takes 2.5 W/(m·K), c takes 797.23 j/kg·K, and ρ takes 2430 kg/m^3. In the analysis, take one parameter as variable and fixed the others so that the trend of the maximum pavement surface temperature with the changing parameter can be investigated. The analysis results are depicted in Fig. 7.

As shown in Fig. 7(a), the maximum pavement surface temperature will decrease by 3.46 °C when the reflectivity increases by 0.1. Theoretically, the pavement surface maximum temperature can be cooled by 23.15 °C when the reflectivity rises from 0.15 to 0.82. However, too high reflectivity will bring some safety problems. In practice, it isn't a good choice to excessively pursue reflectivity. It can be seen from Fig. 7(b), the smaller the thermal conductivity (the higher thermal resistance), the higher the maximum temperature of the pavement surface, which consistent with the conclusion of Du et al. [66] and Huang et al. [77] that the thermal resistant pavement can increase the surface temperature. The thermal resistant pavement can restrict the downward transfer of heat so that the temperature of the middle and bottom layers of asphalt pavement can be regulated, while the surface temperature will increase due to the accumulated heat. The benefits of thermal resistant pavement should be assessed based on the complete pavement temperature field. The cooling effects of pavement with heat exchange system and thermoelectric pavement can be assessed through the energy change. As shown in Fig. 7(c), the surface temperature will reduce by 3.62 °C with each reduction of 100W/m^2 in energy.

The latent heat of materials is generally about a few hundred to a few thousand kJ/kg. For example, the latent heat of ice is 355 kJ/kg at one-atmospheric pressure, and the latent heat of water evaporation at 38°C is 2409.88 kj/kg. However, the specific heat capacity of water is 4.2 kJ/(kg·°C), which means the sensible heat of a temperature difference of 10 °C is only 42 kJ/kg. Permeable and water retaining pavements can be cooled through water evaporation. Theoretically, the cooling effect can be assessed using the heat taken away by water evaporation. The specific heat capacity of asphalt mixture is about 0.92 kJ/(kg·°C). For the asphalt pavement with a depth of 6 cm, the sensible heat per °C per m^2 is about 116.24 kJ. The heat for evaporating 0.482 kg water is equivalent to the heat of changing the temperature by 10 °C for 1 m^2 asphalt pavement with a depth of 6 cm. However, in practice, the heat for evaporating water is not only from asphalt pavement but also from environment, so it is difficult to precisely estimate the water consumption only by the latent heat of water evaporation.

The latent heat of PCMs used in asphalt pavement is usually in the range of 29 - 150 kj/kg. In this paper, an average of 89.5 kj/kg was taken for analysis. The calculation shows that the heat of changing the temperature by 10 °C for 1 m^2 asphalt pavement with a depth of 6 cm is equivalent to the latent heat of 12.99 kg PCM. For PCM asphalt pavement, in addition to the latent heat, the change of pavement specific heat capacity should also be included in the cooling effect assessment. It can be seen from Fig. 7(d), the pavement surface maximum temperature decreases with the increase of pavement specific heat capacity. The increase of pavement specific heat capacity from 800 j/kg·K to 1600 j/kg·K can bring pavement surface maximum temperature a reduction of 8.59 °C.

In terms of construction convenience, permeable pavement, thermal resistant pavement and PCM asphalt pavement are the most convenient because they don't require any additional construction work. The construction of

