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Road Thermal Collector for Building Heating in South Europe: Numerical Modeling and Design of an Experimental Set-Up

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Abstract: The combination/integration of renewable energy and storage systems appears to have significant potential, achieving high-energy results with lower costs and emissions. One way to cover the thermal needs of a building is through solar energy and its seasonal storage in the ground. The SMARTEP project aims to create an experimental area that provides for the construction of a road solar thermal collector directly connected to a seasonal low-temperature geothermal storage with vertical boreholes. The storage can be connected to a ground-to-water heat pump for building acclimatization. This system will meet the requirements of visual impact and reduction of the occupied area. Nevertheless, several constraints related to the radiative properties of the surfaces and the lack of proper thermal insulation have to be addressed. The project includes the study of several configurations and suitable materials, the set-up of a dynamic simulation model and the construction of a small-scale road thermal collector. These phases allowed for an experimental area to be built. Thanks to careful investigation in the field, it will be possible to identify the characteristics and the best operation strategy to maximize the energy management of the whole system in the Mediterranean area.

Keywords: road thermal collector; borehole thermal storage; alternative energy system

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1. Introduction

The exploitation of traditional energy resources has, to a large extent, led to a critical point, where it is now critical to reconsider the terms of energy and focus on sustainable energy reasonableness, so that energy satisfies the energy of the present without compromising the ability to meet the needs of future generations. Currently, the energy sector is strongly committed to a policy of replacing fossil fuels with renewable and low-impact energy carriers; the transition is needed, by increasing energy consumption around the world. Renewable energy, such as wind, solar, and geothermal energy, can replace the current primary energy supply sources, especially if improvements can be made to energy conversion, transport, and distribution systems. Thanks to the great efforts of the scientific community, these systems have been optimized in order to function as efficiently as possible in terms of cost and CO_2 emissions. In particular, there seems to be great potential, in achieving the same results with lower costs and low emissions, through the combination and integration of renewable energies with storage systems. There is great theoretical potential for the use of solar energy capable of covering the heat demands of buildings; the technical potentials at the latitudes of the Sun Belt are greatly influenced by the possibility of storing heat from the summer to the heating period. One way to cover the heating demands of a building is represented by the use of solar energy and its seasonal accumulation in the ground, where the stored energy can be reused when necessary [1].

The collection of solar energy is commonly entrusted to solar collectors installed on a roof or ground. An alternative solution is represented by road thermal collectors (RTC), i.e., installation of pipes embedded in paved surfaces such as asphalt surfaces, sidewalks, roads, and parking lots. Asphalt, being a material with high thermal capacity, represents an alternative low-cost heat storage system. These surfaces are already present, and since the road surface must be resurfaced periodically, the energy system can be installed very easily during a generic maintenance phase. From the point of view of energy production, the significantly larger areas of the asphalt collectors can compensate for their expected lower efficiencies, justifying the investment for the power produced per unit. In addition, asphalt surfaces can continue producing energy, even during the night. The solar energy captured in this way can be used for different applications: in combination with accumulation systems (wells), for road safety and maintenance, keeping the roads free from snow during the winter period, reducing the cost of regular roofing road, or for the decrease in surface temperatures by reducing the effect of the heat island. Unlike traditional manifolds, this system meets the needs of reducing visual impacts, not occupying surface areas that are not always available where necessary. Finally, this system will make it possible to exploit the absorption capacity of the road surface in areas characterized by high sunshine, energetically redeveloping areas that are generally dedicated to something else (roads and parking lots).

Based on these considerations, the University of Palermo, through the SMARTEP project "sustainable model and thinking of renewable energy parking" [2], is creating an experimental area, where, in addition to the development of an innovative intelligent energy parking system, it envisages the construction of a road thermal collector for collection of solar energy, directly connected to seasonal low-temperature geothermal storage, with vertical probes. This research project's various objectives include being able to investigate the best solution and boundary conditions for a commercial diffusion of an RTC system with geothermal storage in the Mediterranean area, maximizing the accumulation phase in periods of greater sunshine. In this research, we experimented in the field of a thermal RTC integrated with a geothermal storage system in the Mediterranean area. In particular, after careful analysis of the sector bibliography, thanks to the SMARTEP experimental area, it will be possible to investigate, in the field, the best solution, configuration, and main boundary conditions that can maximize the efficiency and effectiveness of an alternative solar system, and innovativeness, such as solar collectors embedded in paved surfaces (asphalt, sidewalks, roads, parking lots), integrated with a geothermal seasonal storage system.

Creating favorable conditions for solar absorption and thermal accumulation leads to a local increase of surface and air temperature, exacerbating hazardous phenomena, such as urban heat islands and overheating [3]. It is, thus, important to identify surface materials that are able to optimize this complex task: ensuring high enough thermal gains for the collectors without comprising the outdoor thermal quality. Crucial parameters include the thermal emissivity, the solar reflectance, and the color, which is an indicator of the visible component of the latter. Several construction materials and natural stones, such as concrete and marble, have higher solar reflectance compared to asphalts, which can enhance thermal mitigation; new technologies, such as near-infrared reflecting coatings, dynamic coatings, and phase change materials, can also be applied to the purpose [4]. For this reason, a research group from the University of Palermo, with collaboration from Enea [5], are simultaneously studying a solution that attempts to counter this phenomenon. In particular, the possibility of using road surfaces in an alternative color to the traditional black, to be used on the RTC, is being evaluated, in order to guarantee high efficiency of the collection system, and at the same time be able to mitigate the heat island effect. Simultaneously, special cool materials could be used in the remaining areas surrounding the RTC areas in order to balance the heating effects with the cooling of the surrounding areas.

Indeed, experimentation in the field will allow calibrating the RTC system with geothermal storage in a highly sunny area in the summer in order to make it competitive with other renewable technologies and, therefore, replicable in other contexts. The results of the proposed research will provide valid support for the design and implementation of sustainability and circularity actions, based on a holistic and life cycle approach that integrates the three spheres of sustainability, which will allow a systemic assessment of energy—environmental, economic, social, and circularity.

2. State-of-the-Art

The solar collectors on asphalt consist of pipes embedded in the road surface in which the pipes are crossed by a heat transfer fluid. Thanks to a process of heat transfer from the flooring to the fluid, a lowering of the temperature of the flooring occurs, which mitigates the heat island effect, simultaneously reducing the risk of permanent deformations. However, what makes asphalt solar collectors interesting is the capability of exploiting the temperature increase by the circulating fluid to collect the thermal energy. In general, RTCs are coupled to low temperature geothermal heat pumps, achieving the right balance between efficiency and running costs. As already mentioned, the energy obtained from an RTC system is generally used for snow melting systems, to decrease the temperatures of the heat islands that are generated in large metropolitan cities, to maintain thermal comfort in the buildings adjacent to the alternative energy system. These collectors can also be placed at the top of a concrete surface, such as pavement, but since the black color increases the absorption coefficient; it has been estimated that higher performance is linked to manifolds made positioned in the asphalt road pavement.

The patent of 1979, entitled "Paving and solar energy system and method" [6], is one of the first works, which describes a system with pipes embedded in the pavement of a roadway or a roof. The inventor, Ion L. Wen-del, says that the fluid circulating in the duct is heated by the flooring, cooling it at the same time, extending its useful life, and reducing the transmission of heat through the roof to the interior of the building. Furthermore, this application, if installed in a large parking lot, could also represent the preheating of the water of some systems, such as swimming pools or spas. The Swiss SERSO system is one of the pioneering applications of this system applied to melt, and consisted of tubes embedded in the deck of a bridge of the Swiss motorway network on road 8 to Därligen in Bern. This project was carried out by Polydynamics SA, Zurich (Swiss), to collect the heat from the road surface of the bridge in the summer, storing the heat produced in an underground heat sink, and using the heat in the winter to heat the road surface of the bridge by providing any ice formation. It has been shown that, in the summer, the system can store 20% of the solar radiation incident on the road surface [7].

The GAIA Snow-Melting system, installed in 1995 in Ninohe, Japan, uses a thermally insulated inner tube and reverse circulation to increase heat extraction efficiency, i.e., cold fluid flows along the ring and hotter fluid flows upward through the inner tube. This apparatus features a control center that manages the system when road conditions meet specific criteria for snowmelt or heat charge [8]. In this system, the heat absorbed by the road pavement is recovered and stored in the ground during the summer period, to then be used to melt snow in winter.

Following these evolutions, many companies have specialized in the construction and installation of systems, capable of producing energy by exploiting the solar radiation collected from road surfaces, and many of these are commercialized systems, such as Dutch Ooms International Holding with its Road Energy Systems (RES) and Winner Way [9]. One of these is the ICAX™ Ltd. Company (London, UK), which has designed and installed a system capable of melting road snow in a playground of a school, and the thermal energy collected is used to improve the indoor comfort condition of the building [10]. The latter was designed using the playground as a surface, where the heat collectors are positioned underneath, formed by reinforced plastic tubes, and the heat-carrying liquid circulates inside, which, once heated by the surface of the park, is transferred to two heat accumulations positioned under the school floor (skins of power—buildings as energy collectors—Bill Holdsworth). The alternative companies and Novotech, Inc. (USA), in collaboration with the Worcester Polytechnic Institute, have developed a system called Roadway Power System, which uses manifolds, embedded in the asphalt road pavement, connected to a turbine system to create electric energy [11]. In order to provide a more complete explanation, some of the main applications and studies of the RTC system from the 1980s to today, are listed below.

