Analysis of research hotspots and trends in energy-pavement engineering

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Abstract. With energy shortages and environmental pollution increasing, pavement engineering has gradually transformed from a single traffic attribute to multi-functionality. The trend of pavement construction from “energy consumption” to “energy supply” is also obvious. Therefore, the “energy-pavement engineering” that combines energy and pavement engineering has quickly become a research hotspot in the field of transportation infrastructure. To accurately and effectively grasp the research hotspots and trends of energy-pavement engineering, the research progress and problems in the field of energy-pavement engineering in the past 20 years are systematically sorted out. Energy-pavement engineering is subdivided into two concepts: energy pavement and pavement energy. Besides, mutual penetrating and integrating while carrying out research around the hot spots of energy pavement and pavement energy is an effective way to deepen energy-pavement engineering research.

1. Introduction

Since entering the 21st century, humanity is facing multiple challenges of unprecedented global energy and resource crisis. With the emergence of the concept of intelligent transportation and driverless driving, the development of road engineering will usher in the trend of integration of two or more networks, such as information network, transportation network, energy network and human life network. Especially in the field of pavement engineering, it has great potential for environmental energy cleaning[1] and energy regeneration as the road surface covers millions of square kilometers in urban and rural areas and is continuously exposed to various types of energy (such as solar radiation, heat and traffic-induced stress)[2]. Therefore, in recent years, the trend of pavement engineering is changing obviously from "energy consumption" to "energy supply".

To promote the transformation of pavement research into intelligent, smart, functional and humanized new multi-functional pavement, and realize the coordinated development of energy, environment and pavement traffic as soon as possible, this paper effectively sort out the transformation of the relationship between energy network and pavement engineering network. Besides, a new concept of energy-pavement engineering two-network fusion is put forward. The research of energy-pavement engineering mainly includes two aspects: energy pavement and pavement energy. Energy pavement refers to reducing the negative impact on the environment by reducing energy consumption and reducing carbon...
dioxide and greenhouse gas emissions in all aspects of pavement material design, production, paving, and maintenance; Pavement energy refers to the conversion of surface energy such as solar energy, light energy, heat energy, load, etc. into electric energy or other usable energy sources to improve the performance of the pavement and serve traffic such as traffic lights. The pavement energy fully realizes the benign symbiosis of the environment, and provides the possibility for the coordinated and intelligent development of "man-vehicle-road", which has excellent development potential. Therefore, using energy pavement as the subject term based on the Web of Science database, this article filters out 2337 documents related to energy-pavement engineering. Then, the research progress and hot spots in the field of energy-pavement engineering are sorted out and explored from the literature co-citation analysis by using Citespace.

2. Research hot topics and trends analysis

2.1. Research status

The annual publication volume of energy-pavement engineering is summarized as shown in Figure 1.

![Figure 1](image)

**Figure 1.** Changes in the number of publications on "energy-pavement engineering" from January 1997 to November 2020.

It can be seen from figure 1 that there were few studies on energy-pavement engineering before 2010. However, from 2009 to 2010, related research increased rapidly, and then the related research gradually increased with the growth of the years integrally. Thus, it shows that more and more scholars are beginning to pay attention to the research in the field of energy-pavement engineering, which is in line with the needs of pavement development and construction at this stage. Due to the characteristic of "interdisciplinary" of energy-pavement engineering, it will be very helpful for research by understanding the distribution of disciplines corresponding to various hot topics. To this end, a co-citation map was drawn for 2,337 literature, and the strength of the co-citation links among literature and the clustering function of the software were used to divide the research hotspots of energy-pavement engineering subject, as shown in Figure 2.
Figure 2. Cluster analysis of co-citation of references on "energy-pavement engineering" (a) from January 1997 to November 2019; (b) from January 1997 to November 2020.

The thicker the line between the literature, the closer the co-citation relationship and the more similar the research contents are. The literature with similar research contents constitutes a research theme. The number of hot topics and their corresponding literature is detailed in Table 1.

