REVIEW IN PERFORMANCE OF PAVEMENT SOLAR COLLECTORS

Nawfel Muhammed Baqer Muhsin*[1], Mohammed Hamed Alhamdo[2]

*[1]*Al-Furat Al-Ausat Technical University, Alnajaf, Iraq.*

[2]Professor, College of Engineering, Almustansiyria University, Iraq.

ABSTRACT

This review article will appraise existing, relevant literature documenting investigations conducted by other researchers. The review will evaluate the methodology used in the other previous work as well as highlight the major findings of their investigations. By reviewing what other researchers have done with regard to the development of solar pavement collectors, this study will identify research gaps that this research stream seeking to fill. The following paragraphs summarize the most relevant scientific works that related to the study.The literature was reviewed in a chronological order just to capture the developments and advancements that have been realized over the years.

Keywords: Performance, Pavement , Solar Collectors, heat collector.

INTRODUCTION

(Sedgwick and Patrick, 1981) Used plastic tubes arranged in a grid put at 20 m beneath a surface which was made of asphalt in a tennis playground in the UK in order to investigate experimentally swimming pool heating system in the summer. The solar radiation and the temperature of the air were 610 W/m^2 and 22^{0}C respectively. They succeeded to make the system provided heating to the swimming pool which was worked at 20^{0}C and 27^{0}C, so that they proved that the system was appropriate for United Kingdom circumstances and less in price in contrast with the traditional solar heater of swimming pool **[1]**.

(Turner, 1986, 1987) The pavement heat collector performance in the summer Explained theoretically, when the maximum temperature of the pavement surface was 70^{0}C and in the winter when the maximum temperature of the surface of the pavement is 15^{0}C for many applications such as swimming pools, water heating for the heat pumps, de-icing roads and bridges. Simple model of one-dimension steady state was used; the researcher concluded that the system of pavement heat collector could be feasible for the previous applications **[2,3].**

(Mirambell, 1990) investigated under mechanical and thermal loads, the stress and temperature distribution in a plain concrete pavement. The author used 3D model with 10 layers across the pavement depth to study the influence of nonlinear temperatures distribution**.** In concrete the temperature gradients across the concrete slab can cause structural defects such as warping and curling.[4]

(Choubane and Tia, 1992) carried out an important technique for treating the nonlinearity of the temperatures gradient. They classified the temperature distribution through the pavement depth to three components as follow: first a component led to axial displacement, second a component led to bending, third nonlinear component. In addition, the researchers presented quadratic equations for the nonlinear temperatures distribution across the depth of the pavement **[5].**

(Leong et al., 1998) investigated the impact of the composition of soil on thermal efficiency as well as heat transfer of solar energy collectors installed on or proximal to the ground. The research established that, due the relatively higher rate of extraction of heat from the soil in addition to the higher thermal conductivity of soil, smaller loops would normally be required for the collectors. Moreover, the researchers appraise several factors to determine the thermal conductivity of soil. The appraised factors include the content of minerals found in the soil, the arrangement, shape, size, and texture of soil particles, the soil's porosity, as well as the content of water/moisture in the soil. One factor emphasized by the investigation is the mineral content, particularly the amount of quartz present in the soil. Quartz has a thermal conductivity of approximately 8W/m.k, which is significantly higher than most common rocks found in soil. Therefore, the overall thermal conductivity of soil heavily depends on the amount of quartz present in the soil **[6].**

(Tom Burnham et al., 2001) presented the temperature distribution inside the concrete slab and present a new method for the thermal expansion coefficient and drying shrinkage [7].

(Van Bijsterveld and de Bondt, 2002) offered an explanation to the negative impact of embedding tubes within asphalt structures. It results in focused stress points at the boundary of the pipes and concrete ultimately initiating cracking. The researchers tried to solve the problem of cracking by a three dimensional reinforcement network that prevented the tubes from cracking under the concentrated stresses. The reinforcement network basically consisted of compact mixture of asphalt, decreasing stress concentration points between the embedded tubes and the grid of reinforced asphalt [8].

(De Bondt, 2003) was based on asphalt solar energy collection surfaces. However, unlike other authors who specifically studied how to improve the efficiency of the solar energy collection devices, he investigated how the energy harnessed from the sun can be put into various uses to protect asphalt pavements from deformation due to high temperatures in summer as well as from ice accumulation in winter. In this study, he suggested a system whereby cold water is allowed to flow in pipes embedded beneath asphalt pavement, absorbing the heat from the summer sun and transporting the hot water to insulated storage tanks hence preventing the asphalt from deforming due to temperature flux. During the cold and snowy winter periods, the flow can be reversed, allowing the hot water from the storage tanks to flow in pipes underneath asphalt pavements to warm the pavements and prevent the accumulation of ice [9].