In 1981, Sedgwick and Patrick experimentally designed a swimming pool heating system in the summer using a grid of plastic pipes laid 20 mm below the surface of a tennis court in the UK. In general, a classic heating system for a swimming pool environment reaches temperatures of 20–27 °C in the summer. In particular, in the summer, due to the climatic conditions typical of the United Kingdom, the pools reach comfortable temperatures with an air temperature of 22 °C and a solar radiation of 610 W/m^2. The system designed by Sedgwick and Patrick was technically feasible and cost effective, as it was capable of providing a temperature of 22 °C [12]. Around 1986–1987, Turner developed a theoretical study—a simple 1D model in the stationary field used to analyze the performance of a road collector in both the winter and summer. In the first case, it envisaged the reaching of the maximum road temperature of 15 °C, necessary for the defrosting of roads and bridges; in the second case, it assessed the achievement of the road temperature of about 70 °C, i.e., a temperature such as to guarantee the heating of the water for heat pumps and swimming pools [13]. Nayak et al. in [14] experimented with a solar system embedded in a layer of concrete and placed on a roof. The collector is made of 10 mm polyvinyl chloride (PVC) pipes and the roof surface has been painted black to increase its solar absorption capacity. The results showed that solar collectors, placed on a concrete surface, could be used as a valid and economically feasible alternative to conventional systems when the air temperature is 35 °C and solar radiation is 1000 W/m^2 [12]. In 2009, Mallick et al. in [15] published a work in which they studied the heat-treated and experimented asphalt pavements for the collection of energy in order to reduce the heat island effect. Using a finite element model, they showed that, in a system with recessed pipes and placed about 40 mm below the pavement, the surface air temperature could be reduced by up to 10 °C. Furthermore, some laboratory tests showed that to increase the system efficiency can be painted the pavement with the black acrylic paint and/or replace limestone aggregates with aggregates containing quartz (increase in water temperature) by 50%, respectively, and 100%. Similar to the previous case, Wu et al. [16] experimented with the installation of road collectors embedded in a bituminous conglomerate and observed that the surface temperature of the pavement could be significantly reduced. Furthermore, in order to improve thermal conductivity and energy exchange efficiency, they also experimented with the use of graphite powders in asphalt pavements. The addition of graphite may slightly increase the leaving water temperature, but to increase the temperature, longer piping and a larger area are required.

Recently, the authors in [17] developed a solar collector made of ordinary and vanadium–titanium black ceramic. For ordinary ceramic, raw materials mainly refer to feldspar, quartz, and porcelain clay, etc. Black vanadium–titanium ceramic, on the other hand, was used as a solar absorbing coating material with a stable solar absorption value of 0.93–0.97. Three systems were developed in this study: a metal plate solar collector system, an all-ceramic solar system, and a glass vacuum tube solar collector system. Maximum thermal efficiency has been verified for the all-ceramic solar system. The all-ceramic solar system could find the right application in a roof of a building where the roofing must feature a structure made of concrete, a waterproof layer, and the insulating layer. Furthermore, the integral ceramic solar collectors being characterized by excellent thermal stability, long life, high thermal efficiency, and compatibility with building materials, can integrate well with buildings, to produce domestic hot water [17].

3. Pavement as Thermal Collector

The high absorption capacity of classic road pavement (temperatures up to 70 °C is reached [18]) has prompted the scientific community to investigate the possibility of using these surfaces as large star collectors. In fact, the absorbed solar energy can be used to heat a collector positioned below the road surface. The collected heat can be used for various applications, such as storage in an underground tank [19] or under the pavement structure [20], to heat adjacent buildings, to defrost streets in winter, to provide hot water [12], or to convert energy using a thermoelectric generator [21]. Furthermore, this type of system would respond simultaneously to two impact phenomena, such as the lively impact and the overheating effect. In fact, the installation of a collector under the road pavement on the one hand would avoid the occupation of large surfaces, not always available near the site of interest; on the other hand, it would guarantee a reduction of the urban heat island (UHI) effect [15,18].

3.1. Energy Balance

The balance equation of an asphalt solar collector takes into account the presence of asphalt and pipes, the air, and the fluid flowing in the pipes [22]. In general, the first heat exchange is in the pavement–atmosphere interface, where are simultaneously present the convection and thermal radiation. This heat flow causes a temperature difference between the asphalt surface and a point located in the pavement at a certain depth, transporting the heat by conduction from the pavement surface to the interior. Inside of the asphalt pavement, the heat transfer is represented by the conduction exchange between the pavement-pipe and the pipe wall. Then, due to the difference between the temperature of the inner surface of the tube and the fluid, the convection transmission causes the fluid temperature to rise.

According to Fourier's law, in an RTC, the heat transfer by conduction occurs from the pavement surface towards the interior; that is to say:

$$q_{cond} = -\lambda n \, \nabla Tn \tag{1}$$

where along the n direction, q_n (W/m^2) is the specific heat flux; λn is the thermal conductivity (W/mK), and ∇Tn is the temperature gradient (K/m). The phenomenon of heat transmission by convection occurs in two different conditions: between the surface of the flooring and the air above it and between the fluid circulating inside the collector and the walls of the collector itself [23]. The two equations are:

Convection heat flux at the pavement surface:

$$q_{conv,pav} = h_c \, (T_{air} - T_s) \tag{2}$$

where h_c is the average convection coefficient of the surface (W/m^2 K); T_{air} is the air temperature (K), and Ts is the surface temperature (K).

Convection heat flux inside the collector

$$q_{conv,col} = h \, (T_s - T_f) \tag{3}$$

where h is the average convection coefficient of the surface (W/m^2 K) and T_f is the fluid temperature (K).

To reduce heat losses, the best condition is represented by a natural convection between air and pavement, but, obviously, this condition depends on atmospheric conditions and wind speed.

On the other hand, to achieve the maximum heat transfer rate in the collector, the system must be designed for slow flow. There are several empirical models, published in the sector bibliography, for the calculation of the transfer coefficient (h_c) [24]. Table 1 shows the most used empirical equations to predict the temperature profiles in pavements.

Table 1. Empirical equations to determine the pavements temperature profiles' [25].

Equations	Model	Reference
$h_c = 698.24((0.00144(T_{ave})^{0.3})(v_w)^{0.7}) + 0.00097(T_0 - T_{air})^{0.3}$ $T_{ave} = (T_0 - T_{air})/2$	Vehrecamp	[26] [27]
$h_c = 5.6 + 4\,v_w$ For $v_w \leq 5$ m/s $h_c = 7.2 + v_w^{\,0.78}$ For $v_w > 5$ m/s	Jurges	[28] [29]
$h_c = (k \times Nu)/L_c$ $Nu = 0664 \times Re^{0.5} \times Pr^{0.33}$ $Re = (v_w \times L_c)/v$	Horizontal flat plate approach	[30] [31] [32]

3.2. Concreate and/or Asphalt Pavements

In the literature, there are Pavement Heat Collector (PHC) applications with asphalt pavements and concrete pavements. In general, concrete is made up of a mixture of aggregates (large and fine), water, and cement; a concrete floor is therefore composed of a base and/or a substrate with a cementitious concrete slab or pavement quality concrete (PQC) on top. Concrete flooring is a valid solution if it represents a durable, weather-resistant, robust, and economical surface [33]. As indicated in [34], in tropical countries, this type of pavement is often used in airport aprons, taxiways, and on the runways and pavements of busy highways. Asphalt, on the other hand, is made up of aggregates that are linked together by a binder (e.g., bitumen) and have a viscous behavior at high temperature and elastic behavior at low temperature. Due to this "viscoelastic" behavior, asphalt pavements are very susceptible to permanent deformations linked to high temperatures and/or longer loading times. However, in particular conditions, asphalt pavement can be an alternative to the concrete pavement; in [35] the PQC mix design parameters are collected. A typical asphalt pavement, on the other hand, consists of a compacted surface, in which there is a subgrade build, a, base and a surface layer directly in contact with traffic loads. In addition, the surface layer, besides ensuring the right friction, smoothness, noise control, and drainage, protects the underlying layers.

Compared to solar collectors embedded in concrete pavements—asphalt surfaces, despite having poorer conductive and thermal storage capacity (thanks to the high absorption coefficient), are able to capture more solar energy; an aspect that can be partially resolved in concrete pavements by painting the surface with dark paints in order to increase the absorption coefficient. Generally, there are surface absorption/emissivity values of 0.9/0.91 for asphalt and 0.65/0.91 for concrete. A disadvantage of using asphalt and not concrete is that is that the high temperatures of the mixture reached during installation can damage the piping system, especially for plastic piping. For this reason, metal pipes were previously used, mainly made of steel (43–54 W/mK), iron (80.4 W/mK) or copper (372 W/mK), however subject to corrosion [25]. In the literature, it is possible to find a comparison among four types of materials that are currently used for the piping in radiant heating systems or road collectors used for melting snow:

- PEX-AL radiant (0.43 W/mK). Pexal® is the system composed of a multilayer pipe made of cross-linked polyethylene (PE xb external layer) and butt-welded aluminum for water conduction (intermediate layer), and another entire layer in PE.
- PEX radiant (0.43 W/mK).
- ONIX radiant (0.29 W/mK). Onyx is a composite of nylon and short carbon fibers that gives 3D printed parts greater strength and a matte black finished surface. Compared to traditional nylon, this new material is approximately 3.5 times stronger, has greater hardness, and an HDT of 140 °C.
- Copper.

