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Thermal and hydraulic analysis of multilayered asphalt pavements as active solar collectors

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HIGHLIGHTS

- A new type of asphalt solar collector has been introduced in this paper.
- The common pipe network has been replaced for a highly porous asphalt layer.
- The use of these collectors contributes to achieve current environmental targets.
- Excellent thermal efficiencies have been obtained in the laboratory tests.
- Further research is needed to increase the low flow rates achieved.

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ABSTRACT

The fulfillment of current environmental aims like reducing fossil fuel consumption or greenhouse gas emissions entails the development of new technologies that enable the use of cleaner, cheaper and renewable energies. Furthermore, the need to improve energy efficiency in buildings encourages scientists and engineers to find new ways of harvesting energy for later uses.

The use of asphalt pavements as active solar collectors is introduced in this article. Several authors have studied the use of roads as an energy source before. However, a new technology is presented in which a multilayered pavement with a highly porous middle layer is used instead of a solar collector with an embedded pipe network. These collectors are fully integrated within the road infrastructure and may offer low cost solar energy for water heating.

The paper includes a brief comment on the state-of-the-art. Then, a broad methodology is presented in which data, materials and procedures needed to run the tests are fully described. Finally, the results of the laboratory tests are stated and discussed.

The prototype used in the laboratory provided excellent thermal efficiency. However, these good results contrast with the low flow rate levels registered during the tests. Thus, although this technology seems to be very promising, new experimental tests should be performed before an effective application is possible.

1. Introduction

The reduction of fossil fuel consumption and greenhouse gas emission to the atmosphere motivates research and development of new energy generation methods: renewable, clean, and respectful of the environment. Asphalt pavements can be heated up to 343 K (70 °C) by solar irradiation during the summer because of their heat-absorbing property [1,2]. Due to these properties and possible uses in parking lots and roadways with adjacent buildings, the supply of thermal energy from asphalt solar collectors is a potential application.

At present, solar energy solutions [3,4] in general and conventional flat-plate collectors [5] for several low temperature applications in particular are widely used. Although these devices have proved to be a suitable technology for those tasks, it is also true that they are costly, constitute a separate entity, need space for their installation and involve a dead load in the building structure. Asphalt collectors attempt to provide a solution to these problems.

Little work is reported in the literature about the areas of design and development of solar collectors made out of construction materials such as asphalt or concrete. Only a few studies have been

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Nomenclature

PA	porous asphalt
BBTM	asphalt concrete for very thin layers
AC	asphalt concrete
$q''_{SW\text{-}SUN}$	solar shortwave radiation (W/m^2)
$q''_{SW\text{-}REF}$	reflected radiation (W/m^2)
$q''_{LW\text{-}PAV}$	pavement outgoing longwave radiation (W/m^2)
$q''_{LW\text{-}ATM}$	longwave counterradiation (W/m^2)
$q''_{CV\text{-}PAV}$	convective heat flux between the air and the pavement (W/m^2)
$q''_{CD\text{-}PAV}$	heat absorbed and transferred by conduction to deeper layers (W/m^2)
$q''_{CV\text{-}FLUID}$	convective heat flux between the pavement and the flowing fluid (W/m^2)
C_p	specific heat (J/kg K)
H_{in}	inlet head (m)
H_{out}	outlet head (m)
ΔH	hydraulic gradient (m)
T_i	inlet water temperature (K)
T_o	outlet water temperature (K)
T_s	surface temperature (K)
I	irradiance (W/m^2)
h	laboratory humidity (%)
T_e	laboratory temperature (K)
q	flow rate (l/s)
Q_{out}	outlet power (W)
E_{in}	inlet energy (J)
E_{out}	generated energy (J)
V_W	total water volume (l)

Greek letters

λ	thermal conductivity (W/mK)
η	thermal efficiency
ρ_f	fluid density (kg/m^3)

done. In these cases, a pipe network has been placed within concrete slabs or asphalt pavements. The materials used for the tubes include metals such as steel, aluminum and copper or polymers such as polyethylene or PVC.

In these systems, the fluid flowing through the tubes extracts the energy accumulated in the hot asphalt or concrete pavements. Then, this energy may be stored as a low-grade heat reservoir. When necessary, the stored energy can be increased through an auxiliary device such as a conventional furnace.

Three main benefits can be obtained from using solar collectors. They can provide a clean and low-cost energy source for heating buildings or providing domestic hot water. The energy collected in summer can also help to keep the roads free of snow and ice in winter. Finally, the high temperatures in the pavement are reduced by extracting heat in the summer, thus increasing the resistance to permanent deformations and life span.

However, an asphalt collector with embedded tubes implies certain problems. Whenever metallic tubes are used, problems of corrosion and difficulties in on-site installation can occur. When using polymer tubes, the poorer thermal conductivity and the more complicated milling and later re-use of the asphalt mix are important drawbacks. Furthermore, the pavement structure is weakened because of the introduction of a flexible element within a much stiffer material. Finally, occasional leakages in the joints between pipes can occur with both materials. In a road, these problems become more critical since very difficult maintenance has to be performed while the road is closed.

For all these reasons, a new multilayered asphalt pavement has been designed and tested in the laboratory. The middle layer is a highly porous layer, up to 27% voids, that allows the fluid to circulate through it while part of the energy available in the asphalt mix is harvested.

A multilayered asphalt pavement offers easier on-site installation and more suitable maintenance when necessary. In terms of thermal efficiency, a porous media provides a wider fluid (water)–solid (asphalt) contact area, which entails higher heat transfer efficiency. On the other hand, meticulous waterproofing must be performed to avoid leakage.

An experimental car park with multilayered asphalt solar collectors has been built [6] in which design and construction issues have been considered. This experimental site is still being monitored.

2. Brief background

Only a few references have been found about research into these non-conventional solar collectors. Most of the papers included in the literature review can be classified according to two different parameters: the material used for the slab (asphalt mix or concrete) and the material of the pipe network inside the slabs (metal or polymer).

The first reference found in the technical literature is the patent obtained by Wendel in 1979 [7]. In this document, a method to heat water by making it flow through a net of metal pipes embedded in as asphalt pavement exposed to solar radiation is described. Two years later, Sedgwick and Patrick [8] develop this application by installing a net of polymer pipes within an asphalt pavement. Results showed how the system was technically feasible at a low cost.

Between the end of the eighties and the beginning of the nineties, several authors continued working on this topic [9–11]. Mathematical models and/or real-scale tests were carried out to investigate the energy performance and suitability of this type of systems.

Al-Saad et al. [12] reported the development, manufacturing and testing of non-conventional flat plate concrete collectors. Three different concrete collectors were constructed according to the material of the network of tubes located inside: steel and two different polymers. An efficiency of 40% was obtained and the collector with steel pipes provided the best performance.

In the mid-nineties, two systems capable of melting ice on roads or preventing its formation were developed in Japan and Switzerland: the GAIA and SERSO systems, respectively. In both cases, the energy absorbed by the pavement during the summer is partially recovered by water flowing through a network of pipes embedded in the asphalt pavement and stored in the ground by means of several boreholes. This energy is used in winter to de-ice the pavement surface.

The effect of cooling and heating asphalt pavements on their durability was studied by Van Bijsterveld et al. [13]. Thermal analyses were performed with a finite element model based on real data from a field test. Polymer tubes were placed inside an asphalt pavement to monitor its temperature over time. It was determined that the depth of the tubes within the asphalt layer is an influential factor for effective operation.