Application of Solar Panels to Roads: A Conductive Asphalt Solar Collector Approach to Winter Snow-Melting and Pavement Energy Harvesting

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Abstract

The accumulation of snow and ice on roadways constitutes a persistent and costly threat to traffic safety during winter months, particularly on critical infrastructure such as bridges, ramps, and airport runways. This paper investigates the use of asphalt pavement as a solar collector — a conductive asphalt solar collector (CASC) — capable of both harvesting solar thermal energy during warmer periods and actively melting snow and ice during winter through embedded hydronic piping. Using a combination of numerical simulation (finite element method) and physical experimentation with an instrumented asphalt slab, this study examines how pipe depth, pipe spacing, and the thermal conductivity of the asphalt mixture influence snow-melting performance. The simulation results indicate that embedding pipes at a depth of 4–10 cm, with a spacing of 0.18–0.4 m, offers the most efficient balance between melting speed, installation feasibility, and cost. Experimental validation using low-temperature circulating water (approximately 25°C) confirmed that snow melting proceeds through three distinguishable phases — an initiation period, a linear melting period, and an accelerated period — and that increasing the thermal conductivity of the asphalt concrete from 1.531 to 2.309 W/m·°C reduced total melting time by approximately 30%. These findings support the technical feasibility of solar-heated roads as a sustainable, energy-efficient alternative to conventional deicing methods such as rock salt application and mechanical snow removal, while highlighting installation cost and design standardization as the principal barriers to widespread adoption.

Keywords: *solar panels; photovoltaic energy; conductive asphalt solar collector; snow melting; pavement heating; renewable infrastructure*

1. Introduction

Solar panels, also referred to as photovoltaic (PV) panels, are composed of multiple solar cells that convert sunlight directly into electricity. These cells are typically constructed from semiconducting materials such as silicon, which absorb incoming solar radiation and convert it into an electric current through the photovoltaic effect: when sunlight strikes the solar cell, it excites electrons within the semiconducting material, generating a measurable current. Beyond electricity generation, solar energy can also be harvested thermally, and one of the more innovative applications of this principle lies in urban and transportation infrastructure — specifically, the use of solar-absorbing road surfaces to actively manage winter weather hazards.

Solar panels and solar-thermal systems offer several well-established advantages. As a renewable energy source, solar energy is abundant and does not deplete finite fossil fuel reserves. Environmentally, solar-based systems produce no direct greenhouse gas emissions during operation, reducing both air pollution and a facility's carbon footprint. They also promote energy independence, allowing individuals, businesses, and municipalities to generate or harness their own energy rather than relying entirely on external power grids, and they typically require minimal ongoing maintenance relative to their operational lifespan.

The application of solar-thermal principles to road heating represents an innovative extension of these advantages into transportation infrastructure. By capturing solar energy during the day — or, in more advanced configurations, storing it across seasons — asphalt pavements can be engineered to actively melt accumulated snow and ice, particularly during the late fall, winter, and early spring months when snow, sleet, and freezing rain pose major hazards to drivers and pedestrians. This is especially critical on high-risk infrastructure such as bridges, elevated ramps, and other sections prone to preferential icing.

1.1 The Problem of Winter Pavement Safety

Preventing snow accumulation and ice formation on roads is a high priority for winter transportation safety, particularly given the widespread use of asphalt concrete in parking lots, airport runways, bridge decks, and roadways. The conventional approach to this problem is the application of deicing agents such as salt, sand, or other granular materials. Salt (sodium chloride) is inexpensive and effective at melting snow and ice under moderate conditions, but its effectiveness drops sharply below approximately −3.9°C, and its widespread use carries well-documented negative externalities, including corrosion of concrete infrastructure and environmental pollution of soil and waterways — concerns that have drawn attention from bodies such as the International Energy Agency (IEA) and the World Health Organization (WHO).

Mechanical snow removal (e.g., snow plows) presents an alternative, but one that carries its own risks: vibration and improper use of heavy equipment can cause surface and structural damage to pavement, and mechanical removal is inherently reactive — it can only be deployed once hazardous conditions are already present, leaving a window of elevated risk before removal occurs. Severe weather conditions can also preclude the safe operation of mechanical equipment altogether.

As an alternative to both chemical deicing and mechanical removal, hydronic (fluid-based) heating systems embedded within the pavement have been explored for several decades. These typically use electrically heated wiring or hot water piping, heated by kerosene or gas boilers, buried within the pavement structure. However, such systems tend to consume substantial thermal energy: field data from installations in West Virginia and Oregon indicate electric energy consumption for snow melting in the range of 500–750 W/m^2, and residential snow-melting systems in regions such as Hokkaido, Japan, have been shown to consume oil at rates comparable to an entire household's annual hot water demand for a modestly sized 20 m^2 installation.