Obviously, the greatest temperature difference between the inlet and the outlet was obtained from the copper piping, followed by that of radiant PEX-AL [23]. In this case, a difference between the two systems of only 3 °C was measured, justifying the opportunity to use PEX-AL as a cheaper material [23]. An aspect of fundamental importance for the realization of an efficient system is the identification of an adequate depth of installation of the piping system; that is, one that is able to maximize the temperature increase of the heat transfer fluid, and at the same time does not compromise the integrity of the pipe itself and the surface of the pavement. In order to avoid negatively affecting the durability and the floor covering without damaging the drowned piping, it is necessary to consider as the laying depth the one in which the "reflective cracks" no longer occur under traffic load. From an analysis of existing commercial systems and literature studies, this depth generally varies from about 40 mm to about 120 mm. If, on the one hand, the installation of the piping network at a depth of less than 50 mm, i.e., very close to the surface layer, obviously guarantees the achievement of higher temperatures of the carrier fluid, on the other hand it presents structural problems related to surface cracks, due to stresses concentrated near the pipes, and technical problems for the remaking of the road surface.

To prevent cracking, a three-dimensional reinforcement grid has been developed in the Ooms Avenhorn Holding commercial system to secure and protect during the laying and compaction of the bituminous conglomerate and to reduce the stresses of the pipes. In addition, a special polymer-modified bitumen known as Sealoflex® [36], a polymer-modified bitumen (PMB), it was developed to improve the quality of the asphalt mix between the pipes and the grid; this mix strengthens the asphalt, doubling its durability over time even if subjected to intense use [23].

Currently, Ooms Avenhorn Holding states that resurfacing is a practical problem when the pipes have been installed to a depth of 40 mm. In order to guarantee an efficient PHC system with pipes installed at a safe distance, it will therefore be necessary to modify the asphalt mixture normally used in order to maximize the temperatures in the heat extraction layer. In particular, the laying of the pipe between a lower layer with high resistance and an upper layer with high thermal conductivity, can increase the transmission of heat by increasing the temperature of the pipes and the water at the outlet.

As an example, in [23], the subsoil temperatures are analyzed using three asphalt mixes and two installation depths of the polyethylene piping at 40 mm and 120 mm, in which the main aggregate of the mixture is limestone. In detail, the reference blend has the following specifications (Table 2):

Table 2. Principal parameters of some aggregates or elements of the road pavement.

Parameters	Recommended Values
Bitumen content	4.9 ± 0.4%
Type of bitumen	100/150
Air voids	4 ± 1.5%
Aggregate classification	Table 5.2 of [23]

An alternative solution is represented by the total replacement of the limestone aggregates with quartzite aggregates in the surface layer and the replacement of the limestone aggregates with a nominal size of less than 10 mm with Lytag for the layer under the pipe. The quartz and Lytag setup has been shown to achieve the same temperatures at a depth of 120 mm as those obtained from the unmodified reference pavement at a depth of 40 mm. The presence of a layer of flooring with high thermal conductivity above a depth of 120 mm, combined with a layer of flooring with high thermal resistance, considerably increases the temperature in the installation area of the pipes. In particular, it was verified that the temperature of the fluid in the pavement at 40 mm and 120 mm depth, compared to the reference pavement, increased by approximately 8 °C and 10 °C, respectively. In fact, in [23] the analysis of the temperature trend of the pavement surface shows that the reduction of the surface temperature of the flooring is greater in the case in which the pipe has been positioned at a depth of 40 mm compared to that laid at 120 mm. In general, it is evident that increasing the conductivity reduces the temperature of the asphalt surface regardless of the heat removed from the fluid; this effect must be taken into consideration for the reduction of the phenomenon of heat islands. However, the authors of the study [23] found a lower efficiency of the experimental system compared to the simulated model, due to the presence of an imperfect connection at the interface between the pipe and the asphalt. This problem could be solved by a possible layer of concrete in correspondence with the pipe. The concrete, due to its greater fluidity during positioning compared to asphalt, shows a good bond with the copper and polyethylene pipes and no signs were observed on the interface area. Therefore, it is probable that, due to its solar absorption capacity, a concrete pavement characterized by a low heat transfer at the pipe/pavement interface and by a higher conductivity, shows better performance than asphalt. Furthermore, the addition of highly absorbent colored surface coatings, a bituminous layer, or a dark additive (fly ash) could guarantee an increase in the solar absorption phenomenon by the pavements.

On the other hand, the construction of concrete solar collection surfaces would move away from the objective of the following work, namely that of exploiting existing low-cost surfaces. In fact, the asphalt surfaces are already present and since the road surface must be resurfaced periodically, the energy system can be installed very easily during a generic maintenance phase. From the point of view of energy production, significantly larger areas of asphalt collectors can compensate for their lower expected efficiency and improve their efficiency in terms of investment for the power produced per unit. Furthermore, asphalt surfaces can continue producing energy even during the night when the solar collectors are not working. Solar energy, captured by asphalt surfaces, can be used for different applications, e.g., in combination with accumulation systems (wells), for road safety and maintenance, keeping the roads free from snow during the winter period and reducing the cost of regular road surfacing; and, finally, the heat island effect can be improved by decreasing the temperatures of the asphalted surfaces.

Additives to Improve the Conductivity of Asphalt Mixes

An improvement of the energy properties of an asphalt RTC is certainly obtained by the correct addition of the solar system. It has been shown that in addition to quartz, which has optimal properties, it is possible to use other aggregates and or additives to improve the thermal conductivity of the asphalt. In [37], the thermal properties of asphalt mixtures with additives with graphite and carbon black (a pigment, produced by the incomplete combustion of heavy petroleum products). Thermal testing indicated that graphite and carbon black improve the thermal properties of asphalt mixes and that combined conductive fillers are more effective than single fillers. Four graphite and carbon black contents of 5, 10, 15, and 20% by volume of the asphalt binder were used to produce the asphalt mix. For all mixes in the study, PG 64–22 asphalt binder was used. Graphite and carbon black are added to replace the traditional aggregate (dimensions of the sieve through 0.075 mm). From the results it is clear as the thermal conductivity increases if increases the content of graphite or carbon black. The mixing was carried out, both dry and wet, showing that a slightly increased thermal conductivity is achieved by the wet process compared to the dry process.

Graphite apparently appears to be better than carbon black from a thermal conductivity point of view, but it has been noted that using a conductive filler mixed with carbon fibers is more beneficial than using a single conductive filler. However, the rheological properties of the modified asphalt binders have indicated that both graphite and carbon black can increase tear resistance on the one hand, and on the other reduce their resistance to thermal cracking. In fact, the two substances at high temperatures increase the shear parameter, but reduce the resistance to cracks at low temperatures.

From study [38], it is evident that the variation in the conductivity of the bituminous conglomerate can be influenced by the content of the binder and the air gap, remaining in any case unchanged for air gap dimensions between 0.5 and 2 mm in diameter. Instead, the addition of graphite with different percentages, from 10 to 40% by the mass of binder, shows an increasing trend in the value of thermal conductivity, almost tripling the value from 0.39 to 0.95 W/mK.

The bibliography illustrates how many and varied experiments and analyses have been in the field for the evaluation of the best configuration to be used to maximize the efficiency of an RTC system. In summary, the analysis of [37–44] made it possible to state that:

- The addition of graphite to asphalt binders causes an increase in the thermal conductivity of the bituminous concrete, resulting in an increase of 24%.
- An increase in thermal conductivity of about 50% of dense bituminous concrete (4% air gap and 6% bitumen) is guaranteed when mixing aggregates, such as diabase and quartzite. This increase is attributed to the thermal conductivity of quartzite, which is approximately twice that of diabase.
- Asphalt mix with high void content has lower thermal conductivity and a lower specific heat capacity than with low void content, because the air has a lower thermal conductivity than the asphalt mix. The conductivity values of bituminous concrete decrease by 3% as the vacuum content increases by 1%.
- A dense asphalt mix is characterized by an high heat conductivity and specific heat capacity, and has a lower heating and cooling rates than porous asphalt mix.
- It has been shown that thermal conductivity is also influenced by the degree of humidity and frost; in particular, in conditions of humidity saturation and freezing, they respectively have a thermal conductivity of 5% and 7% higher than that of its dry state. In general, the thermal conductivity of saturated asphalt concrete is higher than that in the dry state, while the thermal conductivity in the freezing state is higher than in conditions saturated with moisture.
- The higher the volute content of an asphalted surface, the higher the operating temperature. The average temperature of the asphalt mixture during heating and cooling is almost independent of the air gap content in the mixture.
- The total amount of energy accumulated in asphalt mixes with different content of air voids, but made from the same materials, during heating and cooling depends only on the density of the mixes.

