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Electrically conductive asphalt concrete for smart and sustainable pavement construction: A review

Dong Lu [a,b,c], Xi Jiang [a], Zhen Leng [a,*], Yanlin Huo [b,c], Daiyu Wang [b,c], Jing Zhong [b,c,*]

[a] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong SAR*

[b] *Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education (Harbin Institute of Technology), Harbin, 150090, PR China*

[c] *School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, P.R. China*

** Corresponding authors. zhen.leng@polyu.edu.hk (Z. Leng) and zhongjing@hit.edu.cn (J. Zhong).*

Abstract: Electrically conductive asphalt concrete (ECAC) is an innovative material that offers numerous possibilities by directly incorporating functional additives (such as metal-based or carbon-based materials) into asphalt binder and mixing it with traditional aggregates and mineral filler. With such a strategy, ECAC possesses a high electrical/thermal conductivity, making it an ideal candidate for sustainable repair methods based on induced heating-healing, snow and ice melting systems on pavements, and piezoresistive sensors for traffic detection in pavement engineering. This paper aims to provide a systematic review of the design and development of ECAC, with a particular focus on the advancements made over the past decade (from 2013 to 2023). The review begins by introducing the composition and fundamental principles underlying ECAC. Subsequently, it summarizes the key aspects related to the design and preparation of ECAC. Moreover, this paper delves into the remarkable multi-functionality exhibited by ECAC, showcasing its potential in practical applications. Through examining various case studies, the review highlights the successful utilization of ECAC in diverse scenarios. This review work can serve as a valuable resource, offering insights and guidance for developing ECAC in the context of smart and sustainable pavement construction.

Keywords: Smart pavement; Electrically conductive asphalt concrete (ECAC); Self-healing; Snow and ice melting; Traffic detection

1. Introduction

Pavement engineering plays a vital role in transportation infrastructure, making it a crucial component for the progress of societies and national economies [1-4]. Asphalt concrete, known for its ease of construction, exceptional flexibility, ductility, and durability [1, 5-8], has been widely adopted by agencies responsible for roads to withstand the combined effects of traffic and environmental factors throughout its service life [9-11]. The concept of a smart pavement, which possesses additional functions or responds to external stimuli, has emerged as a new paradigm in pavement design [12, 13]. This transition from conventional pavement to a "smart, multi-functional, and sustainable" model is viewed as a crucial strategy for promoting economic recovery and prosperity, with many countries strongly embracing this vision.

Typically, asphalt concrete can acquire smart and multi-functional abilities by transforming it from an almost insulating material to a conductor or semiconductor, known as electrically conductive asphalt concrete (ECAC) [5, 14, 15]. An easy-to-implement approach is to directly add functional additives, such as metal-based materials [13, 16-19] and carbon-based materials, such as carbon fiber (CF) [20-22], graphite powder (GP) [23, 24], carbon black (CB) [25], carbon nanotubes (CNT) [14, 26], and graphene nanoplate (GNP) [27, 28], into asphalt binder and then mixing it with aggregates and filler. With such a design, the electrical resistivity of the asphalt concrete (has a resistivity of 10^9-10^{11} $\Omega\cdot$cm at ambient temperature [15, 24]) can be dramatically reduced by several orders of magnitude [24, 28], depending on the dosage and type of the admixed functional additive and its distribution inside the concrete. In this situation, the introduced functional additive can create a conductive path inside the asphalt concrete, demonstrating excellent electrical conductivity, thermosensitive, and strain/stress sensitivity [15, 29, 30]. Thus, ECAC has many potential applications in pavement engineering, such as induced heating-healing [2, 13, 17, 18, 31], snow and ice melting [32, 33], and traffic detection [34-36]. The applications of ECAC can improve the safety and lifespan of the pavement while reducing maintenance costs throughout its service life, thereby driving the advancement of pavement engineering and facilitating the realization of smart pavement and smart transportation.

Despite the increasing number of recent studies on electrically conductive asphalt concrete (ECAC), its practical applications in pavement engineering remain limited due to high investment costs and unstable performance [12, 17, 37-39]. Additionally, the mechanisms behind the electrical and thermal conductivity of ECAC in practical applications are still not well understood [15, 24, 30]. These gaps are primarily attributed to the failure to address the following issues: i) how to achieve high-quality dispersion and uniform distribution of admixed functional additives (or functional aggregate or filler) inside the ECAC; ii) quantitative evaluation of the distribution of admixed functional additives inside the ECAC has still lacked; and iii) how to cost-effectively and efficiently develop ECAC in practical applications. Therefore, there is an urgent need to review the existing literature on the development and applications of ECAC to address the current challenges and expedite its practical implementation. Based on this, this review provides a comprehensive summary of the development and applications of ECAC. This review provides a comprehensive summary of the development and applications of ECAC, starting with an introduction to the principles of ECAC. It then focuses on the design and preparation methods for ECAC, followed by an examination of its multi-functionality and several case studies highlighting its applications in pavement engineering. By reviewing the current state of research, this review work aims to enhance the understanding of ECAC and offer guidance for the development of smart and sustainable pavements.

1. Principle and composition of ECAC

Typically, ECAC consists of four components [34, 40-42]: functional additive, asphalt binder, aggregates, and filler (see **Fig. 1**). Selecting suitable raw materials and the mix design is crucial for preparing ECAC [32, 36, 43, 44]. In developing ECAC, the challenge was to effectively improve its conductivity for multi-functional use without compromising its road performance [5, 12, 15]. This section systematically introduces the principle and composition of ECAC.

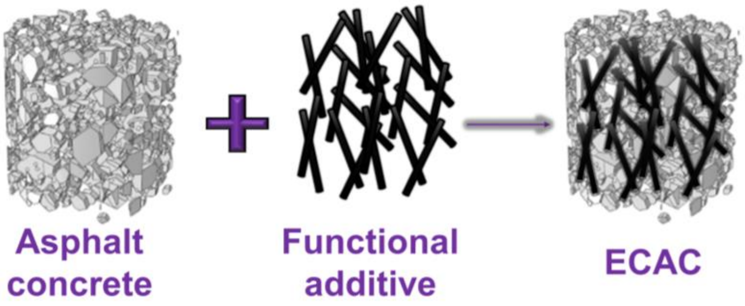

Fig. 1. Illustration of ECAC structure: functional additive is distributed inside the concrete.

1.1. Asphalt binder

Asphalt binder is an insulating material and accounts for ~5 vol% of asphalt concrete [5, 45-47]. Generally, the functional additive is directly mixed with asphalt to enable it to be a semiconductor/conductor and then produce conductive asphalt-based ECAC [35, 48-50]. In such a system, all kinds of asphalt, such as virgin, aged, polymer modified, and emulsion [2, 51-54], can be used for preparing ECAC. The advantages of this strategy include high operability and excellent applicability [1, 55-57]. However, note that the prerequisite for achieving a high electrical conductivity of ECAC is that the dosage of the admixed functional additive should be over the percolation threshold and uniformly/continuously distributed inside the concrete, which is undoubtedly very challenging [28, 58-61]. More seriously, additional dispersion processes are usually performed to pre-mixing the asphalt and functional additive, which is a time-consuming and high-cost process, thus limiting the development and practical applications of the ECAC [62-64].

Some parameters, such as binder type and binder-to-aggregate ratio, have a minor effect on the electrical property of conductive asphalt-based ECAC, considering asphalt itself is non-conductive material [12, 14, 25, 61, 65]. While the type, distribution, and dosage of the admixed functional additive are crucial to the performance of ECAC, which will be discussed in detail in the next section.

1.2. Functional additives

Similar to developing conductive cement concrete [66-68], the key to developing ECAC is constructing a conductive network within the asphalt concrete matrix [60, 61, 69, 70]. As summarized in **Fig. 2**, the commonly used functional additives are available in different types, sizes, and shapes. This section discusses the properties of different kinds of functional additives and their impact on the performance of ECAC.

