applied sciences

MDPI

Article

Asphalt Heat Recovery Application for Sustainable Green Energy

Angel Dogeanu, Laurentiu Tacutu, Elena Iatan *, Alin-Marius Nicolae and Catalin Ioan Lungu

Faculty of Building Services, Technical University of Civil Engineering Bucharest, 66 Pache Protopopescu Blvd, 021414 Bucharest, Romania; Angel.dogeanu@utcb.ro (A.D.); laur.tacutu@gmail.com (L.T.); Alin-marius.nicolae@utcb.ro (A.-M.N.); clungu@yahoo.com (C.I.L.)

* Correspondence: elena.iatan@utcb.ro

Abstract: Increasing demand for energy due to comfort requirements in the built environment coupled with development of road networks and amplifying heat island effect call for a comprehensive approach that can answer both issues. The lifespan of an asphalt layer is affected by surface temperature. In this paper, we aim to study the feasibility of heat recovery and its effects in terms of energy harvesting efficiency and asphalt surface temperature by creating a numerical model and validating the model based on onsite measurements at laboratory scale. The experimental setup was developed at Technical University of Civil Engineering in Bucharest, and measurements were monitored during the summer. The heat recovery system used for this study was made of copper pipes, and material cost and layout optimization need to be addressed in future studies. The numerical model was validated using measured data. During this study, we obtained favorable results in terms of heat recovery, reducing surface temperature and selection of system materials. Further research is required for heat recovery system and pump automation (based on the surface temperature), in order to optimize energy consumption and improve overall efficiency.

Keywords: sustainable development; green energy; asphalt collector

check for updates

Citation: Dogeanu, A.; Tacutu, L.; Iatan, E.; Nicolae, A.-M.; Lungu, C.I. Asphalt Heat Recovery Application for Sustainable Green Energy. *Appl. Sci.* **2022**, *12*, 1196. https://doi.org/10.3390/app12031196

Academic Editor: Sumin Kim

Received: 1 December 2021
Accepted: 17 December 2021
Published: 24 January 2022

1. Introduction

Human activities have affected around 75% of the global non-iced terrestrial environment [1]. Although urban areas occupy a small area equivalent to about 0.5% of the global surface of the planet [2], more than half of the world's population (with an estimated growth of up to 66% by 2050) currently lives in urban areas [3] and asphalt-covered surfaces are increasing. Asphalt is the main material used as a finish for road surfaces and parking areas for vehicles. Its color leads to heat absorption and an increase in surface temperature. On the basis of measurements, it was observed that the temperature of the asphalted surfaces can reach values as high as 72 °C on a usual day [4]. This contributes to the intensification of the effect known as the "urban heat island effect" or UHI [5]. The effect of the UHI has significant consequences on the quality of life of city occupants and is the source of a significant number of environmental problems in urban areas.

Thus, it has been observed that with intensification of the UHI effect, emissions of volatile organic compounds increase [6], and these have a negative impact on pedestrian health [7]. Another negative effect observed apart from increased urban heat island effect is generated by the impact on the strength of internal structure of the asphalt layer. It was shown that at high temperatures, plastic deformations occur with damage to the structure of the material, thus leading to a rapid decrease in its lifespan and implicitly to an increase in the operating and maintenance costs of asphalted surfaces [8].

Reference [9] shows the negative influence that high temperatures have on the lifespan of the asphalt layer in terms of decreasing the lifespan of the asphalt from 20 years for a surface temperature of 57 degrees Celsius to only an 8-years lifespan for a surface temperature of 70 degrees Celsius. Other studies have focused on the effect of thermal radiation generated by an asphalt layer and the additional consumption generated by building air conditioning systems [10].

Given the available thermal potential, a number of applications can be identified in which the thermal energy recovered from the asphalt layer can be used through Asphalt Mounted Solar Collectors [CSA]. Thus, an industrial application in which we can use this technology is the use of fluid that crosses the asphalt layer to heat digesters that aim to generate anaerobic methane gas (given that this technology requires a temperature of around 30–35 °C [11] for optimal operation). Digesters are used to "treat" wastewater that is rich in organic matter, which is the case in most municipal domestic wastewater treatment plants. [12]. It is known that this fermentation process uses thermal energy [13] resulting from the cogeneration process in order to achieve optimal parameters. This thermal energy may be capitalized by selling to other consumers if we use a CSA-type system in the hot season to cover the necessary process' thermal energy. Another way of use is coupling with geothermal storage systems so that it can be used to defrost critical areas of highways or bridges [14] without using fossil fuels or chemically or mechanically aggressive materials for the asphalt layer. Implementation in such a way leads to reduction of operating costs and emissions due to the use of fossil fuels.