3.3. Pavement Types and Characteristics

In general, from a technological point of view, asphalt pavement from the road surface to the inner layers is structured as follows:

1. Surfacing: (a thin asphalt surface and a binder course): it is divided into surface and binder layers; it is the layer in contact with traffic loads and protects the lower layers from bad weather;
2. Base (asphalt/unbound granular material) represents the main structural layer that provides most of the strength and load distribution properties of the flooring;
3. Sub-base (unbound granular material/Bitumen or cement stabilized material): located between the base and the sub-base serves as structural support, particularly when building upper layers;
4. Subgrade: in situ compacted material/cement stabilized/ unbound granular material; usually natural ground or artificial ground;
5. The asphalt, present in the first layers of the pavement, is generally made up of aggregates that are bonded together by means of a binder (bitumen);

From a thermo-physical point of view, the typical values of the thermal properties of asphalt surfaces are [25]:

- Thermal conductivity between 0.74 and 2.89 W/mK;
- Specific heat between 800 and 1853 J/kgK;
- Thermal diffusivity between 1.2 and 16.8 10^{-7} m^2 s.

While, as regards the mixture of bituminous materials, it is possible to distinguish mainly two types:

- Hot asphalt (hot macadam asphalt: HMA);
- Cold asphalt.

HMA is a blend in which all materials are mixed at a high temperature; there is the asphalt concrete (AC) (known as Dense Bitumen Macadam (DBM)) and hot rolled asphalt (HRA). As it is known, the mixing method affects the thermal performance of the flooring itself. In Table 3, there are some specifications of the aggregates normally used.

Table 3. Thermal conductivity of most used aggregates of the road pavement.

Aggregates	Thermal Conductivity [W/mK]
Quartzite	5.5–7.5
Granite	3.0–4.0
Limestone	1.5–3.0
Basalt	1.3–2.3
Bitumen	0.15–0.17
Cement	0.29
Waterfall	0.6
Air	0.024

4. Case Study

To evaluate the feasibility of an RTC system integrated with a geothermal storage system installed in the Mediterranean area, to accumulate thermal energy in the summer for winter air conditioning—at the University of Palermo campus, a theoretical-experimental study was launched, which involved the installation of a small-scale RTC prototype, in which to investigate some alternative scenarios and a large-scale prototype that will see the installation of an RTC system directly connected to a geothermal field. In particular, the entire development of the work involved:

Phase 1: identifying some possible solutions for laying an RTC system by varying the stratigraphy and the solar reflectance;

Phase 2: designing an experimental set-up for small-scale laboratory testing;

Phase 3: implementing the experimental set-up in the small-scale laboratory;

Phase 4: designing an experimental set-up for large-scale field verification;

Phase 5: developing a dynamic model of the RTC system in TRNSYS (Transient Systems Simulation Program) environment [45];

Phase 6: implementing an experimental set-up in the field on a large scale;

Phase 7: validating the model with data monitored in the field;

Phase 8: identifying the best RTC system solution to maximize performance in the field coupled to a BTES (Borehole Thermal Energy Storage).

The research carried out so far has allowed us to develop the project from Phase 1 to Phase 5. In this work, after a careful bibliographic analysis, the authors illustrate the main results obtained so far, while in the paragraph "Future Objectives" briefly explain the continuation of the work whose results will be published in a second work.

4.1. Identification of Some Possible Stratigraphy (Phase 1)

Based on what has been analyzed above, it is obvious how the activation of the surface layers, or in which the pipes are installed, leads to an increase in the performance of the RTC system. The activation of these surfaces, on the other hand, leads to a significant increase in costs and to greater attention in the installation and management phase of the RTC system. To identify the best solution that in energy, environmental, and economic terms is the most effective and sustainable, the first analyses were based on the performance of the RTC, in which the surface layer is formed of asphalt or concrete, and the geometric configuration of the drowned pipe is made to vary. In detail, the first analyses included the following three configurations:

First configuration

Hydraulic configuration: serpentine piping with a pitch of 12.5 cm.
Stratigraphy:

- Layer 1 mat, made of asphalt about 4 cm;
- Layer 2 binder in bituminous conglomerate of about 7 cm;
- Layer 3 reinforced concrete screed of about 7 cm;
- Layer 4 of 20 cm cement mix;
- Layer 5 of the drainage system of about 25 cm, made in such a way as to convey the water collected during the rain in the central and lower part of the caisson;
- Layer 6 of 10 cm insulation.

Second configuration

Hydraulic configuration: parallel piping with 12.5 cm pitch.
Stratigraphy:

- Layer 1 mat, made of asphalt about 4 cm;
- Layer 2 binder in bituminous conglomerate of about 7 cm;
- Layer 3 reinforced concrete screed of about 7 cm;
- Layer 4 of 20 cm cement mix;
- Layer 5 of the drainage system of about 25 cm, made in such a way as to convey the water collected during the rain in the central and lower part of the caisson;
- Layer 6 of insulation of 10 cm.

Third configuration

Hydraulic configuration: parallel piping with 12.5 cm pitch.
Stratigraphy:

- Layer 1 reinforced concrete screed of about 18 cm;
- Layer 2 of 20 cm cement mix;
- Layer 3 of the drainage system of about 25 cm, made in such a way as to convey the water collected during the rain in the central and lower part of the caisson;
- Layer 4 of 10 cm insulation.

Table 4 shows the main thermophysical characteristics of the project and the thicknesses of the RTC system to be built in the experimental area within the UNIPA (University of Palermo) campus.

Table 4. Thermophysical characteristics of the RTC system.

Layer	λ [W/mK]	c_p [J/kgK]	ρ [kg/m^3]	ε	α	s [m]
Asphalt	0.85	850	2400	0.9	0.9	0.11
Binder						
Reinforced concreate	1.4	840	2100			0.07
Cement mix	1.2	840	1700			0.2
Drainage	0.4		1500			0.25
Eps	0.034	1130	30			0.2

In all three configurations, the piping will be installed in the middle of the third layer.

The radiative properties of the external layers are crucial to collect the impinging solar irradiation: the lower the solar reflectance (either the higher the solar absorptance), the higher the solar gains. Conventional materials exhibit favorable properties, the solar reflectance of the new asphalt is about 5%, increasing to 15% after ageing; concrete is about 25%. Materials with high solar absorptance and very low water permeability, equally, create favorable conditions for Urban Heat Island (UHI), taking into account that urban pavements account for 29–45% of the city footprint [18]. The UHI mitigation thus calls for the application of high reflective urban materials, for pavements as well [46]. With the objective of balancing these two opposite design requirements, some solutions were developed and optically characterized.

Spectral reflectance measurements were carried out, three 21 × 21 cm samples, colored in black, brown, and dark brown. The measurements were conducted using a Perkin Elmer Lambda 950 dual-beam spectrophotometer, equipped with a 6-inch Spectralon coated sphere. The measurement was of relative type and it was performed against a calibrated Spectralon reference; the measurement uncertainty was 1%. Spectral measurements and the calculation of the broadband parameters solar (sol), visible (vis), and near infrared (nir) ranges were carried out in accordance with the relevant standard [47]. Given the texture of the material and the geometry of the incident beam (about 15 × 5 mm), three measurements were made on each sample to evaluate the repeatability of the measurement. Since the difference between each single measurement and the average of the three was always less than 1%, the latter was assumed sufficiently accurate. The reflectance values in the relevant spectral regions, referring to the 0–100% range, are presented in Table 5. The emissivity was also measured using a broadband emissometer in the 2.5–40 micron range. Measurements were carried out at 80 °C; the three samples scored the same emissivity value: 0.88.

Table 5. Experimental reflectance measurements of road surfaces.

Reflectance (%)	Black	Brown	Dark Brown
Sol	7	11	10
NIR	10	17	16
Vis	4	6	6

The proposed solutions fall within the conventional (5–15%). In general, the samples have higher reflectance in the near infrared than in the visible: 6% for black and 10–11% for browns, thus exhibiting a modest band selectivity. In this sense, the tested materials are of potential interest for road solar collectors because of the high solar absorptance but do not exhibit suitable performances for UHI mitigation purposes. For these applications, however, the solar reflectance (absorptance) might not be the only parameter shaping the thermal performance of the finishing layer. As explained above, the whole covering package of the system should create favorable conditions to transfer the absorbed heat to the buried pipes with consequent reduction of the surface temperature. The complexity of the system, thus, calls for accurate identification of the solar properties of the external layer able to optimize the solar collector performances as well as the mitigation of the urban overheating.

4.2. Design of an Experimental Set-Up for Small-Scale (Phase 2)

The research work soon led to the development and realization of a prototype set-up for the measurement of temperatures in three different configurations. The experimental set-up involves the measurement of physical quantities within a wooden tank structure, hereinafter referred to as a box. The experimental set-up includes, in addition to the box, to be built according to the following diagrams and descriptions, a hydraulic and measuring system. In order to be able to experiment at the same time with different configurations and different boundary conditions, it was decided to design a system capable of containing three different stratigraphy (Figure 1).

The system provides for the construction of the box with the presence of internal insulating partitions, in each of which a previously waterproofed layer of insulation will be inserted. The waterproofing, which will be carried out by bagging the insulation in polyethylene sheets, must also be guaranteed in the contact surfaces between the wooden panel and the material present in the three configurations.