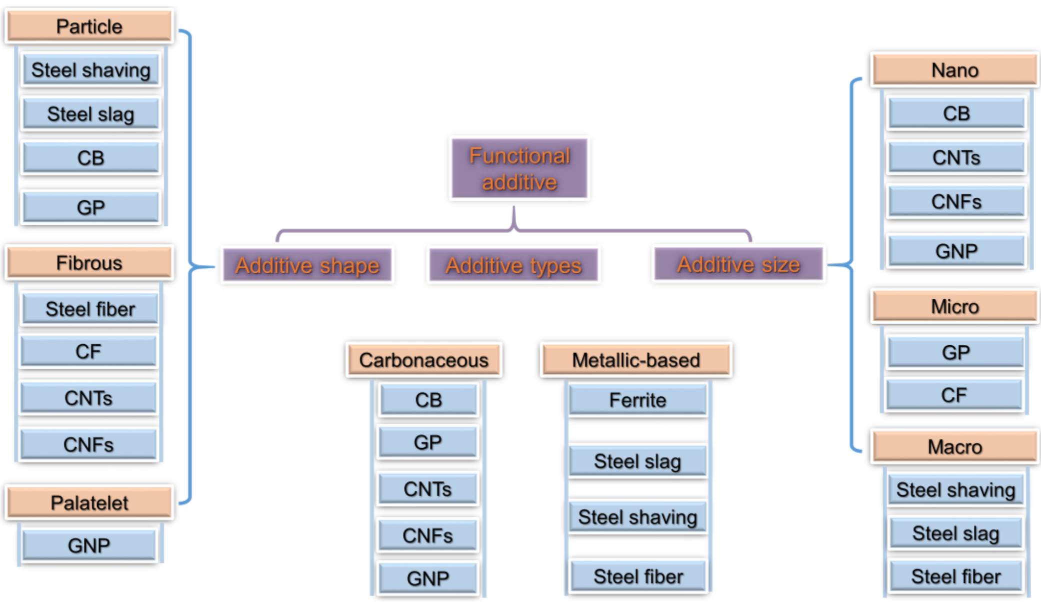

Fig. 2. Functional additives used for developing ECAC.

1.2.1. Metallic-based materials

Metallic-based materials, such as steel fiber [17, 71, 72], steel wool [17, 64], and ferrite [18, 73-76], are cheap materials that can render asphalt concrete electrically conductive (as shown in **Fig. 3**). For instance, García et al. [77] first explored the influence of admixed steel wool on improving the conductivity of ECAC for self-healing applications. However, the bulk electrical resistivity of ECAC containing steel wool is hardly affected by its length or diameter due to the limited size (**Fig. 3b**), and its lowest value was only 1×10^4 Ω·m. Liu et al. [76] proved that adding waste ferrite into ECAC can improve its electromagnetic wave-absorbing efficiency, which is a cheap and sustainable way to develop ECAC (**Fig. 3c**).

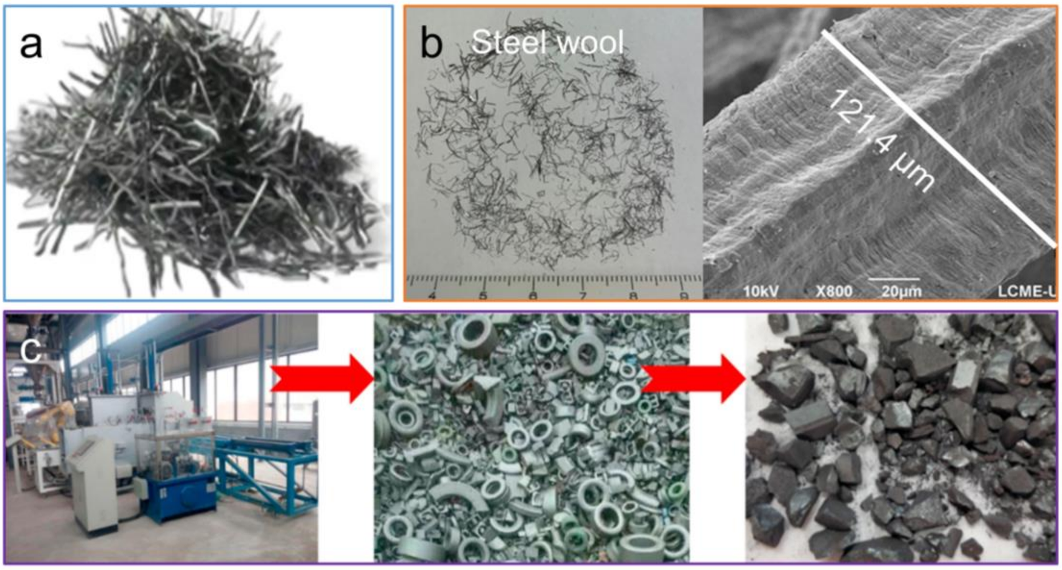

Fig. 3. Metallic-based materials for preparing ECAC: (a) steel fiber [78], (b) appearance and SEM images of steel wool [17], and (c) recycling of waste ferrite [76].

1.2.2. Carbonaceous materials

As shown in **Fig. 4**, carbonaceous materials, such as carbon fiber [20, 21, 29, 39, 79], one-dimensional (0D) carbon nanomaterials (e.g., carbon black and graphite powder) [62, 80, 81], one-dimensional (1D) nanofibers (e.g., CNT) [26, 82, 83], and two-dimensional (2D) nanosheet (e.g., GNP) [63, 84, 85], are good candidates to develop ECAC because of they are insoluble to moisture and have minor oxidation in the environment, implying it has excellent chemical stability in ECAC [5, 56, 63]. Among all these functional additives, CF has a length of several centimetres (**Fig. 4a**), a resistivity of 10^{-2}-10^{-4} $\Omega\cdot$cm, Young's modulus of 300 GPa, and tensile strength of 200-3500 MPa [86-88], as well as a better affinity with asphalt concrete, enabling CF-based ECAC to have desirable structural and electrical properties, making it structurally and functionally desirable in terms of acceptability. In addition to increasing asphalt concrete's fatigue life and thermal cracking resistance, CF-based ECAC can achieve high conductivity and demonstrate self-healing, self-heating, and self-sensing abilities [89-92]. The percolation threshold needs to be determined by varying the amount of CF dosage to achieve the highest electrical conductivity for ECAC [20, 21]. The incorporated CF does change the bulk properties of the ECAC [21]. However, the high cost and highly challenging dispersion process limit the practical applications of CF-based ECAC.

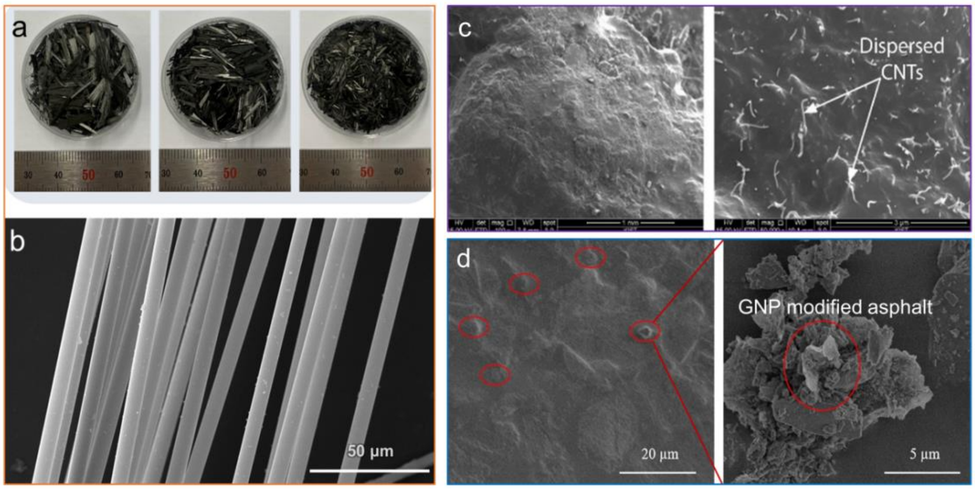

Fig. 4. Carbonaceous materials used for preparing ECAC: (a) appearance of CF and its (b) SEM image [93], (c) SEM images of (left) plain asphalt concrete and (right) ECAC with 0.5wt% CNT [26], and (d) SEM of GNP modified asphalt [94].

As typical 0D carbon nanoparticles, CB and GP have an electrical resistivity of 0.1-2.3 Ω·cm and 10^{-4} Ω·cm, respectively [95, 96], and the characteristics of low-cost and high availability make them suitable for developing ECAC. The admixed extremely high dosage of CB or GP can decrease the resistivity of ECAC, mainly due to 0D nanoparticles being challenging to form continuous and stable conductive pathways inside ECAC. For instance, Chen et al. [97] used a high dosage of GP (22 vol%) to enhance the electrical/thermal conductivity of ECAC and thus leading to enhanced efficiency of asphalt concrete. Note that CB or GP has an inert nature surface, as well as the excessive dosage of conductive nanoparticles tends to form agglomerates inside the concrete, which may impair the performance of the mixture, considering that the aggregate and functional additive modified-asphalt interface is sensitive to the concrete's performance [20, 80]. Indeed, as reported by the previous study [20], the inherent lubricating characteristic of GP (>20%) added to hot mix asphalt can greatly reduce the Marshall stability and dynamic stability of asphalt concrete. Additionally, the low aspect ratio of the 0D nanoparticles makes them less effective in improving the conductivity of concrete than fibrous additives (e.g., CF, and CNT) [21, 26, 29, 76]. However, 0D nanoparticles-based ECAC exhibits higher signal stability than that fibre materials-based ECAC [26, 59]. Fortunately, combining 0D nanoparticles (i.e., CB and GP) with fibrous CF is an ideal choice to produce conductive asphalt-based ECAC, fully exploiting the two additives' synergistic effect.