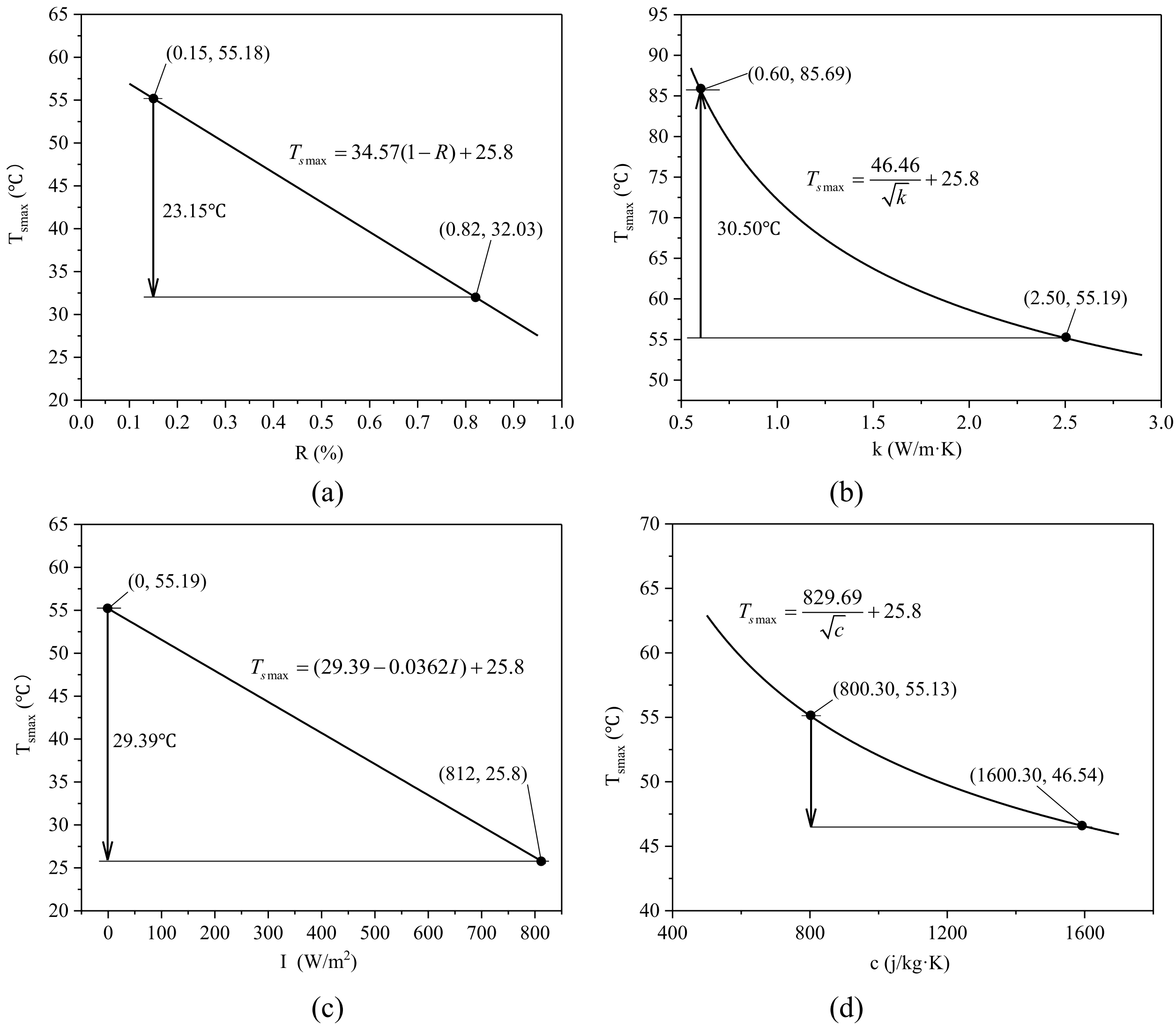

Fig. 7 **a** The cooling effect of reflection enhancement; **b** The cooling effect of increasing thermal resistance; **c** The cooling effect from energy angle; (**d**) The cooling effect from specific heat capacity angle

heat-reflective coating and water retaining pavement is relatively convenient. Only a small amount of additional construction work is required. In contrast, embedding heat exchange system or thermoelectric system into asphalt pavement will be complex work. From the perspective of maintenance, the heat-reflective coating, thermal resistant asphalt pavements and PCM asphalt don't require special maintenance. The permeable pavement and water retaining pavement only need to be watered regularly. However, both embedded heat exchange system and thermoelectric system require a large amount of additional maintenance work. According to the above comparative analysis, the advantages and disadvantages of various regulation techniques can be summarized as shown in Table 7.