Another applicability is the operation of ground-to-water heat pump heating systems with vertical boreholes. It has been observed that the COP (coefficient of performance) of the heat pump decreases by up to 50% [15] after 10 years in situations in which the thermal loads during the heating and cooling period are not balanced, and Romania is also in this situation from a meteorological point of view. The CSA solution could be used for thermal regeneration of vertical boreholes [14] in order to help increase and maintain the energy efficiency of these types of heat pumps. Such an implementation would also implicitly reduce the payback time of the investment by reducing operating costs.

At international scale there is a growing interest in similar applications [16–18]. Thus, since 1995, the Swiss government has funded and supported the development of the SERSO system in a research grant [19]. Its purpose was to collect thermal energy from asphalt surfaces in the hot season and store it in rock deposits for reuse during the cold period of the year to defrost bridges. In [19] are presented the components of theSERSO system. A similar approach is presented in a study conducted in China [20].

Other studies have proposed the connection of CSA systems with geothermal systems [21] in order to regenerate them thermally for situations in which thermal energy extracted during the cold season is higher than the one reintroduced in the soil during hot season; this is also the case of Romania.

The ATES (Aqvifer Thermal Energy Storage) System [22–24] shown is a thermal energy storage system for defrosting runways and parking areas. Such system was implemented at Gardermoen International Airport in Oslo, Norway. None of the presented solutions aim to recover the thermal energy from the CSA in order to reuse it (e.g., for preparation of domestic hot water).

In the context of legislative changes and the obligation to comply with European standards nZEB (nearly Zero Energy Building), both require a high-performance building envelope and at least 30% of primary energy consumed by the building to be obtained from renewable sources; therefore, the research aims to have more weight in this context.

2. Materials and Methods

The experimental model was developed at the Technical University of Civil Engineering Bucharest. For the experimental setup development, several steps were performed. The first stage was the design of the heat recovery system. Copper pipes were used to make the register (network) of pipes because of their good behavior at high temperatures of asphalt mixtures (185 °C for casting and 155 °C for compaction). The register is made of an array of copper pipes with a diameter of 12 mm spaced at 15 cm. In the upper and lower part, a distributor-collector type system with a diameter of 18 mm was implemented to ensure an identical flow for all branches. Figure 1 shows the concept of the heat recovery register.

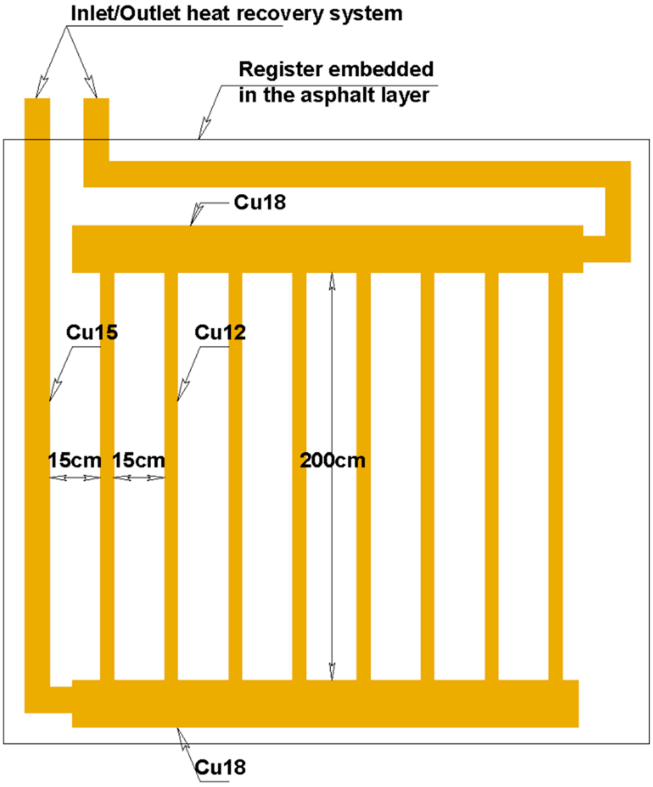


Figure 1. Heat recovery register geometry.

The integration of the thermal energy recovery system in the asphalt layer implemented the following sequence of layers, as presented in Figure 2 (i) a layer of BA8 asphalt with a thickness of 60 mm (hot-mix asphalt layer, without additives, commonly used for the construction of the asphalt carpet of parking lots), (ii) register made of copper pipe embedded inside this surface at a depth of 50 mm, and (iii) the existing layer made of concrete. The joints were made by soft welding using a Sn97Cu3 alloy that has a melting temperature between 230–250 °C, which is above the casting temperature of the asphalt mixture. The geometry of the register is shown in Figure 1.