As a 1D carbon nanofiber, CNT is a tube structure made of single-layer graphene [98-100], with an excellent electrical conductivity of ~10^{-2} Ω·cm and tensile strength of 200 GPa [101]. As such, it is regarded as an outstanding candidate for decreasing the ECAC's electrical resistivity [102-104]. Thus, it is an attractive functional additive with multi-functional properties and an excellent reinforcing effect. However, the performance of CNT asphalt-based ECAC is primarily related to their distribution quality inside the matrix [105]. Therefore, more studies should be performed to increase the dispersion quality of the admixed CNT in the concrete as much as possible.

GNP is a 2D nanosheet consisting of graphene stacks [93, 106, 107], known for its outstanding mechanical and excellent electrical properties [108-110]. It has a higher electric mobility than CNT [111-113], making it an ideal candidate for developing ECAC. Similar to the significant reduction of ECAC's resistivity with CF-linked 0D conductive nanoparticles, the resistivity of ECAC can also be dramatically decreased by using CF-linked GNP. For example, Arabzadeh et al. [23] produced ECAC for de-icing and anti-icing in winter, which was achieved by modified asphalt mastic with 0-2.5 vol% CF combined with 5 vol% GP. Carbon is the most abundant element in nature, and the carbonaceous materials have achieved industrialization [114], which provides an excellent opportunity to develop multi-functional ECAC.

Overall, the conductivity improvement potential of metallic materials in developing ECAC is lower than that of the carbonaceous materials [15, 24, 52]. The former can only reduce the electrical resistivity of ECAC to around 100 Ω·m, which does not meet the requirements of some practical applications [7, 60, 61, 115]. Additionally, the admixed metallic materials may rust and corrode during long-term service, which could seriously affect the performance of ECAC [56, 64, 116]. In contrast, carbon-based materials are good candidates to develop ECAC because they are insoluble to moisture and have minor oxidation in the environment [38, 117, 118], implying it has excellent chemical stability in ECAC. They perform better in improving the electrical and thermal conductivity of concrete as compared to using metallic materials. Especially, CF has a much higher aspect ratio and thus can bridge the isolated functional additives, supporting the combined usage of CF and carbon-based nanomaterials to build hierarchical conductive pathways in ECAC, resulting in a significant increase in ECAC's conductivity.

1.3. Aggregate

Aggregates account for up to about 95% of the volume of asphalt concrete [119-121], which serves as a framework for the composite system and is filled and covered by the asphalt binder [1, 122, 123]. However, the shortage of natural aggregate is becoming increasingly severe and finding a candidate to alleviate this plight is urgent.

Steel slag is a by-product of the steel industry, and there is a lack of effective recycling approaches, which has caused environmental problems such as soil contamination, water pollution, and a shortage of landfills [124-126]. Therefore, the efficient recycling of steel slag to replace natural aggregates in civil engineering has economic and environmental benefits [125, 127-129]. With the development of smart, multi-functional, and sustainable pavements, self-heating, self-healing, and self-sensing asphalt pavements are gradually being proposed and developed by using functional aggregates, mainly due to the high iron (FeO and Fe_3O_4) content in steel slag (as shown in **Fig. 5a**) [130]. As presented in **Fig. 5b** and **Fig. 5c**, in their recent works, Liu et al. [115, 118] proved that the admixed steel slags demonstrate uniform distribution inside the ECAC with the assistance of X-ray computed tomography (CT). Additionally, magnetite rock (Fe_3O_4) contains ferrous (FeO) and ferric (Fe_2O_3), and its resistivity is about 4.0×10^{-3} Ω·m [2, 58, 131], enabling magnetite an effective candidate aggregate substitute for the development of ECAC, it also has a higher dielectric constant than natural rocks and therefore exhibits a better microwave absorption efficiency in ECAC.

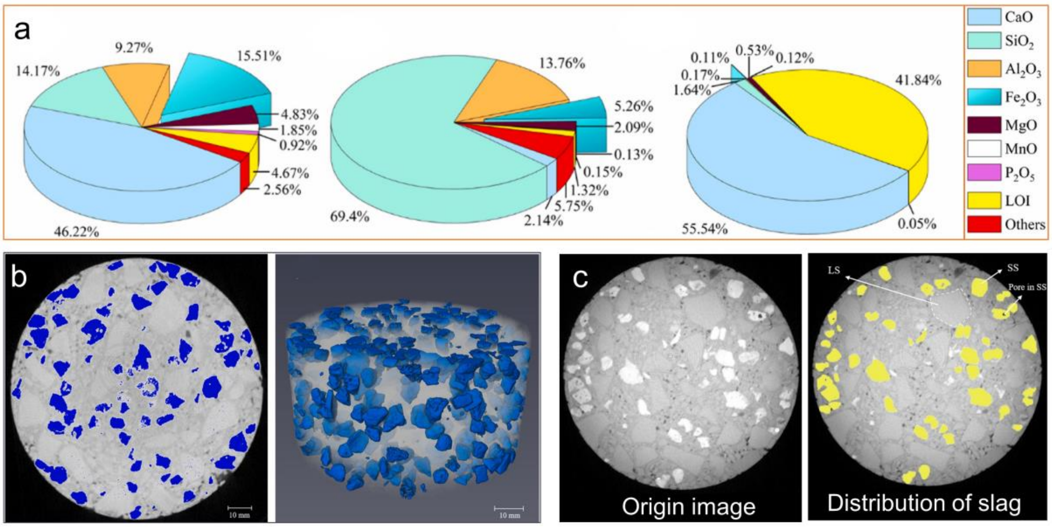

Fig. 5. (a) Element composition analysis of steel slag (left), basalt filler (middle), and mineral filler (right) [130]; (b) distribution of steel slag in ECAC: (left) 2D image and (right) 3D model [132]; CT slice image: (left) original and (right) identification of steel slag in the 2D image [128].

Compared with the conductive asphalt-based ECAC, conductive aggregate-based ECAC containing steel slag has many benefits, such as low cost and easy operation [123, 127, 132]. As such, using steel slag as a thermally conductive aggregate is a promising option for improving the thermal conductivity of concrete, allowing for the electrothermal melting of snow on asphalt pavements [75, 128, 133]. However, admixed steel slag only slightly reduces the resistivity of asphalt concrete [122, 123, 127]. This is expected because it is almost impossible for the steel slag to build up a continuous and efficient conductive path in the concrete due to the isolation of the non-conductive asphalt and the limited electrical conductivity of the steel slag itself [127, 129]. Additionally, the bonding strength between steel slag and asphalt is the most crucial indicator to ensure the durability of ECAC; however, previous studies suggested that the bonding strength of steel slag and asphalt is controversial [124, 127], highly dependent on its quality and source.

1.4. Filler

Some functional powders, such as ferrite and fly ash, containing metal oxides, can replace mineral powder to enhance the heating efficiency of ECAC [73, 74, 134, 135].

Ferrite is a magnetic iron oxide and a common microwave-absorbing material that can be induced by microwave radiation with excellent heat generation efficiency; it has been extensively applied for the self-healing of asphalt pavements [13, 17, 18, 74]. For example, Zhu et al. [73] replaced 80% of the mineral powder with ferrite powder, resulting in a 38% increase in the heat production capacity of ECAC. Additionally, fly ash is an industrial by-product, which is produced when coal is burned in thermal power stations, and it has a SiO_2 of 46.6 wt%, an Al_2O_3 of 12.4 wt%, and a Fe_2O_3 of 9.7 wt%, which has good ability in microwave absorption and thus used to increase the microwave heating efficiency and self-healing efficiency of ECAC [135].

In general, the heating-healing ability of conductive filler-based ECAC is far lower than that of the conductive asphalt-based ECAC or conductive aggregate-based ECAC, considering the limited volume fraction of filler in ECAC.

2. Design and preparation of ECAC

According to previous studies [1, 62, 73, 74, 127, 128], there are three strategies to develop ECAC: functional additive is directly mixed with asphalt to develop conductive asphalt-based ECAC, using conductive aggregate to replace natural aggregates to develop conductive aggregate-based ECAC, and using conductive powder to replace mineral filler to develop conductive filler-based ECAC. The preparation process for these three types of ECAC is as follows:

Conductive asphalt-based ECAC can be prepared using two methods: dry and wet mixing methods. Functional additives like fibers and carbon-based nanomaterials can be directly mixed with asphalt binder using the wet method, and then mixing it with aggregate and mineral filler (**Fig. 6**). In the dry method, however, functional additives (e.g., steel fiber and carbon fiber) are mixed with aggregate before binding with asphalt binder. The dry mixing method can reduce the flocculation of fibers in asphalt concrete and makes the mixing process easier. In fact, the dry mixing method has been widely used to produce fiber-reinforced asphalt concrete in the lab and in practical applications [26, 136]. Due to its practicality, the dry mixing method is a promising method for admixing functional additives for preparing ECAC.