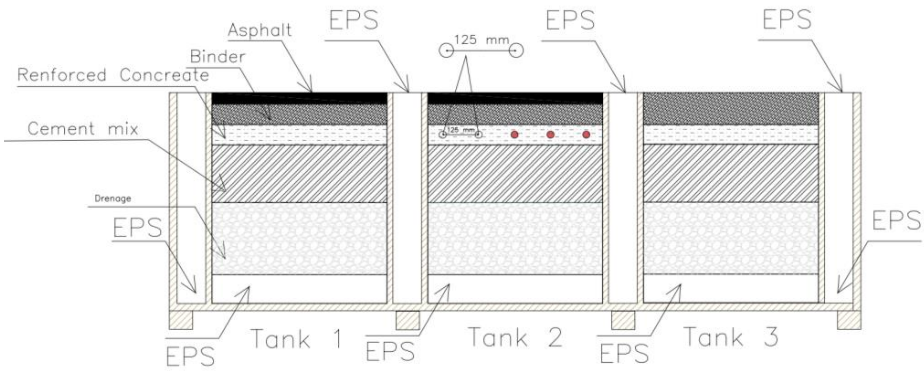

Figure 1. Experimental set-up schema configuration.

In each tank, the installation of the three configurations previously foreseen were analyzed. Figure 2 shows the three stratigraphy, i.e., tank 1 refers to the first configuration; tank 2 refers to the second, and the last tank to the third configuration.

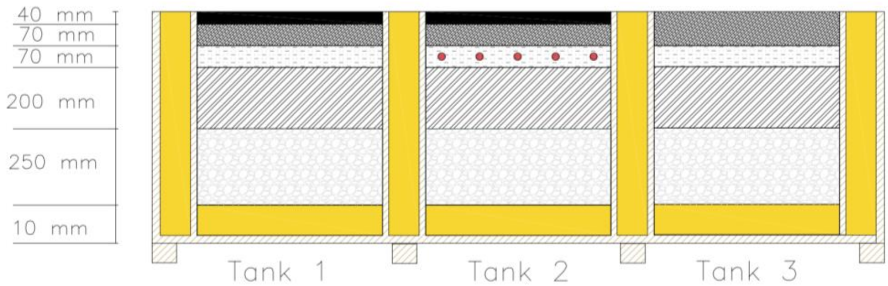

Figure 2. Experimental set-up schema geometrical configuration.

For the project to be successful and since the system will be exposed to atmospheric agents, the following specifications are expected:

- Wooden panels for the construction of formwork for reinforced concrete framed structures, Resistant to water and bad weather according to the En 13353 standard (SWP/2). In particular, a 27 mm thick wooden panel is foreseen for the external and bottom surfaces and 21 mm thick for the internal separating baffles.
- The panels were treated with a suitable resin-based paint or similar to give lasting resistance to atmospheric agents, according to the En 13353 (SWP/2) standard.
- The box is not in direct contact with the floor, but is placed on a wooden support base for outdoor use.
- The insulating panels (sections in yellow) are rigid PIR type (polyiso polyurethane foam), i.e., rigid high density insulated material with conductivity between 0.02 and 0.03 W/mK
- The use of a vapor barrier polyethylene sheets) for waterproofing the contact layer between wooden panels and the insulation layer
- At the base of each tank, there is a light draining layer of 25 cm. Furthermore, to ensure water drainage from this Section, it was necessary to prepare a through-hole (as per drawing), in each centerline of the three tanks, in which to house a rigid PVC drainage pipe included in the supply.
- The installation of the exhaust pipe guarantees the seal with the vapor barrier.

Geometry was designed for the body; the gross body dimensions are as follows:

- Length: 2.445 m;
- Width: 1.796 m;
- Height: 0.627 m;
- Total area: 4.41 m^2;
- Total volume: 2.76 m^3.

The hydraulic system that is being built will follow the following system scheme (Figure 3).

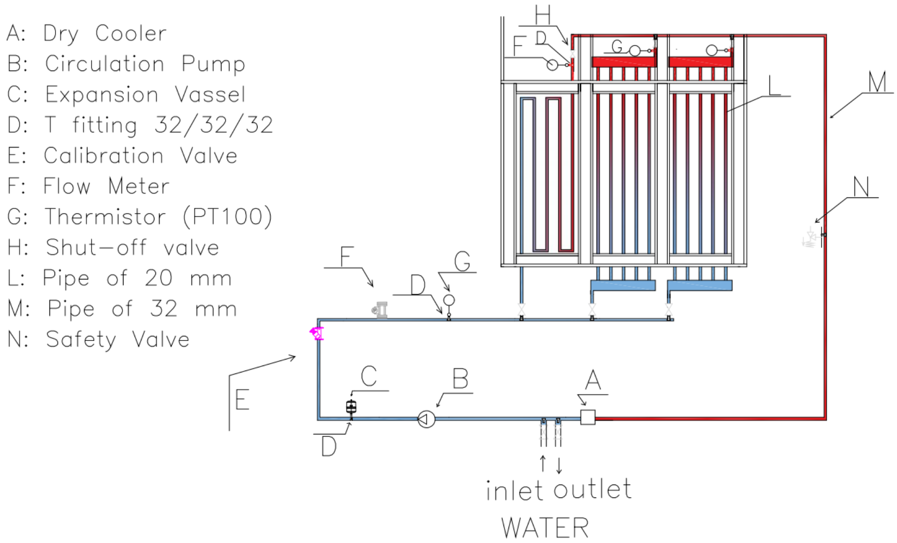

Figure 3. Hydraulic schema.

As indicated in the picture, there is also a measurement system with temperature sensors on the cold side and hot side of the system and flow meter, which will be installed during the implementation of the experimental set-up. Furthermore, the climatic data in the field at the same time will be monitored.

4.3. Experimental Set-Up in the Small-Scale Laboratory (Phase 3)

In order to validate the results and to be able to hypothesize the best design solution that maximizes the efficiency of the RTC system installed in Palermo, it is necessary to carry out an experimental campaign. For this reason, at the same time as the theoretical study and after the design, a small-scale experimental prototype installed at the University of Palermo campus is being installed. The test bench faithfully follows the previously designed schemes and stratigraphy. Below are the photos of some phases of the installation to date (Figures 4 and 5).

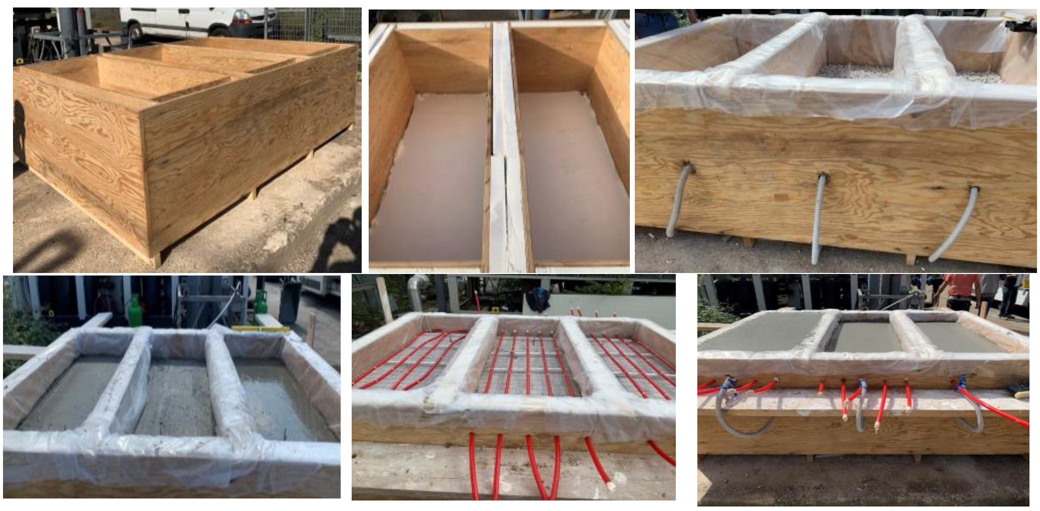

Figure 4. Some phases of the installation of the RTC Box.

In particular, the insulation layer, the drainage layer, and the first layer of lean concrete were put in place. Two constantan copper thermocouples were embedded in the latter for each single tank. In fact, the entire system will be monitored along with all the layers up to the surface where it will be laid the road mat. At the same time, the air temperature, wind speed, direction, and horizontal global solar irradiation will be collected.

Figure 5. Some phases of the installation of the RTC Box.

The prototype will be the experimental base in which to experiment in the field and on a small scale all the alternative solutions previously hypothesized and others that will be considered appropriate, in this way, it will be identified as the best solution to be implemented in the Mediterranean area. In detail, the small-scale prototype was born from the idea of being able to experiment on a reduced model with different geometric configurations, materials and alternations of stratigraphy's that can represent an alternative and improved solution to the model envisaged on a large scale. In detail, the research group decided to develop a dynamic model that is calibrated with the data monitored in the field. A dynamic model, created with the TRNSYS software (Thermal Energy System Specialists, LLC, Madison, USA) with data in the field will then be validated, guaranteeing the reliability of the results. In this way, the effects of the application of alternative solutions, configurations, and/or materials to the basic configuration will be predicted numerically, also allowing a parametric analysis for the identification of the best solution. In order to assess whether a solution, configuration, and/or choice of alternative material packages highly reliable in the field, a small-scale field trial is necessary. This set-up, thanks to its small size, will allow one to experiment with various solutions, to select those that make the system more efficient, reducing time and, above all, costs. For example, the step of adding a small area of road pavement, which may not lead to expected results, does not impact economically as that of adding the entire experimental area. Figure 6 presents some stages of laying of the RTC system at the UNIPA experimental area; this phase is being completed.