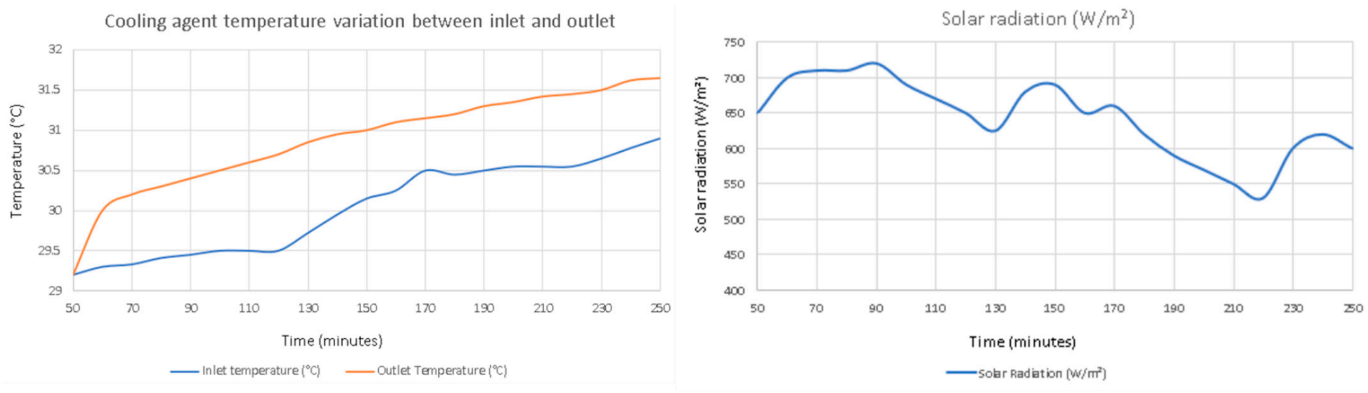

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 2. (**a**) Support layer uniformity; (**b**) incorporation of copper register and coating with 5 cm of BA8 asphalt; (**c**) stand after compaction; (**d**) monitoring of solar radiation level with Ahlborn Star Pyranometer FLA 628 S; (**e**) monitoring of temperatures with Ahlborn acquisition station and K-type thermocouples.

The circulation of thermal agent (water) between CSA and a water tank with a volume of 500 L was performed using a circulation pump. This water tank volume was selected to ensure a good gradient of temperature. The temperature gradient measurements and the heat exchange efficiency were performed by simultaneously measuring, at several points, the temperature of thermal agent and on the CSA surface. Images from different stages of conducting the experimental stand are presented in Figure 2. Temperature sensors (thermocouple type K) were used, and data were logged using an Ahlborn acquisition station. Solar radiation was measured using an Ahlborn Pyranometer FLA 628S was used. Water flow was constant during the measurements and equal to 450 L/h.

3. Experimental Results

In order to evaluate the feasibility of thermal energy recovery from CSA, a constant flow pump was used to circulate the cooling agent in CSA during several summer days. An Ahlborn Almemo data logging station was used to monitor these temperatures, and K-type thermocouples were used as temperature sensors and mounted in several areas of the experimental setup (top asphalt layer, 2.5 cm depth, the surface of the copper pipes, air temperature, etc). Previously, the thermocouples were calibrated using a thermostatic bath. This configuration was chosen to take into account the low thermal capacity of the pipe wall. The graph in Figure 3a shows a sample of data measured during the validation period of the experimental setup and highlights the temperature variations of the cooling agent, observing the increase in its temperature. Throughout the monitoring of the CSA system, monitoring of the variation of direct and indirect solar radiation was performed in parallel using an Ahlborn Star FLA 268S pyranometer. Figure 3b shows the variations in the solar intensity monitored during the in situ measurements.



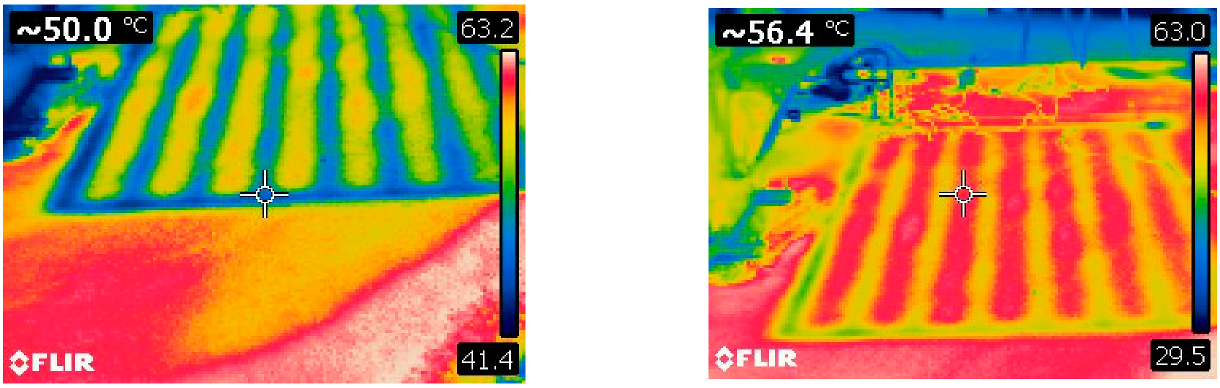
(**a**) (**b**)

Figure 3. (**a**) Sample coolant temperatures monitored during a test; (**b**) monitoring solar radiation using a pyranometer.