Table 1. Research hot topics and the number of corresponding documents

| Topic sort | Subject name          | Number of documents | Topic sort | Subject name          | Number of documents |
|------------|-----------------------|---------------------|------------|-----------------------|---------------------|
| #0         | Life cycle assessment | 60                  | #0         | Asphalt solar collector | 71                  |
As of November 2020, the top six literature in the field of energy-pavement engineering with the highest citation frequency and the related hot topics are summarized in Table 2.

### Table 2. The top six most cited documents.

| Citation counts | Reference | Year | Topic sort |
|-----------------|-----------|------|------------|
| 67              | Santamouris M, 2013, RENEW SUST ENERGY REV, 26, 224 | 2013 | #4         |
| 66              | Rubio M C, 2012, J CLEAN PROD, 24, 76 | 2012 | #2         |
| 51              | Santero N J, 2011, RESOUR CONSERV RECY, 55, 801 | 2011 | #1         |
| 46              | Qin Y H, 2015, RENEW SUST ENERGY REV, 52, 445 | 2015 | #4         |
| 46              | Bobes-jesus V, 2013, APPL ENERGY, 102, 962 | 2013 | #0         |
| 40              | Pan p, 2015, RENEW SUST ENERGY REV, 48, 624 | 2015 | #0         |

2.2. Trends analysis of hot topics

2.2.1. Main hot topics and trends analysis of energy pavement. As a traditional research direction of energy-pavement engineering, the research theory and framework of energy pavement have been relatively mature. It can be seen from figure 2 that, in addition to different orders, the main hot topics of the study of "up to November 2020" and "up to November 2019" are basically the same, focusing on life cycle assessment (LCA), heat island effect, warm mix asphalt (WMA), etc. The main research themes of energy pavement were analyzed as follows:

1) Life Cycle Assessment (LCA)

It studies the potential environmental impact of a product throughout its life cycle from material acquisition to production, construction, maintenance/repair, use and disposal[3]. The citing document in this hot topic was first cited in 2008. Subsequently, the number of literature on LCA research increased rapidly, with 32 articles published in 2018 and 2019 respectively, which was 1.6 times the number of publications in 2017. From November 2019 to November 2020 (the latest year, the same below), more than 30 articles were published. Among them, Huang Y et al.[4] published a study on the LCA of asphalt pavement construction and maintenance in 2009, which promoted many subsequent studies such as pavement network sustainability, passive cooling, warm mixing technology, LCA, big data analysis and many other contents. In addition, in 2011, Santero NJ et al.[5] published a critical review, whose citation frequency reached the highest in this subject and was the most influential citing literature in this subject in 2011. In the lastest a year's study, Peng B et al.[6] and Wang H et al.[7] made quantitative calculations of carbon emissions when considering environmental factors. However, Peng B mainly focused on carbon emissions during construction, and lacked consideration of carbon emissions during construction.
emissions during the production of raw materials, road operation, maintenance and demolition; Wang H mainly studied carbon emissions from asphalt pavement maintenance during construction and use. In terms of improvement technology, Cong L et al.[8] found that polyurethane pavement, as a new type of pavement, is more in line with the requirements of energy conservation, environmental protection and sustainable development compared with asphalt pavement.

2) Heat island effect
The earliest definition of the concept of heat island was Manley et al.[9]. Since then, related scholars began to establish a connection between the heat island effect and pavement construction. The citing document in this topic was first cited in 2008. Since then, the research focus of heat island effect mainly focuses on asphalt renewable pavement, cement concrete pavement, rainwater collection, LCA, maintenance strategy and other research modules. According to figure 2, the research literature published by Santamouris M et al.[10-11] in 2013 and 2014 by Rossi F et al.[12] in 2014 has the significantly higher burst values than other literature, indicating that these three literature were widely cited in a short period of time and played an important guiding role in the research during 2013-2014. In the lastest a year's study, Nwakaire CM et al.[13] summarized past studies on heat island, especially on pavement. Pigliautile I et al.[14] explored the evolution law of pavement research methods under the influence of urban heat island. Parison S et al.[15] studied the thermal performance of 12 standard and cool pavement structures coupled with pavement-watering in the lab under heat-wave-like conditions. It is obvious that more and more scholars focus on establishing the connection between pavement and heat island effect.