Figure 6. Experimental area in the UNIPA Campus.

4.4. Design of an Experimental Set-Up for 1:1-Scale (Phase 4)

The study of the RTC system, the object of the research in the Mediterranean area, has, as its final aim, the subsequent integration with a BTES system to create a seasonal thermal energy storage system. In this case, the RTC plant system will in fact be aimed at collecting thermal energy from the solar source through the piping system embedded in the ground, to be directly connected to a geothermal storage system. In fact, the project involves the installation of the entire RTC + BTES system in an experimental area within the university campus of Palermo. The area, identified for the realization of the large-scale experimental set-up, is represented in the following Figure 6.

For the large-scale set-up, on the basis of what has been indicated above, and of the available area, 15 pipes 20 m long connected in parallel, with 25 cm spacings, intercepted by two collectors (intake manifold and delivery manifold). The piping supplied is of the PE-Xa type Rehau Rautherm S type characterized by an external diameter of 32 mm and a thickness of 2.9 mm (Figure 7).

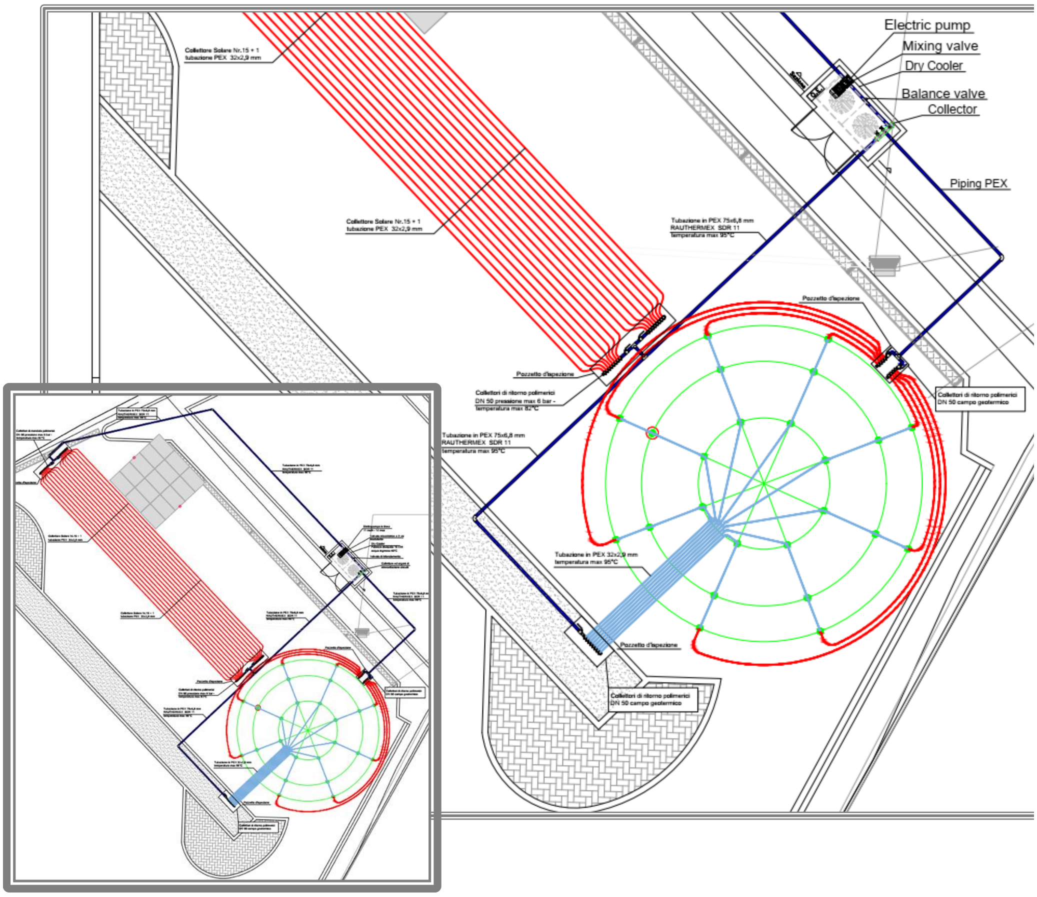

Figure 7. RTC + BTES schema of the experimental set-up.

The entire collection system is buried at a depth of about 14 cm (axis of the pipeline). For the correct sizing of the system, pure water was considered as working fluid (Table 6) and a turbulent motion with Re equal to 10,000 was imposed.

Table 6. Specific characteristics of the thermal fluid (Water).

Thermal Fluid		Unit
ρ	1000	kg/m^3
c_p	4189.99	J/kgK
μ	0.00089	kg/ms
λ	0.5944	W/mK

The chosen pipe has a diameter of 0.0291 m, or an area of 6.65×10^{-4} m^2; based on these data and the hypothesis of turbulent motion, the value of the estimated optimal flow rate is equal to

$$m = Re \cdot \mu \cdot (A/d) = 0.204\ (kg/s) \quad (4)$$

which corresponds to a volumetric flow rate of

$$V = m/1000 = 0.000204\ (m3/s) \quad (5)$$

and with a speed of

$$v = V/A = 0.307\ (m/s) \quad (6)$$

Assuming an RTC area of 80 m^2, i.e., 4 m wide and 20 m long, it is possible to place 15 pipes with 0.25 m pitch, for a total mass flow rate of 3.058 kg/s, or approximately 11,008.84 kg/h. The piping system must be positioned and anchored to the depth, as planned, by means of a 6/8 mm electro-welded metal mesh, which will be previously placed on top of the mixed cement layer. Downstream of the RTC system, a temperature probe (PT100 type), an automatic vent valve, and a safety valve are installed on the delivery pipe to the BTES system. The BTES plant system is aimed at storing thermal energy from a solar energy source through a system of 24 "U" probes. It will consist of eight head probes connected in parallel (one per circular sector) and three probes arranged in series in each branch of the circuit. Each probe is characterized by a length of 15 m each (30 m of pipe) and a starting depth of 0.58 m. Each pipe is characterized by an external diameter of 28 mm corresponding to an internal diameter of 26.2 mm. The entire BTES storage system is intercepted by two collectors, as shown in Figure 8. The stratigraphy of the ground above the BTES system is shown below in Table 7.

Table 7. Thermophysical properties of the stratigraphy to be carried out in the experimental area above the BTEES.

	λ (W/mK)	c_p (J/kgK)	ρ (kg/$m^{3]}$)	ε	α	s (m)
Wear mat	0.85	850	2400	0.9	0.9	0.11
Binder	0.85	850	2400			0.11
Mixed cement	1.2	840	1700			0.2
EPS	0.034	1130	30			0.2
Ground	0.85	800	1890			20

The total mass flow will be sent to eight geothermal probes, corresponding to a head mass flow of 0.328 kg/s per probe. For a hypothesized pipe with a diameter of 0.026^2 m, or with an area of 5.39×10^{-4} m^2, we obtain a Reynolds number equal to 20,825.3. The piping that connects the manifolds of the two systems is characterized by an external diameter of 40 mm corresponding to an internal diameter of 36.3 mm in multilayer coated with a suitable layer of insulation. In this Section, the operating conditions are characterized by a total mass flow rate of 3058 kg/s, a speed of 2955 m/s and a Re number equal to 120,247.93.

The following components will be installed on the return pipe from the BTESS to the RTC:

1. Dry cooler;
2. Circulation pump;
3. Expansion vessel;
4. PT100 temperature meter;
5. Flow rate adjustment valve;
6. Flowmeter;
7. Two ball valves with cock for filling and discharging the hydraulic circuit;
8. Shut-off valves.

The final circuit also includes a By-pass branch of the BTESS system. Below, in Figure 8, a detail of the RTC + BTES system.