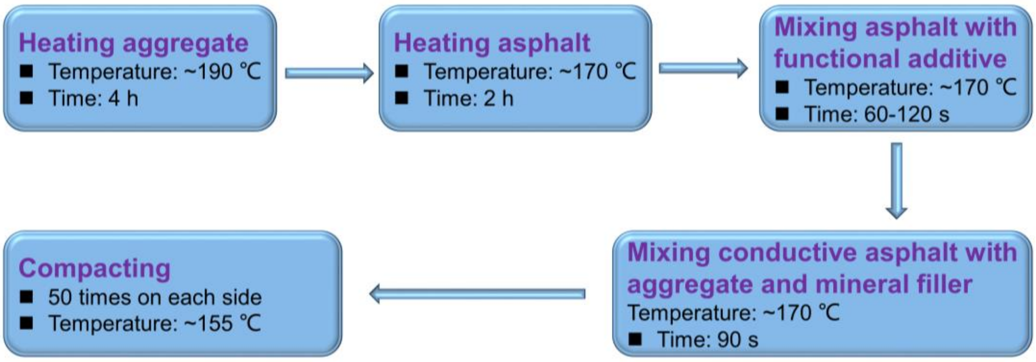

Fig. 6. Preparation process of a typical conductive asphalt-based ECAC.

Conductive aggregate-based ECAC is prepared by replacing natural aggregates with conductive aggregates. The replacement level mainly depends on the type of conductive aggregates [127, 128, 136]. Other steps are consistent with the preparation of conductive asphalt-based ECAC. Similarly, conductive filler-based ECAC is prepared by replacing the same volume of mineral fillers with functional fillers [73, 74, 134].

3. Multi-functionality of ECAC for sustainable pavement construction

The well-dispersed functional additive can form a continuous/stable conductive channel inside ECAC, enabling it to exhibit outstanding conductivity and heating-healing ability [1, 56, 62, 82]. As illustrated in **Fig. 7**, under the stimulation of external energy (e.g., microwave or magnetic field), ECAC can be induced heating to heal microcracks to restore the asphalt concrete’s performance [116, 128, 129, 137, 138]. Additionally, heat can be generated by the applied voltage on ECAC for snow and ice melting [20, 21, 139]. Stress (or force), strain (or deformation), and cracks (or damage) of asphalt concrete structures can be detected based on the relationship between the external force and electrical signal (i.e., electrical resistivity) [5, 140, 141]. Additionally, ECAC can be prepared in the form of a piezoresistive sensor and thus used for traffic detection (e.g., traffic volume monitoring and dynamic weighing of roads) [81, 84, 142].

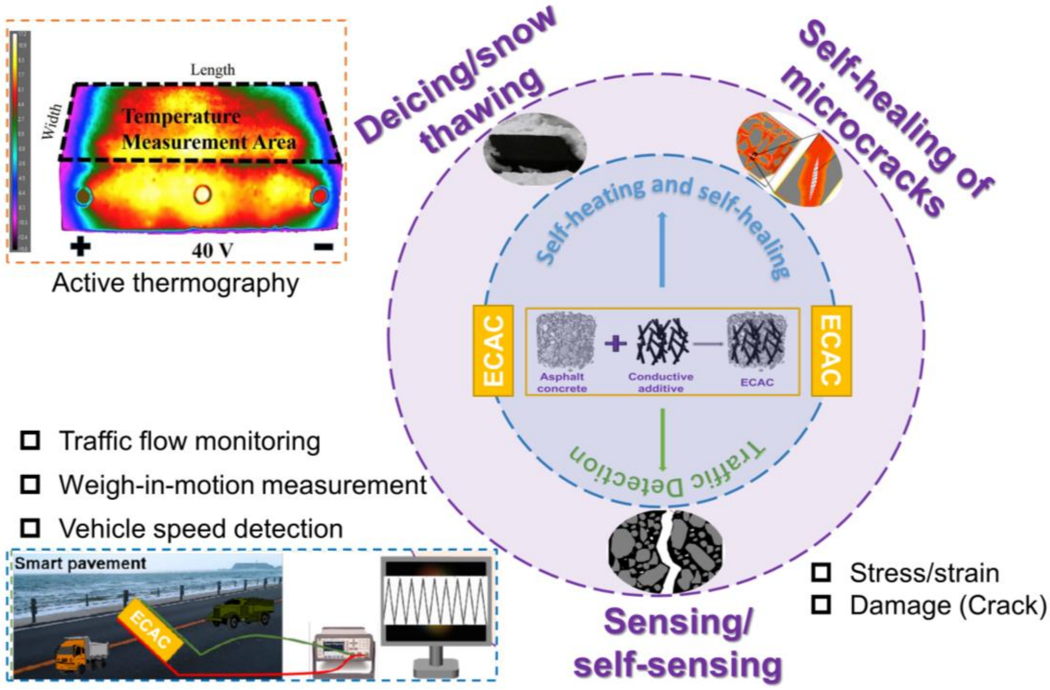

Fig. 7. ECAC and its potential applications in pavement engineering.

3.1. Induced heating-healing of ECAC as a sustainable maintenance technique

3.1.1. Principles of induced heating-healing of ECAC

Asphalt binder is a self-healing material and it can repair microcracks when providing enough rest time between loading cycles [55, 143]. When the edges of two microcracks are close together, as well as the asphalt binder can flow over their surfaces and create cohesion, the microcracks thus have a chance to heal, i.e., the cracks close [144, 145]. The self-healing of asphalt concrete is a complex process and involves multiple/complex factors, such as the asphalt's activation energy, the state of microcracks, and the capillary flow through the microcracks [137, 145, 146]. Previous studies have shown that the induced healing process of asphalt binder is highly related to temperature [55, 143, 145, 146]. Under an external energy source, the rising temperature can improve the capability to heal microcracks and enhance the healing efficiency of ECAC [56, 80, 123]. In this context, increasing electrical conductivity and sensitivity of asphalt concrete to the electromagnetic field/microwave is the most efficient approach to heal the microcracks [56, 116, 147, 148]. Some functional additives, such as steel fiber, CF, and carbon-based nanomaterials, are good microwave/electromagnetic sensitive materials, which can promote the induced heating-healing of ECAC [80, 149, 150].

As presented in **Fig. 8**, some technologies (i.e., heating sources), such as induction heating coil, microwave radiation, and infrared radiation, have been extensively used to promote the induced heating-healing of ECAC. Among these technologies, the former two methods have been more frequently used and efficient for induced heating of ECAC [2, 151-153], especially, microwave radiation has received more attention in recent years because of some benefits (e.g., polar molecular orientation effects and uniform heating) [1, 122, 128], while the latter one has a lower efficiency of induced heating, although it can simulate solar radiation.

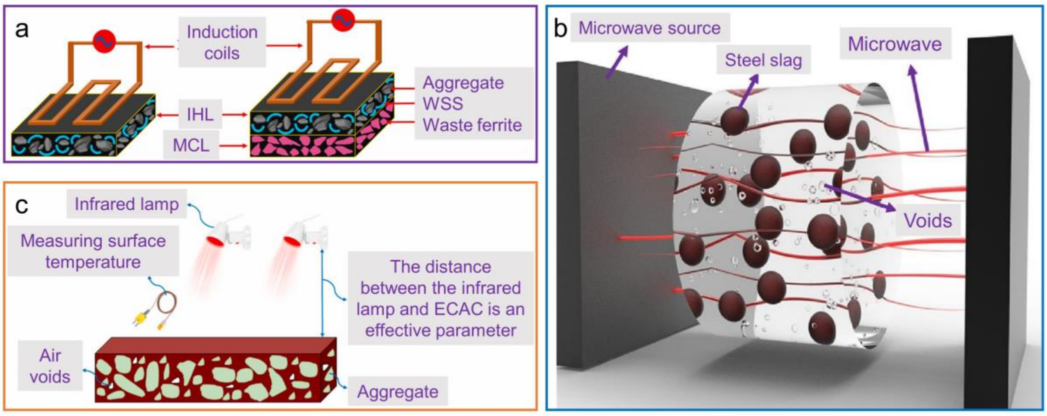

Fig. 8. Some technologies are used to promote the induced heating of ECAC: (a) induction heating coil [13]; (b) microwave radiation [1]; and (c) infrared radiation [151].