3) Warm mix asphalt(WMA)
It was proposed earlier in 2002 that the improvement of WMA could promote the sustainable development of infrastructure such as roads[16]. This technology is mainly used to control the temperature during asphalt mixture mixing and pavement compaction. Unlike other hot topics, it’s aim is to alleviate the current situation of excessive energy consumption and environmental pollution in pavement construction. In 2012, the research achievements of WMA increased significantly. For example, Rubio MC et al.[17] has published 19 papers, who was the core to form an association network. However, although this technique he studied has been applied in practice and has been well evaluated, it still lacks a complete guiding theory and normative index. In the lastest a year's study, to reduce environmental pollution and energy consumption, Kutuk-Sert T et al.[18] pointed out that the combined use of WMA and recycled materials in the asphalt mixture can effectively reduce energy consumption and negative environmental impact; Calabi-Floody AT. et al.[19] assessed the gas emission, energy consumption, and production cost of WMA compared natural zeolite with reclaimed asphalt pavement (RAP).

2.2.2. Main hot topics and trends analysis of pavement energy. Pavement energy mainly includes light energy, solar thermal energy, geothermal energy, mechanical energy produced by moving vehicles and pedestrians, rain and wind, etc. Compared with fossil fuels, pavement energy collection technology can not only generate green renewable energy, but also be used to roadside applications[20]. Therefore, the research on pavement energy has attracted much attention in the past two years. As of November 2019, the representative topic of pavement energy is topic #3 energy harvesting. Research hotspots under this hot topic mainly focused on piezoelectric energy harvester (PEH)[21], electromagnetic energy harvester[22], solar energy collector (SC)[23], thermoelectric generator (TEG)[24] and photovoltaic (PV) applications[25].

As of November 2020, the research on energy collection has been changed to take asphalt solar collector as the representative, involving energy collection, heat conduction, conductive asphalt concrete, snow and ice melting, air convection, electromagnetic and other contents. In the latest study, Johnsson J et al.[26] used the self-developed software HyRoSim to determine the influences of pipeline spacing, fluid velocity and albedo on the performance of pavement solar collector. At present, it is possible to absorb and utilize road thermal energy and light energy comprehensively. It is foreseeable that the simultaneous
collection and utilization of thermal energy, piezoelectric energy, light energy, piezoelectric energy and other energy sources may also be the future research directions. How to make full use of the characteristics of natural environment and artificial environment to recycle multiple energy at the same time is also a question we need to think about in the future.

3. Trends analysis of associations among hot topics
It can be seen from Figure 2(a) that compared with pavement energy, scholars still paid more attention to energy pavement such as asphalt pavement regeneration, urban heat island effect, and warm mix asphalt. Therefore, there are more relevant references than other topics, and there is a lot of overlap between topics. On the periphery of the map, there are fewer intersections among themes, and there are fewer references for each theme itself, such as ground source heat pipe, asphalt solar collector, PCM, fiber reinforced material, etc. This shows that these topics have not formed a complete framework, so it has great research space and value. Considering that the relationship between fatigue life, water damage, vehicle-pavement collaboration and energy-pavement engineering has been initially established, the in-depth study of these relationships is more conducive to grasp the research progress of energy-pavement engineering at the present stage.

4. Conclusions and recommendations
This article traces and analyzes the research hotspots in the field of energy pavement engineering by sorting out relevant documents in the field of energy pavement engineering. Conclusion as below:

(1) In recent years' research, the hot topics of energy pavement are basically the same, mainly including LCA, WMA, heat island effect, etc. However, the hot topic of pavement energy has changed from energy collection to asphalt solar collector, which indicates that the research in the last year focuses more on the collection and transformation of solar heat and light energy. Although the research on pavement energy has made progress, there is a lack of specific standards and guidelines in the concrete implementation, so the application of pavement energy theory to practice needs further study.

(2) The research of existing pavement engineering is focusing on energy conservation and environmental protection. Energy-pavement engineering effectively combines the energy network with pavement engineering network. The establishment of energy-pavement engineering network promotes the multiplier effect between energy and technological innovation in pavement engineering.

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