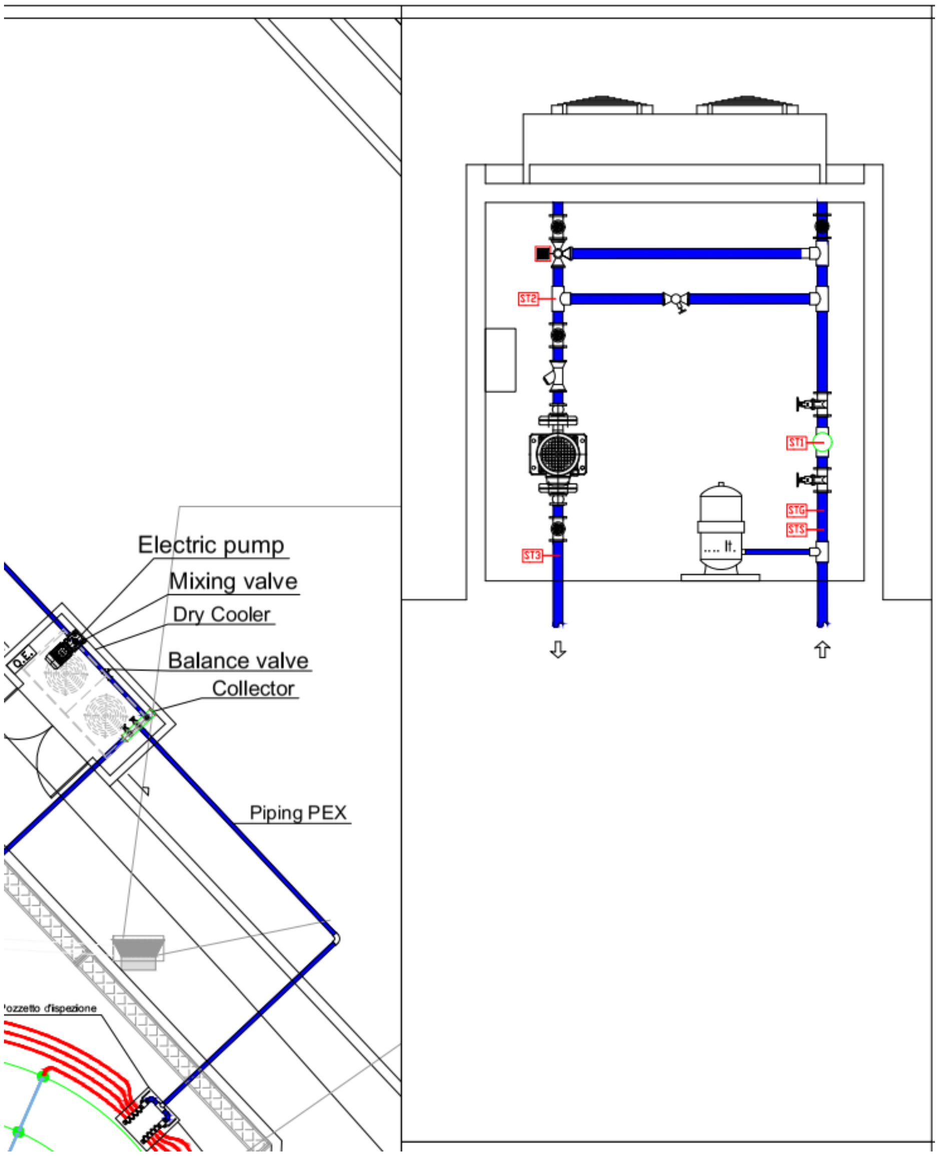

Figure 8. A detail of RTC + BTES of the experimental set-up.

4.5. Development of a Dynamic Model of the RTC System (Phase 5)

In order to evaluate the operation and management of the thermal loads of the RTC system, a model was created with TRNSYS software [47]. Figure 9 shows the scheme of the model built and implemented on the TRNSYS dynamic simulation platform.

In this first phase, the 1:1 scale model of the RTC system was created with the thermophysical characteristics of the stratigraphy indicated in Section 4.4, taking into account the stratigraphy considered in Table 7 and all the geometric and thermophysical parameters, the boundary conditions, and the management system envisaged for the 1:1 model, faithfully respecting the provisions of the experimental area.

Obviously, this model will be calibrated with the data that will be monitored in the field. Furthermore, thanks to the experimental set-up on a small scale, alternative and improvement solutions of the entire RTC system can be evaluated and then proposed in the large-scale system.

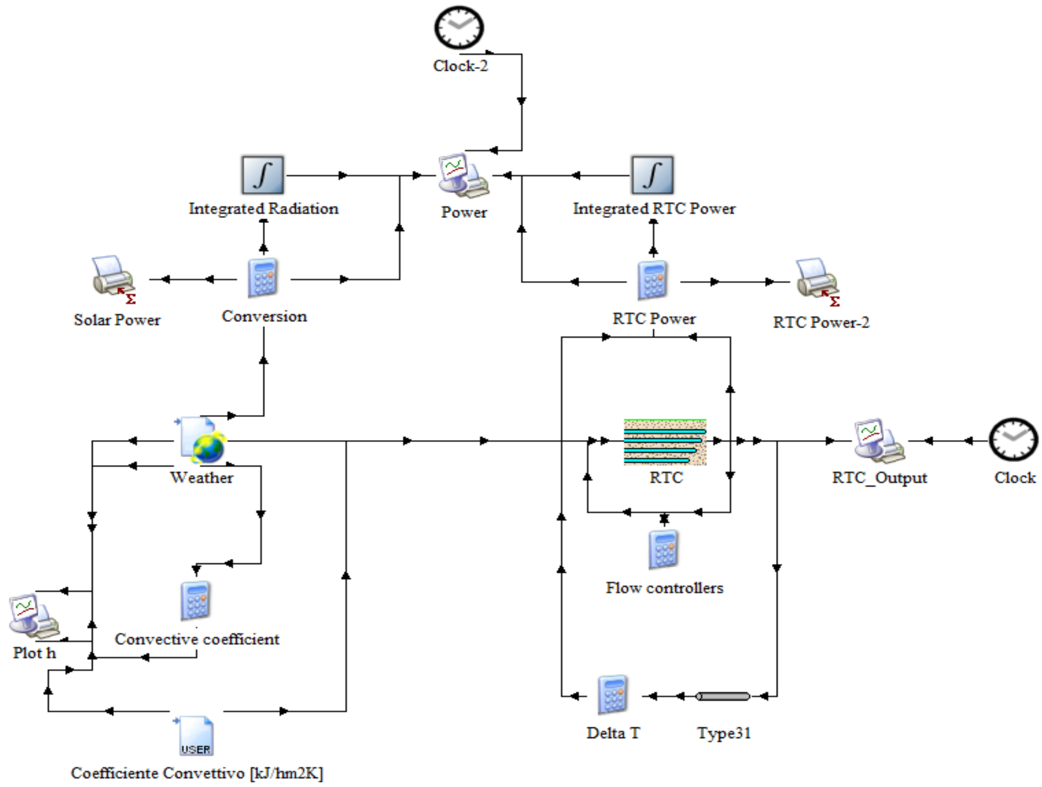

Figure 9. TRNSYS model schema.

The results of the first simulations, from April to October, are illustrated below (Figure 10); in more detail, the first graph shows the trend of temperatures inside the soil in ordinary conditions, i.e., in the absence of an RTC that removes heat.

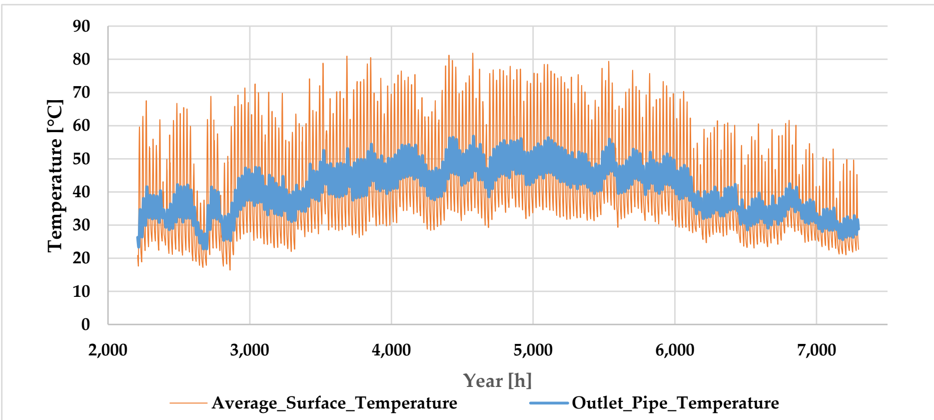

Figure 10. Temperature trend of the surface pavement and at the depth where the pipeline is located without the RTC system.

Table 8 shows the data related to the surface temperature and into the soil at the depth where the pipeline is located, indicating the maximum, minimum, and average values.

Table 8. Temperature value in the surface of the pavement and in the soil.

Temperature	Pipe Depth (°C)	Surface (°C)
Max	56.86	81.88
Average	40.91	42.54
Min	22.79	16.41

In order to respect the evaluations previously carried out in Section 4.4, the temperature trend was evaluated for Re = 10,000 (Figure 11). In this case, the RTC system influences the trend temperature, decreasing the values.