4. Qualitative Infrared Thermography Assessment

At the asphalt surface level, the heat transfer occurs by convection, conduction, and radiation. The phenomenon that negatively influences the heat consumption related to the air conditioning systems of the surrounding buildings is the radiation phenomenon. According to the Stefan–Boltzmann law, the variable that would reduce the energy radiated to the building is influenced by the temperature of the asphalt surface. The hypothesis of this study is that the surface temperature of the asphalt pavement can be reduced due to heat transfer to the register of pipes embedded in its surface.

For this, to compare the situation with and without, temperatures of some asphalt test areas without a cooling system and with a cooling register were obtained. The two areas were subjected to the same values of solar radiation, which are located next to each other. The data obtained from the two temperatures measurement used, quantitatively (using K-type temperature sensors) and qualitatively (by thermography, a non-invasive method) were compared between them Images taken with the thermography camera are shown in Figure 4 These results confirm that a lower temperature can be obtained on the pavement surface and, implicitly, the reduction of heat transfer by radiation exerted by the asphalt layer on the building for the studied period by at least 10%.



(**a**) (**b**)

Figure 4. (**a**) Thermographic image of the area located (**a**) above the CSA and (**b**) between the CSA pipes.

5. Numerical Model

In addition to experimental campaigns, a numerical study was conducted in Ansys Fluent with the experimental stand geometry. The numerical study was done in order to study in depth the phenomenon and to compare the results obtained from the two approaches. The results from the numerical study were post-processed using Tecplot software. The geometry of the numerical study that was made in the Design Modeler of Ansys Workbench and can be seen in Figure 5. It reproduces the geometry of the experimental approach, both in terms of shape and structure, as well as the dimensions and configuration of the pipeline route.

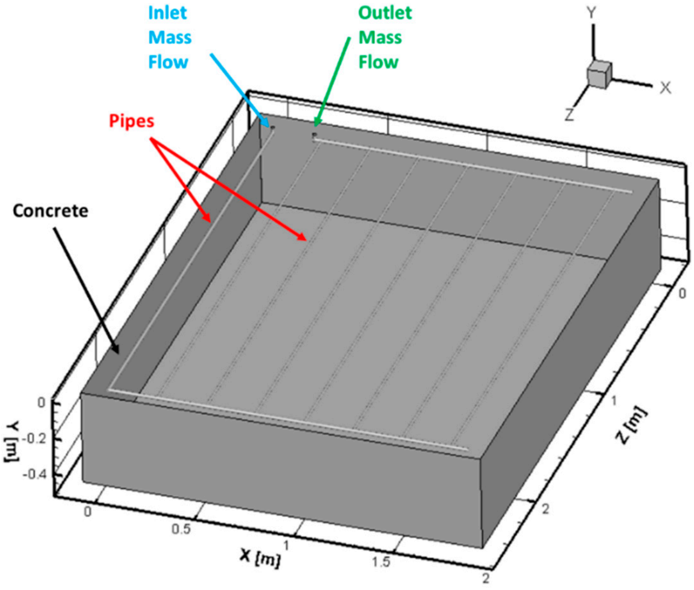


Figure 5. Numerical model geometry.

The numerical case has the dimension of 2600 × 2000 × 500 mm, with the pipes incorporated at a depth of 40 mm from the surface. The calculation grid contained 9.7 million tetrahedral elements. The “inflation” option was used for generating boundary layers, resulting in five boundary layers at the level of the pipes with a smooth transition, depending on the size cell and the number of cells in the respective area. At the same time, in order to improve the quality of the elements, the high smoothing mesh option was used.

Figure 6 shows the calculation grid in the areas of interest. From here, one can see how the grid was generated in terms of boundary layers, cell dimensions, and the transitions at the level of the tetrahedral elements.