The self-healing capability of ECAC refers to the ability to heal (restore/repair) damage, which restores the performance and extends the life of damaged asphalt concrete [18, 31, 115]. The healing process of ECAC includes rebonding within the asphalt binder and rebonding between the asphalt binder and aggregate [154-157]. Specifically, the induced heating-healing process of ECAC induces five major steps: temperature rise, movement of the melted asphalt binder within the crack, crack closure, crack edge wetting, and crack fusion [55, 122, 143, 144]. As presented in **Fig. 9**, the cracking-healing process is proposed in the lab to assess the induced healing efficiency (i.e., healing index, *HI*) of ECAC [130], which can be calculated according to Equation (1) [31, 153]:

$$HI = \frac{F_1}{F_0} \times 100\% \quad (1)$$

where F_0 and F_1 are the maximum tolerated load and breaking force after healing (N), respectively.

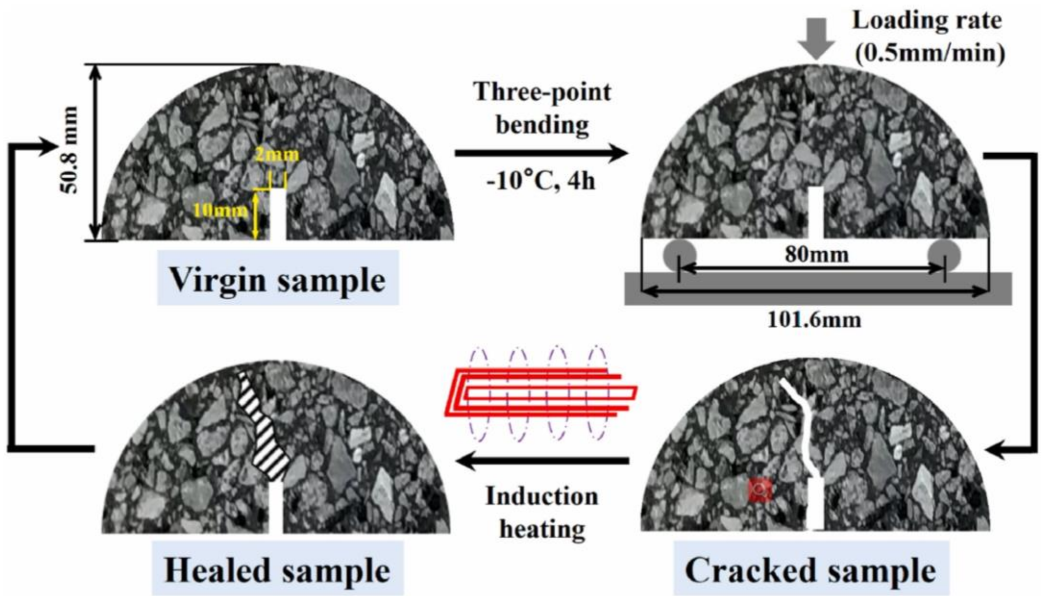

Fig. 9. Healing performance test procedure of ECAC specimens in the lab [130].

HI can also be defined as the ratio of the fracture energy (E_1) to the initial fracture energy (E_0) of the ECAC sample after the healing process, as follows [152]:

$$HI = \frac{E_1}{E_0} \times 100\% \quad (2)$$

In addition, the *HI* for ECAC crack induced heating-healing under cyclic loading is defined by Equation (3) [153]:

$$HI = \frac{N_P - N_{0.5}}{N_{0.5}} \quad (3)$$

where N_p is the number of cycles after healing, and $N_{0.5}$ is the number of cycles where the ECAC has a 50% probability of rupture before healing.

3.1.2. Affecting parameters on induced heating-healing of ECAC

The composition of asphalt concrete can greatly affect the electrical conductivity, thermal conductivity, and road performance of ECAC [2, 5, 14, 46, 158]. Specifically, the heating healing ability of ECAC increases with the increase of asphalt binder content. [159]. According to previous studies [58, 160, 161], the asphalt type has a minor influence on the induced heating process. Typically, softer asphalt binders (or lower viscosity) have a higher healing capacity because the energy level required to induce the healing process is lower [62]. Additionally, the self-healing efficiency of ECAC is highly dependent on time and temperature [56]. For example, García et al. [55] indicated that after heating at 70°C for 5 min, the white contact spots started to increase, and the cracking surface decreased, as shown in **Fig. 10.**

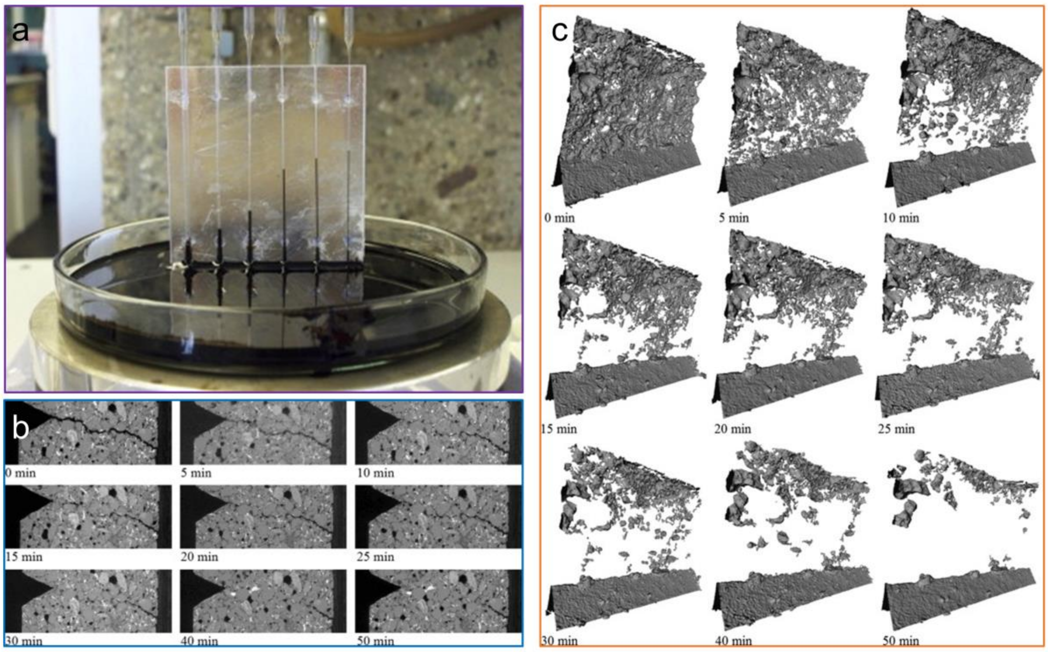

Fig. 10. (a) Capillary flow experiment; (b) CT images of the healing process; and (c) CT reconstructions of a crack that healed at 70 °C [55].

According to previous studies [73, 74, 134, 162], the asphalt film in open-graded ECAC is thicker than in dense-graded ECAC, resulting in a higher continuity of formation of conductive networks and vortices in the mixture modified by functional additives. This leads to a faster and more efficient healing process under induced heating in the former

[162]. Additionally, Salih et al. [162] considered that the internal pressure generated by the asphalt binder during the induced heating process could cause damage to the dense-graded ECAC and reduce the fatigue life accordingly, as shown in **Fig. 11**. Moreover, higher levels of aggregate packing in dense asphalt can increase cracking of aggregate particles [163], and these cracks cannot be fully healed during the induced heating-healing treatment [16, 55, 143, 153]. Additionally, open-graded ECAC has a low surface area, which can improve its healing ability through thicker binder films and fewer interfaces between the aggregate and asphalt binder [143].

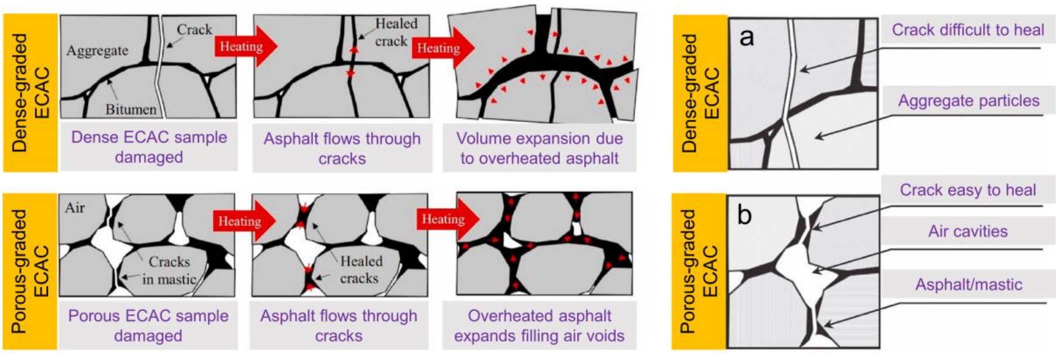

Fig. 11. Phenomena change inside (a) dense ECAC and (b) porous ECAC during heating [162].