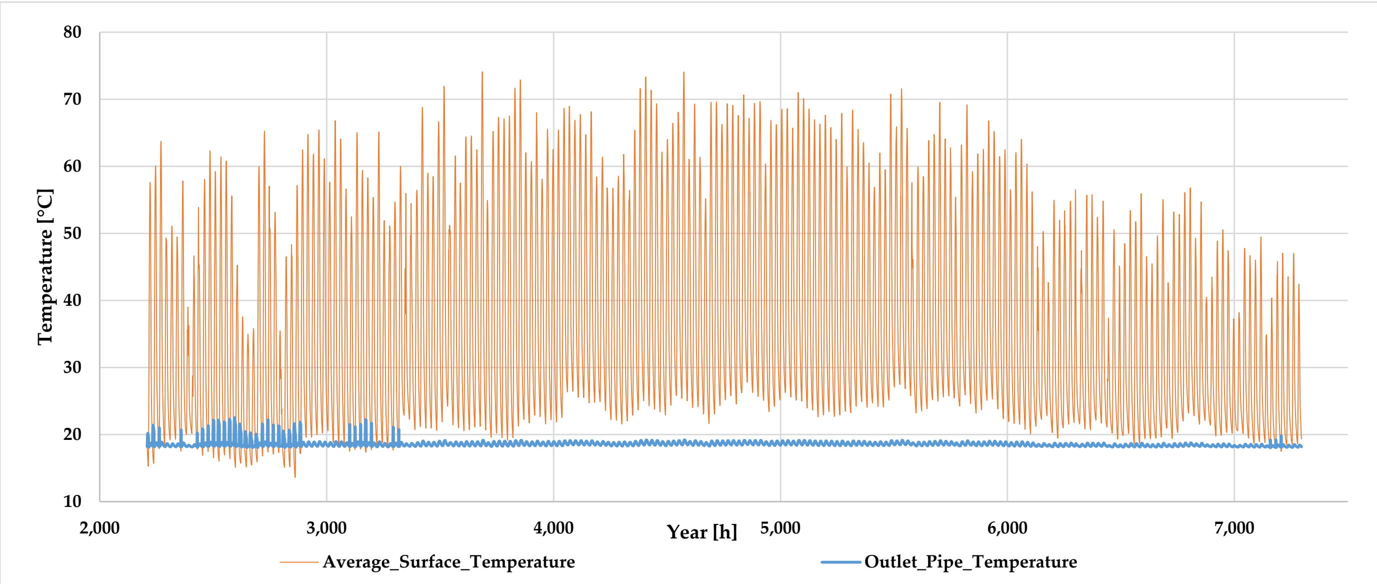

Figure 11. Temperature trend of the surface pavement and the pipeline for the RTC system with Re = 10,000.

The maximum, minimum, and average values of the water temperature at the outlet of the pipe are indicated in the Table 9.

Table 9. Temperature value in the surface of the pavement and in pipeline with Re = 10,000.

Temperature	Pipe (°C)	Surface (°C)
Max	22.53	74.08
Average	18.63	13.64
Min	18.06	36.18

The comparison between the solar and RTC power trend is illustrated in Figure 12.

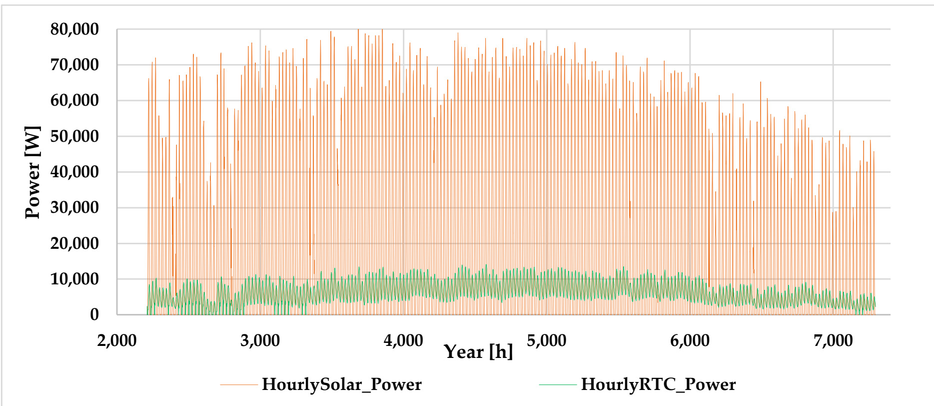

Figure 12. Solar and RTC power trend for the RTC system with Re = 10,000.

Generally, a maximum power of 14.3 kW and an average power of 6.17 kW have been evaluated, compared to an incident solar energy of 105,096 kWh, 31,529 kWh have been removed from the RTC system, for an overall efficiency of 30%.

This evaluation was carried out considering an inlet temperature to the system of 18 °C and setting a double control system that stops the circulation pump when:

- The temperature gradient between the surface and the ground, at the pipe laying depth, is less than and/or equal to zero.
- The temperature of the pipes is lower than the water inlet temperature, which is 18 °C.

In the first case (Figure 10), the trend of temperatures inside the soil in ordinary conditions is show, i.e., in the absence of an RTC that removes heat, while Figure 11 describes the trend temperature of the RTC system in ordinary conditions (Section 4.4). The comparison underlines as the RTC system reduces the temperature of the surface of about 10 °C; on the contrary, the RTC system deeply influenced the temperate in the soil, reducing all values even more than half.

This model will subsequently be calibrated with the data monitored in the field and then hypothesize alternative solutions to those identified in the first phase. In this way, it will be possible to choose the solution that will allow optimizing the system and identifying the best configuration. At the same time, this solution will be integrated with the contemporary study that will be carried out on the BTES system.

4.6. Future Objectives (From Phase 6 to Phase 8)

The possibility of being able to install a 1:1 scale system of an RTC system directly connected to a BTES at the Palermo campus, will allow to investigate this technology and evaluate its performance in the field.

The simultaneous field experimentation in a small-scale system will allow identifying the best geometric, technical, and thermophysical choices that can improve the efficiency and effectiveness of the system and, therefore, identify the best solution to be applied in the system on a real scale.

In this way, it will be possible to investigate the use of an RTC for the construction of a low temperature geothermal field, in order to explore the potential for seasonal heat storage and subsequent use in heat pump systems or for pre-heating of the water. The integration between a useful energy source and a storage medium is the real challenge of this research, especially in a highly sunny area in the summer, such as southern Italy; that is, the identification of the best solutions to be adopted to maximize the efficiency of the system in the Mediterranean area, and the identification of the best practices for the development of a renewable system that is competitive with today's market.

5. Conclusions

The collection of solar energy is commonly committed to solar collectors installed on roofs or the ground. An alternative solution is instead represented by the installation of solar collectors embedded in paved surfaces, such as asphalt surfaces, sidewalks, roads, and parking lots (road thermal collector). Solar energy, captured by asphalt surfaces, can be used for different applications, e.g., in combination with accumulation systems (wells), for road safety and maintenance, keeping the roads free from snow during the winter period and reducing the cost of regular road surfacing. Furthermore, the heat island effect can be improved by decreasing the temperatures of the asphalt surfaces. The present research proposes investigating the use of an RTC for the construction of a low-temperature geothermal field, in order to explore the potential for seasonal heat storage and subsequent use in heat pump systems or pre-heating of the water. This system makes it possible to exploit the absorption capacity of the road surface in areas characterized by high sunshine, energetically redeveloping areas that are generally dedicated to something else (roads and parking lots).

The study, design, and validation of a RTC with seasonal geothermal storage could guarantee the development of an alternative, sustainable, and low global impact renewable energy system. Preliminary results deduced from numerical analysis, carried out using a model developed in TRNSYS, show that an RTC (with a capturing surface of about 80 m^2) can produce thermal energy from the sun, with an annual average global efficiency of about 30%. On average, in correspondence of a total water flow rate of about 3.06 kg/s distributed over 15 exchanger pipes, having a length of 20 m and spaced 25 cm, it is possible to reach a water temperature rise of about 2 °C. Moreover, the same numerical results show that, with an inlet water temperature of 18 °C, it is possible to reduce the average pavement surface temperature from 42 °C down to 14 °C during the operation period of the RTC (from April to October).

The entire study, which refers to the SMARTEP project, involves the design and construction of an experimental area within the University of Palermo (Italy), unique in the whole panorama of the Mediterranean area.

Author Contributions: Conceptualization: A.D., G.C., A.B. and M.B.; methodology: A.D., G.C., D.P.; software development: A.D.; validation: A.D. and D.P.; formal analysis: A.D. and A.B.; investigation: A.D. and M.Z.; writing: G.C. and A.B.; supervision: M.B. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

A	area [m^2]
c_p	specific heat [J/kgK]
d	diameter [m]
h	average convection coefficient of the surface [W/m^2 K];
n	direction of vector
q	specific heat flux [W/m^2]
$q_{conv,coll}$	Convection heat flux inside the collector [W/m^2]
$q_{conv,pav}$	Convection heat flux at the pavement surface [W/m^2]
m	flow rate [kg/s]
Nu	Nusselt Number
Re	Reynolts Number
s	Thickness [m]
T_{air}	air temperature (K)
T_f	fluid temperature (K)
Ts	surface temperature (K)
v	fluid speed [m/s]
V	volumetric flow rate [m^3/s]
α	Absorption coefficient
ε	Coefficient of emissivity
λ	Thermal conductivity [W/mK]
μ	Dynamic viscosity [kg/(m s)]
ρ	Density [kg/m^3]

Acronyms

AC	Asphalt Concrete
BTES	Borehole thermal energy storage
DBM	Dense Bitumen Macadam
HMA	Hot Madacam Asphalt
HRA	Hot Rolled Asphalt
PCM	Phase Change Materials
PHC	Pavement Heat Collector
PQC	Pavement Quality Concrete
RES	Road Energy Systems
RTC	Road Thermal Collector
SMARTEP	Sustainable model and thinking of renewable energy parking
UHI	Urban Heat Island
UNIPA	University of Palermo Campus

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