Some researchers suggested incorporating multiple regulation techniques to achieve a better regulation effect. Li et al. (2013) [102] tried to make comprehensive use of reflection enhancement and evaporative cooling approaches. Karlessi et al. (2011) [151] introduced PCMs into heat-reflective coating. The laboratory test results showed that the PCM heat-reflective coating can obtain an extra temperature reduction of 8°C than the ordinary heat-reflective coating. The applications of comprehensive utilization of multiple regulation techniques are rarely reported by now, which needs further research.

Table 7 Advantages and disadvantages of different regulation techniques

TechniqueType	Advantages	Disadvantages
Reflection enhancement	Good cooling effect, Low cost, Easy construction	Poor durability, Poor skid resistance
Increasing thermal resistance	Low cost, Easy construction	Poor pavement performance
Evaporative cooling	Environmentally friendly, Low noise	Need water
Heat exchange system	Good cooling effect, High and low temperature adjustable	Difficult construction
Energy conversion	Energy availability	Immature technology
Energy storage	Good cooling effect, Intelligence	Technical complexity

Summary

The asphalt pavement high-temperature regulation techniques were reviewed. It has great potential to regulate the high temperature of asphalt pavement through taking specific technical measures. In the context of climate change, asphalt pavement faces severe challenges from high-temperature. Asphalt pavement high-temperature regulation will become an important technical measure to adapt to climate change. It is necessary to conduct systematic and in-depth research.

Although the evaluation of the cooling effect of various asphalt pavement high-temperature regulation techniques can be seen in the existing literature, it is still very difficult to compare the results between different studies. This mainly because there is no relevant standard for the test and evaluation of asphalt pavement temperature field. It is necessary to develop the test and evaluation standard of asphalt pavement temperature field to meet the needs of asphalt pavement permanent deformation analysis, so as to provide a unified test and evaluation means for related research.

Generally, the temperature field of asphalt pavement will be totally affected by the temperature regulation measures. However, most studies on the evaluation of cooling effect only focused on the change of temperature in one or some parts of the pavement structure. The comprehensive evaluation of asphalt pavement temperature field was rarely seen in the literature. It is necessary to comprehensively evaluate the effects of various high-temperature regulation techniques on the temperature field of asphalt pavement, so as to precisely assess the improvements of asphalt pavement high temperature performance brought by the regulation techniques.

Each asphalt pavement high-temperature regulation technique has its own advantages and disadvantages. Some have other functions. Some will compromise the pavement performance. How to balance high-temperature regulation and pavement function and performance is an important topic in this area in the future. In addition, comprehensive utilization of various regulation techniques showed certain advantages, which is also an important approach in this area.

Abbreviations

GMST: Global mean surface temperature; AR6: Sixth Assessment Report; IPCC: Intergovernmental Panel on Climate Change; RCPs: Representative concentration pathways; SBS: Styrene-butadiene-styrene; SMA: Stone matrix asphalt; OGFC: Open-graded friction course; Rvisi: Visible reflectance; Rnir: Near-infrared reflectance; Rtotal: Total solar reflectance; CE: Shale ceramic; FB: Floating beads; FAC: Fly ash cenosphere; PCMs: Phase change materials; NiTi APCEP: NiTi alloy phase change energy-storage particles; EGD: Ethylene glycol distearate; PEG-4000: Polyethylene glycol-400; SA: Stearic acid; PA: Palmitic acid; PEG: Polyethylene glycol.

Acknowledgements

Not applicable.

Authors' contributions

ZG, LZ, JW and ZX collected and synthesized references. ZG created tables and figures to present the data, and drafted and wrote the manuscript. YM initiated the project and conceptualization, reviewed, and edited the manuscript. LW reviewed and revised the manuscript. The author(s) read and approved the final manuscript.

Funding

This work was funded by the National Key R&D Program of China (Grant Number: 2019YFE0117600).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 8 February 2022 Accepted: 13 April 2022
Published online: 03 July 2022

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