Some other factors, environmental/loading conditions, environmental distresses (e.g., moisture, freeze-thaw, and aging), and physical damages (e.g., crack width, damage density, breaking temperature) all affect the self-healing ability of ECAC [2, 56, 58]. In particular, conductive aggregate-based ECAC is expected to replace conductive asphalt-based ECAC because of their uniform dispersion, low cost, and ease of operation. However, high-quality functional aggregates need to be developed instead of simply using steel slag. Future studies should focus on conducting additional experimental evaluations, numerical modeling, and field assessments [158, 164-166].

3.1.3. Case studies of ECAC for induced heating-healing

During the long-term service life, asphalt pavements eventually develop various diseases under the coupling effect of harsh environmental conditions and traffic loads [5, 46, 167]. Typically, these diseases start from various microcracks (e.g., thermal and fatigue cracking) in asphalt mixture [1, 37, 168]. That is to say, cracking is a driving force behind decreased service life and increased maintenance costs of asphalt pavement [2, 55, 143]. As such, attempting to heal them via functional materials and heating/healing techniques is an efficient approach to reverse damage induced in asphalt concrete.

For example, Sun et al. [71] investigated the heating ability of steel fiber-modified ECAC pavement under microwave irradiation (i.e., using a 90 kW road maintenance truck in practical application), and found that with the curing of microwave irradiation, the heating rate of ECAC's surface could reach as high as 26 °C/min (see **Fig. 12a**). Fu et al. [13] developed a novel ECAC pavement by using metal waste, and it was found that the maximum surface temperature of the ECAC pavement with the best operation scheme was up to 93.5°C in field heating tests (see **Fig. 12b**). Additionally, Amani et al. [152] found that the efficiency of ECAC in inducing heating healing was found to decrease with increasing aging (see **Fig. 12c**). Therefore, to ensure the efficiency of induced heating-healing of asphalt concrete, it is recommended to avoid asphalt aging as much as possible and to reduce the number of the induced heating cycle.

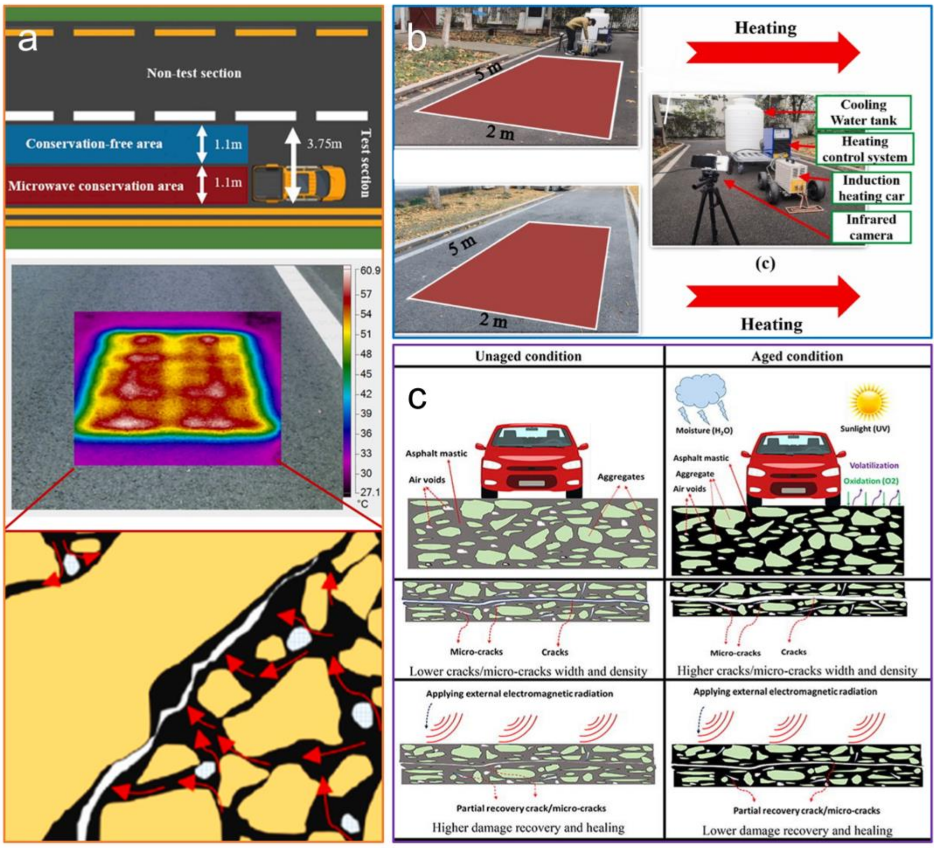

Fig. 12. ECAC and its application in self-healing of asphalt pavement: (a) conservation zoning diagram and boundary of microwave curing area [71]; (b) dynamic induction heating car and infrared temperature distribution [13]; and (c) influence of ageing level on heating-healing ability of ECAC [152].

Recently, Fu et al. [17] tried to address the problem of temperature gradient distribution in the ECAC pavement by using waste steel shaving and steel wool fibre in the upper and lower part of ECAC, respectively (see **Fig. 13**). This is a very valuable attempt. However, more studies should be done in the future and systematic analysis/design of gradient healing behavior inside ECAC.

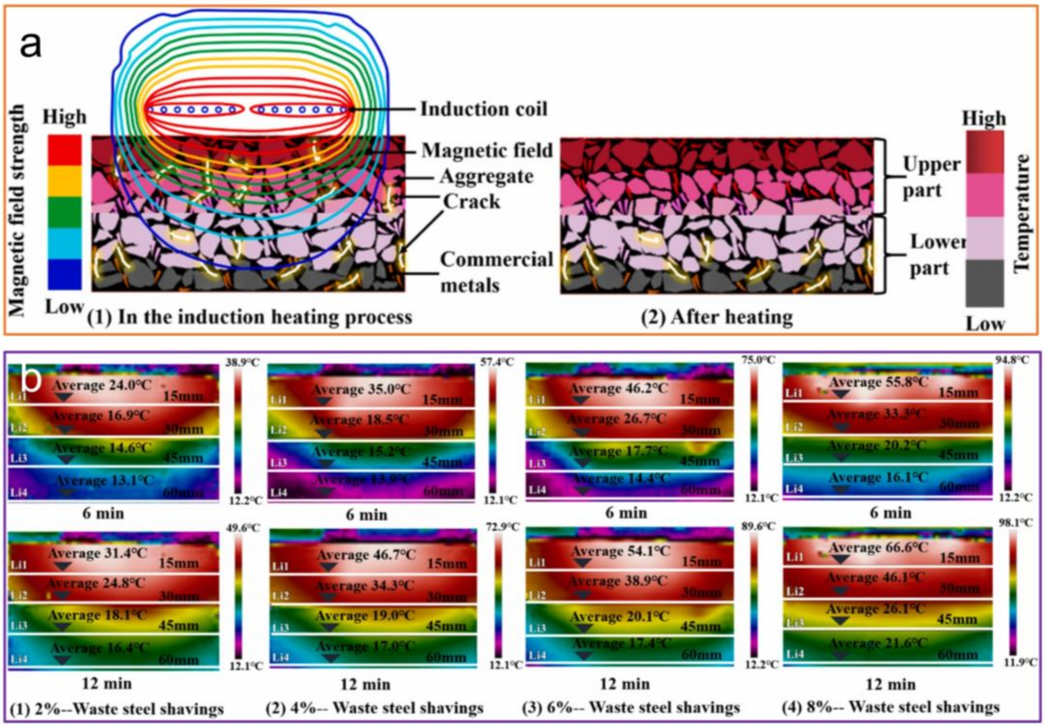

Fig. 13. (a) Induction heating of conventional inductive healing asphalt mixture and (b) temperature distribution field of ECAC containing waste steel shavings.

3.2. ECAC for anti-icing and deicing applications

3.2.1. Principles of ECAC through resistive heating

Typically, functional additives are mixed with asphalt/mineral filler to prepare conductive asphalt mastic, which can fill the air voids in the aggregate system, namely, conductive asphalt-based ECAC [20, 21]. It can be regarded as a promising way to obtain self-healing capacity and is thus used for the anti-icing or de-icing of asphalt pavements [128, 133, 139, 169]. Recently, several studies have proven that applying steel slag to replace natural aggregate can produce conductive aggregate-based ECAC [128, 133, 169], which is another efficient approach to use as a heating element for de-icing. The volume resistivity of ECAC is obtained based on Ohm's law (Equation 4):

$$\rho = \frac{R \times S}{L} \tag{4}$$

where ρ is the calculated resistivity (Ω·cm); R is the resistance (Ω); S is the cross-section area of the sample (cm^2); and L is the distance between the electrodes.