(Hasebe et al., 2006) studied experimentally the asphalt solar collector to produce the electricity. By using the temperature difference between the cool water (provided from the river) and the warm water (supplied from embedded tubes in the pavement) at a thermoelectric generator, the electric power was produced. The authors focused on the influences of outlet water temperature on the produced electricity and concluded by the increasing the outlet temperature, the output power increased **[10].**

(Carder et al., 2007) conducted an experiment to determine the variation of temperature in a control versus an experimental pavement. After a specific season (May through to September), the researchers subjected one pavement to heating with the energy stored in solar energy storage units whereas another pavement was left unexposed to such heat. The results showed that the temperature of the experimental pavements were about 3^0C higher than the temperature of the control pavement all through the winter period, an achievement that significantly enhanced the preservation of the experimental pavement from the effects of very low temperatures [11].

(Inalli and Esen, 2007) presented a research based in Turkey where they used a horizontal GSHP system to assess the impact of looping on COP of the system. The researchers used two GSHP systems with lengths of 2m and 1m. Assessing the working of the system from November of 2002 to April of the next year, the researchers established that the use of deeper installations of loops had the possibility of markedly improving the COP of the GSHP system by approximately 5%. Also, the researchers determined that the lengths of the tubes embedded in the GSHP system determined the size of landmass and other related materials required to successfully install and operate the system hence total cost of installing the system was dependent on the length of the embedded tubes. Finally, the researchers evaluated the length of tubes required for a borehole/trench using a particular heat energy abstraction factor, expressing the outcomes in watts per meter of the required length (W/m). The obtained values ranged between 40W/m and 70W/m for then upright system. Additionally, this study determined that the values were dependent on factors such as the thermal conductivity of the soil, annual operation of the heat pumps, as well as the amount of trenches in the surrounding area [12].

(Cabeza et al., 2007) used an experimental research on two full scale test structures. One of the two test houses had a microencapsulated 5wt% PCM (T_{melt}=26^0C, H_{melt}=250KJ/Kg) embedded in the concrete that formed the wall. The researchers established that in addition to recording 2^0C as the lowest temperature reading, the room with no PCM fittings had the highest interior dry bulb ambient temperature roughly 1^0C higher than the reading in a room fitted with PCM [13].

(Bentz and Turpin, 2007) shows set out to address the problem of freeze/thaw cycles witnessed in bridges made of concrete especially during the winter period. In order to reduce the amount of these unwanted cycles, the researchers proposed the used of concrete modified/reinforced by PCM. The study used numerical solutions to compute the impact of the PCM-modified concrete on the amount of freeze/thaw cycles. By using a 15wt% PCM, the researchers were able to record an impressive 30% decrease in the amount of freeze/thaw cycles on the targeted concrete bridges [14].

(Hunger et al., 2009) focused evaluation of hydration, fraternization rheology, as well as the post-toughening features of self-compacting concrete modified with microencapsulated PCM. Through experimentation and modelling based on numerical solutions, the researchers established that the use of 5wt% PCM (T_{melt}=23^0C, H_{melt}=100KJ/Kg) could reduce the highest hydration temperature of concrete by approximately 28% [15].

(Mallick et al., 2009) used a finite element analysis method, were able to establish that, by making sure that the operating fluid running across embedded pipes in pavements flows approximately 40mm underneath the pavement surface, the average temperature of the surface of the pavement could be approximately reduced by 10^0C. Furthermore, the researchers conducted a micro-scale lab experiment to investigate the effect of varnishing the top surface of asphalt with black acrylic coat and replacing limestone aggregates with combinations containing high percentages of quartz on the efficacy of the system. The investigation established that the two alterations enhanced the efficacy of the system by 50% and 100% respectively. In this case, the efficacy of the system was calculated from the increase in water temperature [16].

(Tarnawski et al., 2009) used simulation model for the COP of a GSHP system with tubes of different lengths embedded 0.5m and 1m below the surface, the researchers established that, although the COP of the GSHP system improved with tube length, the COP only increased up to a particular tube length beyond which it was not economically beneficial to increase tube length in an attempt to improve the COP of the GSHP system [17].