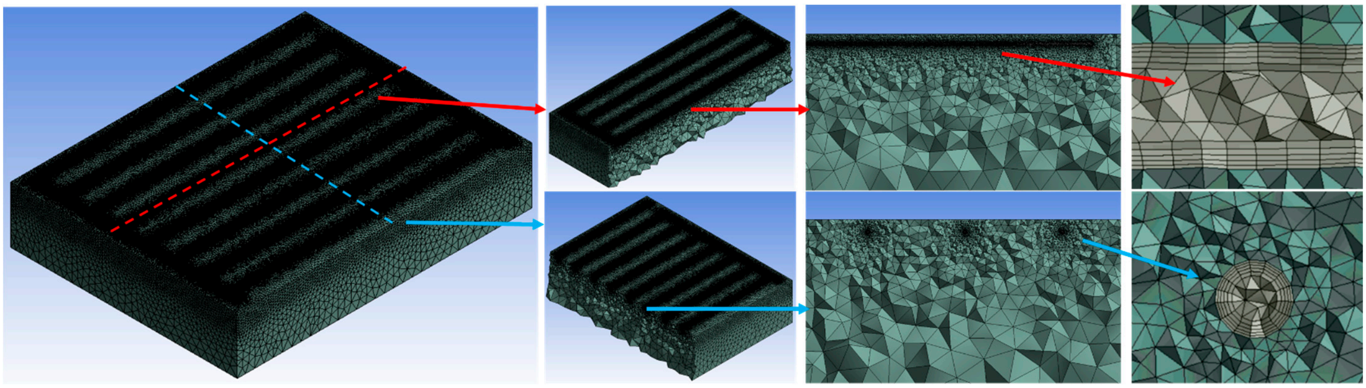


Figure 6. Numerical model calculation grid.

The boundary condition data imposed on the numerical study were obtained from measurements performed on the experimental stand.

The numerical calculation used RANS equations (Reynolds-averaged Navier–Stokes equations), while the calculation was performed in "steady-state conditions". A step-by-step approach was used to test and simulate the case gradually, initially using stationary conditions with heat transfer through conduction and subsequently, after checking the case, using solar radiation conditions. The gravitational force function was also activated ($9.81\ \mathrm{m/s^2}$) in the numerical model. The turbulence model used to study the flow of the fluid through the pipes was k-ω SST. A "pressure-based solver" was used for calculating the pressure and velocity equations, using the "Coupled" algorithm for "Pressure–Velocity Coupling", with "Least Squares Cell Based", "Second Order", and "Second Order Upwind". The radiation model used was Surface to Surface (S2S), with the "Solar Ray Tracing" option activated, considering normal (ideal) weather conditions. The values of direct and diffuse solar radiation were obtained from the experimental measurements, imposing values of $725\ \mathrm{W/m^2}$ (constant) for direct solar radiation and $125\ \mathrm{W/m^2}$ (constant) for diffuse solar radiation. The thermal agent fluid used in the numerical model was water, similar to the experimental measurements. Regarding the simulation of heat transfer through the solid material, the numerical model used the general characteristics of an asphalt (density $2243\ \mathrm{kg/m^3}$, specific heat 920 J/kg·K, thermal conductivity 0.75 W/m·K). The initialization of the case was "Hybrid Initialization", while the convergence on the numerical calculation was set to 10^{-6}. The thermal agent mass flow rate was 0.125 kg/s, similar to the one used in the measurements.

The numerical model took into consideration the heat transfer through conduction (asphalt and pipes) and radiation (sun radiation). As a simplifying hypothesis regarding the air force convection, it was shown in previous studies that heat transferred through air force convection has a very small proportion in the total heat transfer [25,26]. Of course, this transfer method is also subject to the context of the location (geographical area, surroundings, etc). Due to this fact, and in order to avoid overwhelming the case with a large number of cells, it was chosen to simulate the study without convection and compare the results from both approaches. If the compared results had shown divergences, the addition of forced air convection would have been taken into account. The numeric simulation through the pipes was governed by fluid mechanics (the equation of mass, momentum, and energy conservation) and heat transfer (forced convection). Results from the numerical model can be seen in Figure 7, where temperature fields are presented in section and frontal plane, while a isometric view can be seen in Figure 8.

If we compare the temperature gradients obtained in the numerical model, which are visually presented in Figures 7 and 8, with the data resulting from the experimental measurements from Figure 4, a good correlation can be observed between the two results, both in terms of the temperature distribution and the range of values obtained.

These preliminary results are encouraging, as they demonstrate the feasibility of using CSA as a method to recover thermal energy and at the same time achieve a local cooling of the asphalt-covered surface.

The thermocouples' positions are presented in Figure 9a. The differences between the numerical and the experimental model are based on the variation of the value of the solar radiation (dynamic) in the case of the experimental setup compared to the numerical model, in which it had a constant value. Results are presented in Figure 9b.