1.2 Solar and Geothermal Alternatives

From the standpoint of energy conservation and CO_2 reduction, alternative heat sources — including geothermal tail water, industrial waste heat, and solar thermal energy — offer more sustainable pathways for pavement heating. Early implementations of this concept include Japan's "Gaia system," a geothermal snow-melting installation using a Downhole Coaxial Heat Exchanger that has been operating since 1995, and the "smart bridge" developed by researchers at Oklahoma State University, which pairs a Ground Source Heat Pump with hydronic tubing embedded directly in a bridge deck. Most prior research in this area, however, has focused on cement concrete pavements rather than asphalt.

Asphalt pavement is particularly well suited to solar thermal collection due to its dark color and excellent heat-absorbing properties: field measurements show that the internal temperature of asphalt pavement can rise to 60–70°C under summer solar irradiation. This property underlies the concept of the asphalt solar collector (ASC), in which fluid is circulated through a network of pipes embedded beneath the pavement surface. During summer, solar irradiation absorbed by the pavement is transferred to the circulating fluid and can be stored underground for later use — for example, to heat adjacent buildings — while in winter, the stored or actively circulated warm fluid can be used to keep the pavement surface ice-free. Because such systems typically achieve higher energy efficiency than conventional boilers or electric heating elements, and because extracting heat in summer and releasing it in winter reduces extreme temperature fluctuations within the pavement (thereby improving resistance to rutting and frost cracking), the ASC concept offers a compelling dual-benefit alternative to traditional snow-melting approaches. Its broader adoption, however, has been limited by relatively high initial installation costs and a lack of standardized design guidelines.

1.3 Scope of Work and Objectives

The thermal conductivity of the asphalt mixture is one of the most important parameters governing the efficiency of an asphalt solar collector. Prior work has shown that incorporating thermally conductive fillers into asphalt mixtures can substantially enhance collector performance, giving rise to the concept of conductive asphalt concrete (CAC). Building on this foundation, the present study has two primary objectives: first, to use numerical simulation via the finite element method to determine optimal design parameters — specifically pipe depth and pipe spacing — for a conductive asphalt solar collector (CASC) intended for snow melting; and second, to construct and test a physical, instrumented CASC system to validate these simulated design parameters under real winter conditions. Because asphalt is a temperature-sensitive material whose modulus and structural strength vary with temperature, this study also considers the effects of non-uniform temperature distribution introduced by the embedded heating system, since regions of elevated temperature are more susceptible to permanent deformation under traffic loading, while cooler regions remain more vulnerable to thermal cracking.

2. Thermal Analysis

Designing an optimal snow-melting system that balances performance against life-cycle cost involves navigating several interacting variables — heating capacity, pipe layout, and control strategy — whose combinations can produce significant differences in both performance and cost. Because weather conditions during snowstorms vary considerably from event to event, computer simulation offers the most practical means of optimizing system design using representative weather data, prior to costly physical installation.

Using a finite element method simulation, the relationship between the thermal conductivity of the asphalt pavement layer, the depth at which the heating pipe is embedded, and the resulting time required to begin melting snow was examined. The asphalt pavement in the simulated structure consisted of three layers, with a total thickness of 18 cm; pipe embedment depths of 4, 7, 10, and 14 cm were tested as design alternatives.

The simulation results show that, at a fixed pipe depth, increasing the thermal conductivity of the asphalt pavement consistently reduces the time required to begin melting snow. Similarly, at a fixed thermal conductivity, embedding the pipe at greater depth increases the time required before melting begins. When pipes were embedded in the bottom asphalt layer, the time to begin melting exceeded 0.5 hours even when thermal conductivity was improved to 5.0 W/m·°C — a performance level considered inadequate for practical winter safety applications. By contrast, embedding pipes in the middle layer, or between the middle and top layers, produced excellent melting performance, with melting beginning within 0.5 hours regardless of whether the surrounding material was ordinary asphalt concrete or conductive asphalt concrete (CAC). Embedding pipes between the bottom and middle layers (using thermally conductive concrete) could satisfy a 1-hour melting requirement, and once thermal conductivity reached 3.0 W/m·°C, melting time could be reliably controlled within 0.5 hours. The relationship between beginning melting time and thermal conductivity was found to follow a power-exponent function.

The area of pavement over which snow melting occurs around each embedded pipe was also examined. Larger thermal conductivity values consistently produced larger melting areas at a given pipe depth, although this effect diminished once thermal conductivity exceeded a certain threshold. To facilitate straightforward construction, embedding pipes between asphalt pavement layers — rather than at the very bottom — was found to be the most practical configuration. Combining the melting-time and melting-area findings, the analysis indicates that when the thermal conductivity of the asphalt pavement exceeds 3.0 W/m·°C, an embedment depth of 4 or 10 cm is advisable, with pipe spacing controlled within a range of 0.18 to 0.4 m to balance installation practicality against cost.

3. Method

3.1 Experimental Setup

A physical, instrumented conductive asphalt solar collector (CASC) system was constructed to validate the design parameters identified through numerical simulation. The underlying mechanism mirrors that of asphalt solar collector (ASC) systems established in prior work, with the key distinction that the asphalt slabs used in the present study were larger in scale. Copper pipes and thermal sensors were embedded within the test slabs at positions determined by the preceding simulation: a pipe spacing of 300 mm and a burial depth of 40 mm, consistent with the general design requirements derived numerically. The copper piping used a nominal outer diameter of 20 mm and an inside diameter of 15 mm. Circulation of water through the piping system was achieved using a metering pump capable of flow rates up to 60 L/h at 0.6 MPa. To minimize heat loss to the surrounding environment, a 15 mm thick foamed polystyrene insulation layer (thermal conductivity 0.038 W/m·°C) was fixed to the outer surface of the piping.