(Pejman Keikhaei Dehdezil et al., 2011) considered diverse concrete mixtures with various densities, thermal conductivities, thermal diffusivities, and specific heat capacities with the major purpose of evaluating thermo-physical features of the materials used in the construction of pavements hence compute the effects of the thermo-physical properties on PSHS an PHC. Like inputs were utilized with a temporary, one dimensional heat transfer model to compute temperature variation with depths of concrete. One major finding from the study was that the use of pavements with high diffusivity and conductive combinations as well as fibres made from metallic elements resulted in an improvement of heat transportation as well as a reduction of thermal stresses across the concrete pavements. Low diffusivity pavements were found to be marginally beneficial as they resulted in better stability of temperature across the slab, eliminating frequent occurrence of freeze/thaw cycles while enabling easier storage of collected heat. However, this advantage was only limited to superficial depths. Other major observations/conclusions from the, is study included**:**

1. Thermal conductivity of concrete was directly and positively related to the degree of saturation of concrete slab as well as the thermal conductivity of the aggregate elements making up the concrete. On the other hand, concrete thermal conductivity was negatively/inversely related to its porosity.
2. The use of metallic fibres to create an unbroken heat path of high conductivity the overall thermal conductivity of the concrete improved.

3. The use of concrete with high thermal diffusivity and highly conductive aggregate elements as well as the addition metallic fibres to the structure resulted in improved heat transportation from the surface of the concrete to the embedded network of tubes filled with the operating fluid [18].

(Wu et al., 2011) studied on micro-scale asphalt pavements whereby the researchers were able to further prove that water running in pipes underneath asphalt pavements can be used to modify and stabilize the surface temperature of the pavements. In a related experimental research conducted in 2009, Wu et al. (2009) designed an experimental investigation into the advantages of utilizing graphite powder as a component of asphalt pavements to improve the efficacy of the exchange of heat energy and enhance overall thermal conductivity of the collector. The addition of the graphite resulted in higher operating fluid exit temperatures hence improved heat exchange efficacy and increased thermal conductivity. Also the researchers attributed the obtained positive results to the utilization of longer tubes and larger surface area for heat transportation. However, the researchers note that the use of graphite could negatively impact the mechanical features of asphalt pavements, particularly due to the lubricating properties of graphite [19].

(Entrop et al., 2011) focused on appraising the harmless application of PCM in concrete surfaces. The study evaluated the efficacy of using the microencapsulated types of PCM for the storage of solar energy which was then used to modify ambient temperature in Dutch houses. Minimum temperatures were, consequently, increased by about 7% whereas the maximum temperatures were reduced by about 16%. A contrast experiment was also carried out by the authors to compare the overall variation of surface temperatures in a control surface and an experimental surface modified by a 5wt % PCM (T_{melt}=23^0C, H_{melt}= 110 kj/Kg) [20].

(Pejman Keikhaei Dehdezi, 2012) presented a theoretical and experimental study about the influence of pavement materials and layer design on the performance of PES. In order to perform analysis and model of PES under different operating circumstances, a virtual 3D transient explicit finite – difference program was improved. The temperatures distribution inside the pavement structure and the outlet fluid temperature was calculated.

The results concluded from that it was possible to do a wide range of thermal developed pavements with suitable mechanical performance, also it was possible to produce asphalt pavement mixture and mechanically acceptable concrete had the value of the thermal conductivity in the range (1.2 to 2.4) W/m.c and 0.5 to 4 W/m.c respectively. A numerical model developed to predict the distribution of temperature as a function of time and depth inside the structure of the pavement and the model was modified to a pseudo 3D to analysis the performance of PES subjected to different operating circumstances. The modified program was able to predict pavement temperature depth and the outlet fluid temperature. Therefore, the program used as a tool for evaluating the optimum dimensions of tube burial depths and loops, furthermore to study the effects of thermo-physical characteristics on the performance of PES for given position if the meteorological information exist. In order to contrast between the thermally-developed pavement structures performances with those of conventional ones, large-scale physical models were made. These were irradiated and by using halogen lamps caused the surface heating. The experimental contrast between unmodified concrete pavements with the thermally modified showed that there was enhancement for both storage capability and the heat collection of concrete pavement structures. Moreover the model used for prediction of outlet water temperatures and temperature depth profile with a good agreement with experimental test and the average error of losses was 1^{o}C. The same contrast for asphalt pavement illustrated that, even the temperature of the surface was changed by the modification of the asphalt; there were contradictions between the predicted surface temperature and the measured one for both the unmodified and modified pavements. By using the X-Ray Computed Tomography XRCT, this study focused on the tube/ pavement interfacial zone IZ. There was improper bonding between the tubes and the pavements matrix which was shown by the X-Ray images. That was the evidence of air void accumulation existed near the tube for the asphalt case. This was not noticed for samples of concrete also there was contradiction in the modeled temperature, in spite of that there is a need for more research to explain the effect of model input factor. It could be demonstrated that for the heat collector systems, the improvement of pavement materials could permit the tubes to install deeper inside the pavement structure with no observed negative effect on their thermal performance when contrast with conventional materials. Furthermore, contrast between various PSHS system showed that their performance, in expression of heat rejection/extraction to and from the pavements depends on the materials of pavements that surrounding the loops. The conventional source heat pump GHSP system like soil included the installation of the loops had the worst performance contrast with the system where the installation of the loops was in concrete. the performance of the PSHS systems improved when the thermal effusively of the concrete pavements surroundings. There was a strong positive logarithmic relationship between the heat extraction rate and the pavement thermal conductivity. Besides, it was observed that concrete pavements with the maximum thermal conductivity had a minimum top-bottom temperatures variation lead to the thermal stress and warping of the concrete pavements also decrease the temperature of the pavement surface decrease if the asphalt pavement had higher thermal conductivity. This led to decrease the rutting in asphalt pavements with the urban heat island effects **[21].**