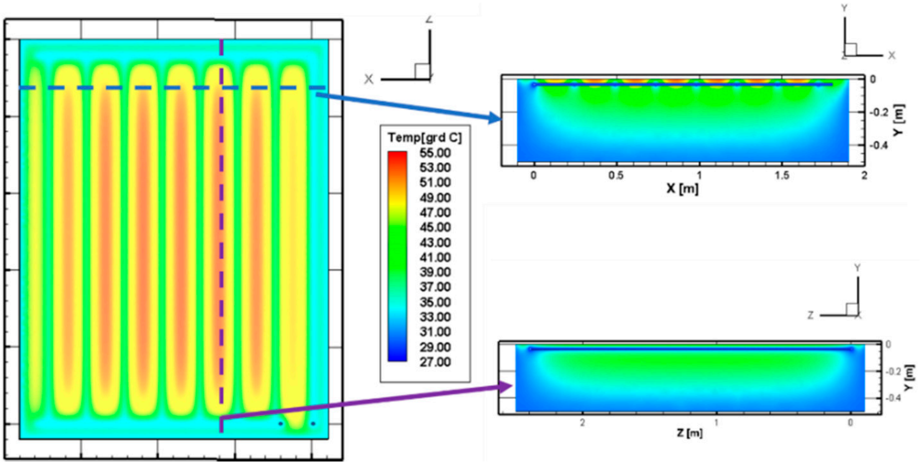


Figure 7. Temperature fields at the external surface and in longitudinal cross-section.

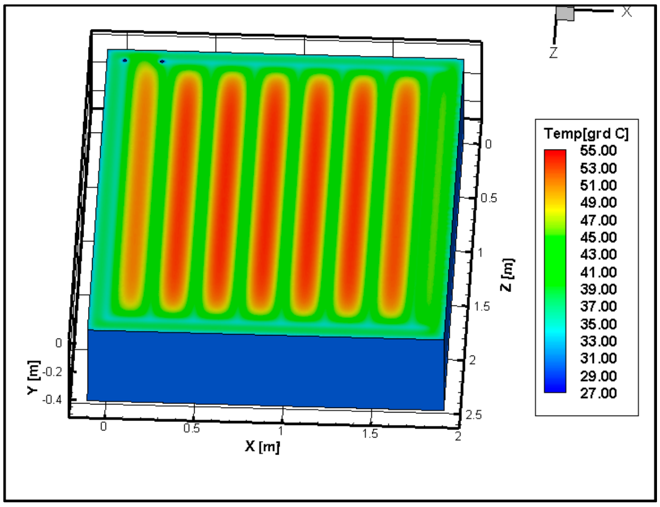
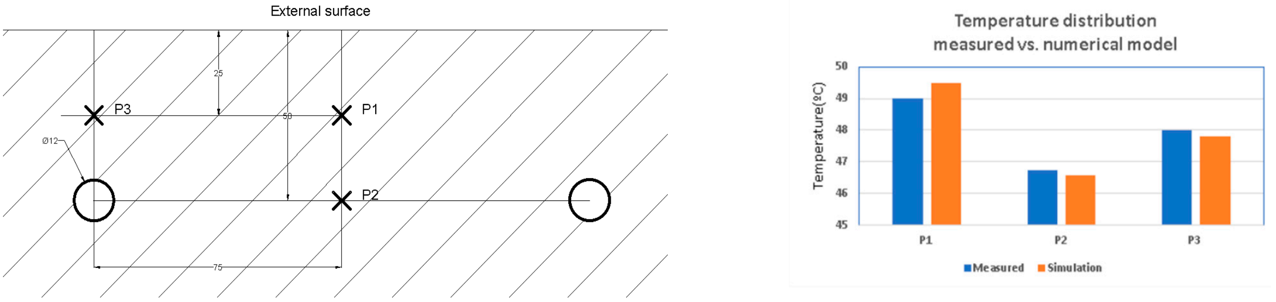


Figure 8. Surface temperature fields, isometric views.

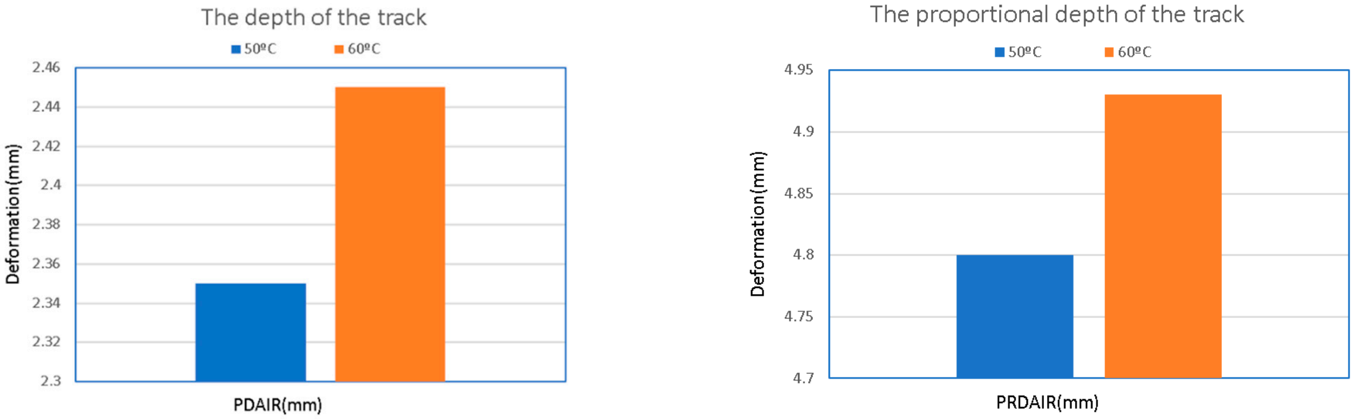


(**a**) (**b**)

Figure 9. (**a**) K-type sensor position (**b**) graphic comparison between measured and simulated data.