3.2 Instrumentation and Measurement

Evaluating snow-melting performance required accurate monitoring of surface temperature and surface conditions throughout each heating cycle. High-precision Pt100 thermal resistors were installed at eleven distinct locations along a line perpendicular to the embedded piping, recording temperature data continuously across successive heating cycles; each sensor was connected to a Keithley 2700 data acquisition system for automated logging. Surface conditions were quantified using the "snow free area ratio" (Ar), a standard metric in snow-melting system design representing the fraction of the pavement surface that is clear of snow, where Ar = 1 denotes a fully snow-free surface and Ar = 0 denotes a fully snow-covered surface, with intermediate values representing partial (striped) melting patterns. Experimental Ar values were estimated visually from digital video imagery captured during snow events. Because direct measurement of surface temperature is difficult under field conditions, infrared imaging technology (IIT) was additionally employed to characterize surface temperature distribution.

4. Findings and Results

Digital imaging of the test slabs throughout multiple snow events provided a clear record of the snow-melting process. Observations confirmed that melting proceeded through three distinguishable phases:

an initiation (starting) period, during which surface temperature rises but visible melting has not yet begun; a linear period, during which the snow-free area ratio increases steadily; and an accelerated period, during which melting proceeds more rapidly as exposed pavement surfaces absorb additional heat directly. Internal pavement temperature variation, tracked via the embedded Pt100 sensors, could similarly be divided into four stages based on the rate of temperature change: a starting period, an accelerated period, a stable period, and a post-acceleration period.

Increasing the thermal conductivity of the asphalt concrete from 1.531 to 2.309 W/m·°C reduced total snow-melting time by approximately 30%, closely matching the trend predicted by the earlier numerical simulation. Non-uniform temperature distribution and fluctuation across the pavement surface were also documented; notably, temperature gradients exceeding 16°C per 15 cm of depth were observed at the end of heating cycles, with even higher gradients occurring when higher-temperature circulating fluid was used — a finding with direct implications for pavement durability, since excessive thermal gradients can accelerate cracking and structural fatigue over repeated freeze–thaw cycles.

5. Discussion, Conclusion, and Implications

5.1 Discussion

Taken together, the simulation and experimental results converge on a consistent set of design recommendations. Embedding heating pipes between asphalt pavement layers — rather than at the pavement's base — offers the best balance of melting performance and construction feasibility. A pipe depth of 4 or 10 cm, combined with a pipe spacing of 0.18 to 0.4 m, is recommended as the general design guideline for conductive asphalt solar collector systems intended for snow-melting applications. Importantly, the experimental results demonstrate that relatively low-temperature circulating water — approximately 25°C — is sufficient to achieve effective snow melting. This finding carries significant practical value: because maintaining high fluid temperatures is unnecessary, systems can be operated with meaningfully lower energy input, reducing both operating costs and overall energy waste relative to conventional hydronic heating systems that rely on higher-temperature circulating fluid.

The application of conductive asphalt concrete (CAC) further accelerates heat transmission through the pavement structure, enhancing both solar energy collection efficiency during warmer months and snow-melting efficiency during winter. While the total time required for complete snowmelt in this study exceeded initial expectations, the overall performance — combined with the demonstrated feasibility of low-temperature operation — supports the practical viability of asphalt solar collectors as a snow-melting solution, particularly for critical infrastructure such as bridges and ramps where reliability is paramount.

5.2 Conclusion

This study demonstrates that a conductive asphalt solar collector, designed using finite element numerical simulation and validated through physical experimentation, offers a technically feasible and energy-efficient alternative to conventional snow and ice management strategies. The recommended design parameters — pipe embedment between pavement layers at a depth of 4 to 10 cm, with spacing of 0.18 to 0.4 m — provide general guidance for future implementations. The observed reduction in melting time with increased thermal conductivity, together with the feasibility of low-temperature fluid operation, positions the conductive asphalt solar collector as a promising direction for sustainable winter road infrastructure.

5.3 Implications and Future Directions

- Infrastructure Safety: Solar-heated pavement systems could substantially reduce winter accident rates on high-risk sections such as bridges, ramps, and elevated roadways.
- Environmental Benefit: By reducing reliance on chemical deicing agents, such systems can lower environmental contamination of soil and waterways associated with road salt runoff.
- Energy Efficiency: The feasibility of low-temperature operation (≈25°C) suggests that these systems could be integrated with existing low-grade waste heat or solar-thermal sources, further improving overall system efficiency.
- Cost and Standardization: Broader adoption will require continued research into reducing installation costs — particularly piping and installation labor — and the development of standardized design guidelines to support engineering adoption at scale.

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