The electron conduction mechanism in ECAC depends on the intrinsic conductivity, contact resistance, and electron tunneling of the admixed functional additives [5, 60, 170]. According to the statistical percolation theory [171], the relationship between ECAC's conductivity and the dosage of admixed functional additive is developed and analyzed, determining the optimal amount of functional additive in ECAC. As shown in **Fig. 14a**, the functional additive's volume is below the percolation threshold (Zone A), and it fails to build a continuous conductive pathway. In this situation, the resistivity of ECAC slowly reduces with the increasing dosage of admixed functional additive. As the dosage of functional additive increases to the percolation threshold region (Zone B), the adjacent functional additives come into direct contact and form stable conductive pathways, which can drastically reduce the resistivity of ECAC by several orders of magnitude. As the dosage of functional filler exceeds the percolation threshold, there are small fluctuations in resistivity (Zone C). In summary, determining the percolation threshold value of functional additives in asphalt concrete is a fundamental parameter for optimizing and developing the electrical properties of ECAC, and the appropriate amount of functional additives should be selected based on this theory before developing ECAC.

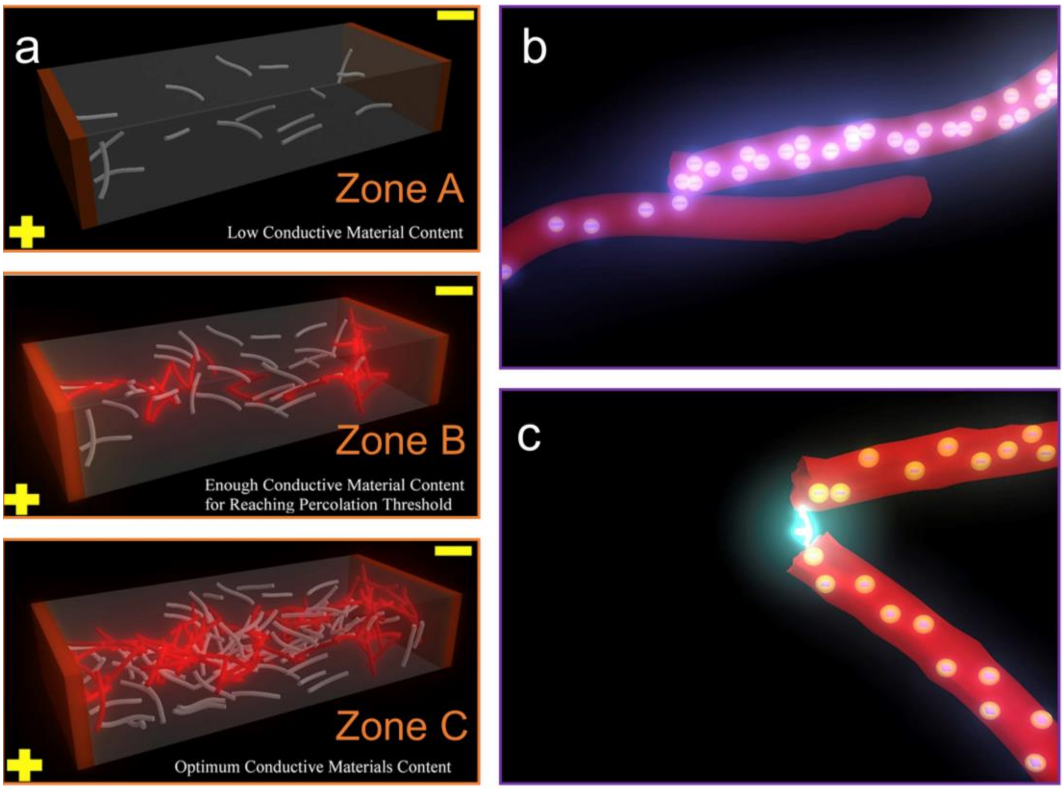

Fig. 14. (a) The relationship of resistivity and filler concentration: (Zone A) insulated phase; (Zone B) transition phase; (Zone C) excessive conductive filler [60, 170, 172]; Electron conduction mechanisms in ECCA: (b) contact resistance; and (c) electron tunneling [21].

If the admixed functional additives come into contact with each other inside the ECAC, the conductive channels would be constructed by the functional additives in direct contact, allowing electric currents to pass through the ECAC, thus making it electrically conductive (see **Fig. 14b**). While some functional additives are dispersed inside the ECAC as isolated particles. Thermal vibrations and electron transitions activate electrons, and as a thin layer of hydrates between these isolated additives, a tunneling effect would occur where electrons can jump over this thin hydration layer and enter the adjacent functional particles (**Fig. 14c**). Especially when a strong internal electric field exists between conducting particles, an electric field emission current is formed, allowing electrons to pass through an electron barrier. The local tunneling resistance R as a function of the interparticle distance d, which can be calculated as follows:

$$R = \frac{d \times h^2}{Ae^2 \times (2m\sqrt{\lambda})} e^{\left[\frac{4\pi d}{h} \times (2m\sqrt{\lambda})\right]} \quad (5)$$

where *h* is Plank's constant; *A* is the contact area of two functional additives; *m* and *e* are the weight and electric charge of the electron; and *λ* is the potential barrier height.

3.2.2. Affecting parameters on resistive heating of ECAC

Material-related factors, including types, combinations, and dosage of functional additives, can affect the volume resistivity of ECAC [25, 84]. Typically, the higher the amount of admixed functional additive (below percolation value), the lower the volume resistivity, as discussed in section 3.2.1. Additionally, external stimuli can significantly affect the electrical conductivity of ECAC. For example, Wu et al. [30] investigated the effect of temperature on the resistivity of ECAC, and they found a 12% reduction in resistivity as the temperature decreased from 38 °C to 30 °C. Note that the effect of temperature on the resistivity of ECAC below the freezing point is significant, considering that if ECAC cannot maintain good electrical conductivity at low temperatures, it cannot be effectively used for anti-icing in winter [133, 173]. However, there is minimal research in this regard.

3.2.3. Case studies of ECAC for anti-icing and snow melting applications

In winter, snow and ice accumulation typically lead to huge economic losses and safety hazards for asphalt pavements, and even tragic loss of life [174, 175]. Although traditional snow and ice removal methods or other heating candidates have been used for many years, some shortcomings, such as environmental pollution and rebar erosion, have limited their applications in pavement engineering [21]. In order to automate winter asphalt pavement operations, it has been demonstrated that heated pavement systems can be constructed to melt snow and ice by resistive heating or microwave heating [20, 21]. In this context, ECAC can be used as a heating element for snow and ice melting on pavements, bridges, highways, and airport sites. For instance, Arabzadeh et al. [21] developed CF-ECAC pavement and they indicated that the temperature of a slab made of ECAC containing 1% CF can increase by 23 ℃ within 25 min; simultaneously, the construction cost increase by approximately 50% as compared to conventional pavement (**Fig. 15a**). Additionally, Gao et al. [176] used 40-60 vol% steel slag in ECAC for microwave de-icing, and they demonstrated that using steel slag is helpful in improving the safety of road traffic in winter based on the comprehensive evaluation results on the supply sources, cost of steel slag, and environmental impact (**Fig. 15b**). Jiao et al. [169] used steel slag to improve the heat transfer efficiency (e.g., the snow melting efficiency of the ECAC increased 25-38 %) of the electrical-thermal pavement system, and found that the road performance parameters of ECAC cna meet the specification requirements (**Fig. 15c**). Future research should explore increasing the volume ratio of functional aggregates in ECAC, which in turn can significantly improve the heat production and heat transfer capacity of ECAC for anti-icing and snow melting applications.