6. Laboratory Tests

At the end of the measurement campaign, several tests were performed by a nationally accredited laboratory to evaluate the behavior of the asphalt mixture at different temperatures and to highlight a favorable behavior at lower temperatures (RDAIR—depth of the track and PRDAIR -the proportional depth of the track, at 50 °C and 60 °C, respectively). The temperature setpoints used for the tests were set based on the values measured during the experimental campaign. The test results are presented in Figure 10a,b, respectively, demonstrating the validity of the premises which estimated superior mechanical properties of the material.



(**a**) (**b**)

Figure 10. Resistance tests at 50 °C and 60 °C for (**a**) RDAIR and (**b**) PRDAIR.

7. Discussion and Conclusions

The present study aimed to analyze and find different types of solution for the two situations mentioned in the article: for summer seasons, maintaining optimal temperatures on the asphalt surface, in order to keep its properties for longer terms, and using the thermal energy of it for other purposes (preparation of hot water for heating, household use, etc), while for winter seasons, to defrost areas of interest (like roads, alleys, etc.)

Also, another purpose of the study was to create a preliminary numerical model and to validate it through in situ measurements based upon a real scale experimental device. The studied model used a heat exchanger based on copper pipes and a hot-mix asphalt layer. During the experimental tests, the coolant flow and the power consumption of the circulating pump were kept constant. The observed correlation between the temperature distributions on the surface of this type of solar collector is promising for future development. Nevertheless, this is the first step, as further studies must be realized, and "the system" must be assessed because the asphalt collector is not the only component in the heat recovery system.

The laboratory tests conducted at standard (no cooling) temperatures and cooling temperatures were favorable in terms of mechanical resistance and showed better mechanical proprieties; they are thus encouraging for further studies in this field.

Heat recovered from the collector can be used to preheat domestic hot water and reduce the heating load of the DHW system. Further studies on the collector surface, the material used for CSA pipes, and the spacing related to the DHW system must be conducted.

Author Contributions: A.D. and E.I. worked on the concept, design of the system, measurements, and data analysis; L.T. managed the numerical simulation; A.-M.N. and C.I.L. assisted during the measurements and data analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Technical University of Civil Engineering of Bucharest, grant number UTCB-CDI-2021-023.