(**Xiao-Yu Sun Xiao et al., 2014)** introduced a kind of all-ceramic solar collector from inexpensive materials. The all-ceramic solar collectors were fabricated from vanadium-titanium black ceramic and ordinary ceramic. The ordinary ceramic raw materials mean majorly feldspar, quartz and porcelain clay, etc. Vanadium –titanium black ceramic was used as solar absorbing coating material with stable value of solar a bsorptance in the range 0.93-0.97. The performance analysis and the characteristics of all-ceramic solar system were given. To contrast, three solar system included of metal-flat plate solar collector, all-ceramic solar system and all-glass evacuated pipe solar collector were manufactured. The highest thermal efficiency occurred in the all-ceramic solar system. During the test period, the heating rate trends of three solar systems were different. The all-ceramic solar system could integrate well with building roof. The appropriate method was given for the integration between the building roof and the all-ceramic solar system, By using integrated method, pitched building roof only needed for the basic concrete structure layer, waterproof layer, leaving course and insulating layer. Solar energy should be utilized due to its massive potential instead of other alternative energy forms. At any way, solar energy also is intermittent and decentralized. It was difficult to collect. Solar collector, as consider one of basic elements of the solar energy collection, should be characterized by low cost. The meaning of the word "low cost" not only means the low cost of solar collector materials, but also the longest lifetime. All-ceramic solar collectors have excellent thermo stability, long lifetime and high thermal efficiency. also it can integrated well with buildings which it can make the construction of building roof easy, prevent the sun for the building roof, and supply hot water for the people in the building. The building integration was the best way for the domestic use of all-ceramic solar collector **[22].**

(**Gert Guldentops et al., 2016)** presented the pavement solar collector (PSC) and its applications to extract low temperature thermal energy. The main goal of this study was to enhance a modeling framework for the pavement solar collector system and compared it with a self-instructed test. This model would permit for a detailed study of the system in order to obtain the optimized design, in addition to study the effect of aging (e.g. reducing the solar absorptivity) on the system performance.

By using the finite elements approach, a modeling framework was improved and presented, in order to predict the pavement solar collector̓s thermal behavior. There was a good agreement between the modeling framework and experimental data with respect to pavement temperature and outlet temperature of the fluid. The analysis of generated heat energy and evaluation the advantages of the system on the pavement life could be obtained. The parametric study on the effect of climate circumstances was carried out by using the modeling framework.

The parametric study was very important to explain the effect of the most significant design factors on the system̓s performance such as; the pavement surface solar absorptivity, the tube depth and the thermal conductivity of the asphalt concrete. The results of this work could be useful to study feasibility of the system **[23].**

(Dan Sun Lijiu Wang, 2016) presented a new kind of passive solar energy utilization technology with PCMs added inside the passive solar collector-wall system. The authors studied experimentally and theoretically the energy saving properties and heat transfer performance. By using the equations of energy balance which contained inner surface of the wall, air in the channel, sunlight board and collector mortar layer the description of heat transfer process of the system was presented. In order to study the energy saving properties in the winter season, experimental room was established. It could be observed from the results that by using the PCMs into passive solar collector-storage wall system helped to reduce the indoor air temperature fluctuations and enhance the indoor air thermal circulation. Hence, this new type of passive solar collector-storage wall system with PCMs could be used in engineering purposes **[24-26].**

Abbreviation

PVC : Polyvinyl chloride
COP : Coefficient of Performance
FEM : Finite Element Method
CFD : Computational Fluid Dynamics

2D : Two Dimension
3D : Three Dimension
CSC : Concrete solar collector
UK : United Kingdom
GSHP: Ground source heat pump
PSHS : pavement source heat store
PSC pavement solar collector
PCM Phase Change Material
XRCT X-ray computed tomography
IZ Interfacial Zone
PES Pavement energy system

LIST OF SYMBOLS

A : Surface area (m^2)
hc :Convective heat transfer coefficient (W/m^2. K)
k :Thermal conductivity (W/m .K)
L : length (m)
Q : Radiation Heat flux (W/m^2)
T : Temperature (°C)
m·: Mass flow rate (kg/s)
T_{melt} : Melting point temperature ^0C
H_{melt} : latent heat KJ/Kg

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