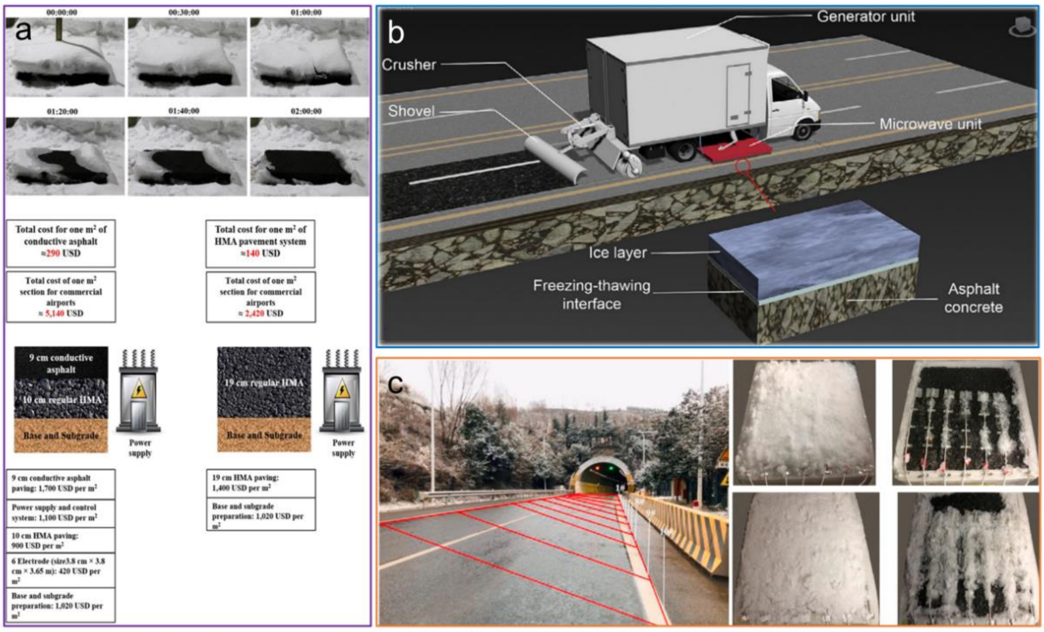

Fig. 15. ECAC and its application in anti-icing and snow melting of asphalt pavement: (a) snow melting capability and cost estimation (slab size: 4.5 m×3.8 m) [21]; (b) using steel slag in ECAC for microwave de-icing [176]; and (c) Jiangjunling tunnel exit and the change of snow layer during the heating process under -3 ℃ [169].

3.3. Self-sensing ability of ECAC and its applications in traffic detection

3.3.1. Principles of self-sensing performance of ECAC

When an ECAC sensor mounted on the pavement is subjected to external forces, several changes in resistance occur, including [171, 177]: (a) changes in the intrinsic resistivity of the functional additive; (b) changes in the bond between the functional additive and the substrate; (c) changes in the contact between the functional additives; and (d) changes in the capacitance [171, 178].

3.3.2. Affecting parameters on the self-sensing ability of ECAC

In addition to the external forces, some factors, such as functional additives dosage, type of functional additives (i.e., diameter, thickness, and aspect ratio), dispersion quality of functional additives, and some parameters of matrix, curing regime, also highly affect the ECAC's self-sensing ability [179-181]. The admixed functional additives dosage dominates the construction and distribution of conductive pathways inside the ECAC [182, 183]. The dosage of functional additives is the most critical factor for concrete to affect resistivity, as discussed in Section 3.1. Note that carbon-based conductive fillers' huge specific surface area tends to agglomerate [15, 52, 64]. Therefore, the selection of the proper functional additives dosage is crucial for the development of ECAC. Fibrous conductive fillers are generally more difficult to disperse than granular ones. The dispersion process also affects the filler distribution inside ECAC. Therefore, the matching dispersion process should be carefully selected according to the characteristics of the functional additives. In addition to the abovementioned factors, loading duration/frequency, sample dimension, and electrode spacing affect the ECAC's sensing property [12, 56, 184].

3.3.3. Case studies of ECAC for traffic detection damage detection

The pavement or bridge integrated with ECAC-sensors can detect essential traffic information, such as traffic flow rate, vehicle speed and density, and implement weighing in motion [83, 140]. Additionally, it can be used for detecting microcracks or damage inside the asphalt pavement based on the relationship between force and resistance [84, 141].

For instance, Gulisano et al. [84] investigated the piezoresistive behavior of ECAC containing electric arc furnace slag (EAFS) and GNP for sensing applications, and it was found that ECAC containing EAFS and 7 wt% GNP exhibited excellent sensing ability in traffic detection and structural health monitoring of pavement (**Fig. 16a**). Dong et al. [185] studied the sensing property of ECAC pavement, and it was found that the fractional change in resistivity has a relationship with vehicle speed and tends to decrease with increasing speed, showing the potential for monitoring vehicle information on the pavement (**Fig. 16b**). Additionally, Birgin et al. [140] developed a novel proof-of-concept self-sustainable weighing in motion technique incorporating ECAC pavements and represented preliminary evidence of feasibility, paving the way for the development of self-powered and low-cost weighing in motion systems, as shown in **Fig. 16c**.

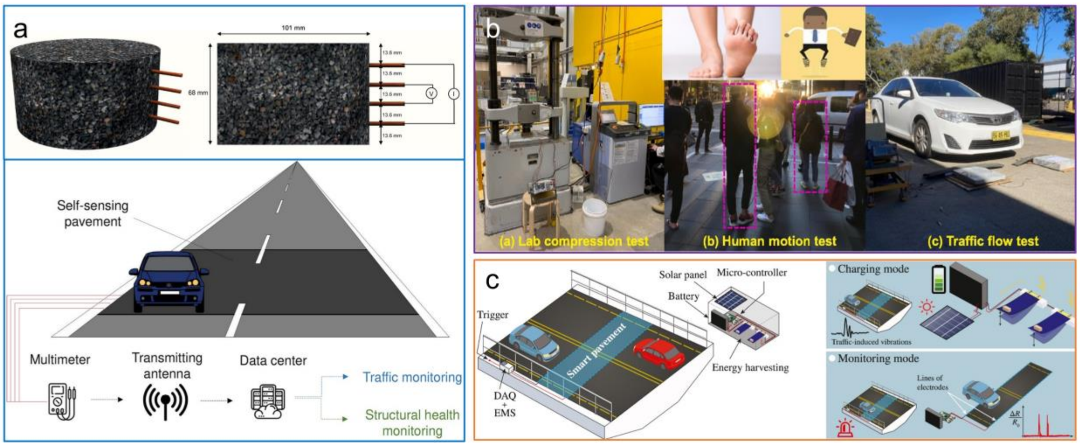

Fig. 16. ECAC and its application in self/self-sensing of asphalt pavement: (a) ECAC samples and its working principle [84]; (b) plate with embedded ECAC sensors for laboratory compression, human motion, and vehicle speed testing [185]; and (c) technology concept of ECAC pavement for traffic monitoring [140].

4. Conclusions and perspectives

Despite nearly two decades of research and development, the composition design, performance optimization, and practical applications of electrically conductive asphalt concrete (ECAC) are still ongoing. There is a need for further efforts to advance its development and application. The following findings and insights are crucial for the continued progress of ECAC:

(1) The addition of functional additives to conventional asphalt concrete can enhance its thermal and electrical conductivity, thereby improving the heat-healing capability. Among the various additives, carbon fiber (CF) is more effective in enhancing the bridging effect and facilitating the formation of conductive networks within ECAC than carbon-based nanomaterials. However, it is worth noting that a combination of CF and carbon-based nanomaterials can be an ideal approach for establishing hierarchical conductive pathways within ECAC.

(2) The heating-healing ability of conductive filler-based ECAC is relatively lower compared to conductive asphalt-based ECAC or conductive aggregate-based ECAC due to the limited volume fraction of filler in ECAC. To advance the induced heating-healing capabilities of ECAC in pavement engineering, future studies should focus on conducting additional experimental evaluations, numerical modeling, and field assessments. These efforts will help in understanding the underlying mechanisms and optimizing the design and performance of ECAC for effective heating-healing applications.

(3) Conductive aggregate-based ECAC is highly recommended for snow and ice melting in asphalt pavements due to its exceptional efficiency and uniform distribution of heat sources. The performance of a heated ECAC pavement system can be adjusted to the proper temperature with voltage or microwave radiation adjustment, which provides efficient and stable heat production efficiency. In order to achieve self-healing of the asphalt pavement while achieving melting of the snow/ice, it is advisable to apply an additional heating process once the pavement ice has melted.

(4) The development of conductive aggregate-based ECAC holds significant promise for the creation of piezoresistive sensors used in traffic detection and structural health monitoring. To advance this field, it is recommended to develop a novel functional aggregate that exhibits high quality while maintaining low cost. The exploration of such aggregates will enable the evaluation of their true potential for various applications within the realm of pavement engineering.

(5) The heterogeneity of the microstructure plays a crucial role in influencing the smart and multi-functional capabilities of ECAC, ultimately impacting its performance and practical applications. To address this, there is a need to develop a micromechanical approach that enables more precise modeling of the electrical properties of ECAC in the future.

CRediT authorship contribution statement

Dong Lu: Writing-Original Draft, Writing-Review and Editing, Data curation.

Xi Jiang: Writing-Review and Editing.

Zhen Leng: Methodology, Writing-Review and Editing, Supervision.

Yanlin Huo: Writing-Review and Editing.

Daiyu Wang: Writing-Review and Editing.

Jing Zhong: Conceptualization, Investigation, Writing-Review and Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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