Data Availability Statement: No applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ellis, E. Anthropogenic Transformation Ofthe Terrestrial Biosphere. *Philos. Trans. R. Soc.* **2011**, *369*, 1010–1035. [CrossRef] [PubMed]
2. Schneider, A.; Friedl, M.; Potere, D. A New Map Of Global Urban Extent From Modis Satellite Data. *Environ. Res. Lett.* **2009**, *4*, 044003. [CrossRef]
3. United Nations. *World Urbanization Prospects, The 2014 Revision*; Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2014. Available online: https://www.un.org/en/development/desa/publications/2014-revision-world-urbanization-prospects.html (accessed on 23 September 2019).
4. Al-Abdul Wahhab, H.I.; Balghunaim, F.A. Asphalt Pavement Temperature Related to Arid Saudi Environment. *J. Mater. Civ. Eng.* **1994**, *6*, 1–14. [CrossRef]
5. Mohajerani, A.; Bakaric, J.; Jeffrey-Bailey, T. The Urban Heat Island Effect, Its Causes, and Mitigation, with Reference to the Thermal Properties of Asphalt Concrete. *J. Environ. Manag.* **2017**, *197*, 522–538. [CrossRef]
6. Tang, B.; Isacsson, U. Chemical Characterization of Oil-Based Asphalt Release Agents and Their Emissions. *Fuel* **2006**, *85*, 1232–1241. [CrossRef]
7. Fahed, J.; Kinab, E.; Ginestet, S.; Adolphe, L. Impact of Urban Heat Island Mitigation Measures on Microclimate and Pedestrian Comfort in a Dense Urban District of Lebanon. *Sustain. Cities Soc.* **2020**, *61*, 102375. [CrossRef]
8. Zhao, Y.; Kim, Y. Time-Temperature Superposition for Asphalt Mixtures with Growing Damage and Permanent Deformation in Compression. *J. Transp. Res. Board* **2003**, *1832*, 161–172. [CrossRef]
9. Mallick, R.B.; Chen, B.-L.; Bhowmick, S. Harvesting Energy from Asphalt Pavements and Reducing the Heat Island Effect. *Int. J. Sustain. Eng.* **2009**, *2*, 214–228. [CrossRef]
10. Tanimoto, J.; Hagishima, A.; Chimklai, P. An Approach for Coupled Simulation of Building Thermal Effects and Urban Climatology. *Energy Build.* **2004**, *36*, 781–793. [CrossRef]
11. Montalvo, S.; Huiliñir, C.; Ojeda, F.; Castillo, A.; Lillo, L.; Guerrero, L. Microaerobic Pretreatment of Sewage Sludge: Effect of Air Flow Rate, Pretreatment Time and Temperature on the Aerobic Process and Methane Generation. *Int. Biodeterior. Biodegrad.* **2016**, *110*, 1–7. [CrossRef]
12. Lew, B.; Lustig, I.; Beliavski, M.; Tarre, S.; Green, M. An Integrated Uasb-Sludge Digester System for Raw Domestic Wastewater Treatment in Temperate Climates. *Bioresour. Technol.* **2011**, *102*, 4921–4924. [CrossRef] [PubMed]
13. Bekon. Brosure. Available online: Https://Www.Bekon.Eu/Wp-Content/Uploads/2017/04/Brochure_Bekon_Mini_En.Pdf (accessed on 23 September 2019).
14. Pan, P.; Wu, S.; Xiao, Y.; Liu, G. A Review on Hydronic Asphalt Pavement for Energy Harvesting and Snow Melting. *Renew. Sustain. Energy Rev.* **2015**, *48*, 624–634. [CrossRef]
15. Qian, H.; Wang, Y. Modeling the Interactions between the Performance of Ground Source Heat Pumps and Soil Temperature Variations. *Energy Sustain. Dev.* **2014**, *23*, 115–121. [CrossRef]
16. Li, Y.F.; Wu, H.Q.; Wang, G.M.; Zhu, B.; Shi, B.W. Experimental Study on the Electrical Road Heating System for Snow Melting. *J. Beijing Univ. Technol.* **2006**, *32*, 217–222.
17. Baumgärtel, S.; Schweighofer, J.A.V.; Rohn, J.; Luo, J. The Performance of Geothermal Passive Heating and Cooling for Asphalt and Concrete Pavement. *Dev. Built Environ.* **2021**, *7*, 100051. [CrossRef]
18. Lai, J.; Qiu, J.; Chen, J.; Fan, H.; Wang, K. New Technology and Experimental Study on Snow-Melting Heated Pavement System in Tunnel Portal. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 706536. [CrossRef]
19. Ceylan, H.; Gopalakrishnan, K.; Kim, S.; Cord, W. Heated Transportation Infrastructure Systems: Existing and Emerging Technologies. In Proceedings of the 12th International Symposium on Concrete Roads, Prague, Czech Republic, 23–26 September 2014.
20. Gao, Q.; Huang, Y.; Li, M.; Liu, Y.; Yan, Y.Y. Experimental Study of Slab Solar Collection on the Hydronic System of Road. *Sol. Energy* **2010**, *84*, 2096–2102. [CrossRef]
21. De Bondt, A.H.; Jansen, R. *Generation and Saving of Energy via Asphalt Pavement Surfaces*; Jansen, R., Ed.; Ooms Nederland Holding B.V.: Deventer, The Netherlands, 2006.
22. De Schepper, G.; Paulus, C.; Bolly, P.-Y.; Hermans, T.; Lesparre, N.; Robert, T. Assessment of Short-Term Aquifer Thermal Energy Storage for Demand-Side Management Perspectives: Experimental and Numerical Developments. *Appl. Energy* **2019**, *242*, 534–546. [CrossRef]
23. Lu, H.; Tian, P.; Guan, Y.; Yu, S. Integrated Suitability, Vulnerability and Sustainability Indicators for Assessing the Global Potential of Aquifer Thermal Energy Storage. *Appl. Energy* **2019**, *239*, 747–756. [CrossRef]
24. Lu, H.; Tian, P.; He, L. Evaluating the Global Potential of Aquifer Thermal Energy Storage and Determining the Potential Worldwide Hotspots Driven by Socio-Economic, Geo-Hydrologic and Climatic Conditions. *Renew. Sustain. Energy Rev.* **2019**, *112*, 788–796. [CrossRef]

25. Mieczkowski, P.; Budziński, B. The Influence of Water on the Heat Loss of Hot Mix Asphalt. *Appl. Sci.* **2019**, *9*, 1747. [CrossRef]
26. Dehdezi, P. Enhancing Pavements for Thermal Applications. Ph.D. Thesis, University of Nottingham, Nottingham, UK, 2012.