

Innovative utilization of tunnel drainage water for de-icing traffic areas

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ABSTRACT: Sustainable heating solutions require new ways of thermal energy extraction. Therefore, low-temperature geothermal heat sources have proven to be reliable and economically advantageous. Utilizing the constant temperature and flow rate of tunnel drainage water enhances this potential by extracting unused and permanently available thermal energy. Particularly for de-icing roads and pavements located close to tunnel portals, road surface-integrated geothermal heating systems require comparatively low temperature levels, which can be realised without using a heat pump. The temperature of the tunnel drainage water, influenced by tunnel air and the surrounding ground, consistently provides sufficient temperatures for defrosting. By applying the method of direct passive surface heating, the drainage water is directly used as a heat transfer medium to operate contiguously arranged heating tubes integrated into asphalt or concrete pavements. As part of a large-scale pilot project near the northern portal of a road tunnel in Füssen, Germany, nine different configurations of passive surface heating systems were designed, installed, and tested over two annual cycles. These configurations varied in surface layer compositions, tube materials, and geometric parameters. In this context, numerous tests were conducted under different snow and ice conditions. The results from this pilot project, combined with extensive numerical studies, demonstrate the viability and efficiency of using tunnel drainage water for passive geothermal heating of road surfaces. Furthermore, significant road and pavement cooling effects were observed when operating the testing facility at high surface temperatures during summer. Consequently, plastic deformations of asphalt surfaces resulting from superheating can be reduced. This paper will report on the conceptual aspects and will present the results of monitoring during winter and summer operation.

KEYWORDS: Pavement de-icing, open-space heating, tunnel geothermics, hydro-geothermal system.

1 INTRODUCTION

Tunnels and other underground structures offer a commonly underestimated geothermal potential. This capability originates from the stored thermal energy of the surrounding soil as well as from the waste heat emitted by road and rail vehicles.

However, numerous of these traffic structures are operated for decades without taking the opportunity to utilize this permanently available energy source. Consequently, retrofitting currently operated facilities with any geothermal application appears to be an innovative concept to tap further sources of renewable energy. In this context, a distinction is usually made between two basic technical methodologies for tunnel geothermal energy designs: the (closed) absorber–heat pump system, consisting of heat exchanger pipes integrated in the tunnel shell, and the (open) hydro-geothermal system, utilizing the tunnel drainage water for direct thermal energy extraction. While the closed system requires a certain heat carrier fluid and, consequently, two separated hydraulic circuits, the hydro-geothermal method uses the thermal energy as an incidental product of the necessary tunnel drainage. From the perspective of construction effort, hydro-geothermal systems appear to be the preferred method for retrofitting already existing infrastructure, if the precondition of a drained tunnel is fulfilled.

The performance of hydro-geothermal energy extraction depends, among other factors, on the temperature of the drainage water, the nature of the surrounding soil material, and the permissible ecological temperature of receiving waters. In order to identify tunnels that are suitable for a hydro-geothermal retrofit, a comparative investigation of various road tunnels in Germany, focusing on the drainage water conditions, was undertaken by Moormann & Buhmann in 2017. As a result of this preliminary assessment, the Grenztunnel Füssen (Füssen border tunnel) at the German–Austrian border was identified as an ideal facility for a pilot study in retrofitting a hydro-geothermal heat extraction system at an existing road tunnel. Furthermore, the northern portal and a nearby located parking lot emerged as suitable for a direct utilization of the extracted thermal energy: a passive, hydro-geothermal powered open-space heating system (Hydronic Asphalt Pavement, HAP) was realized to maintain snow- and ice-free conditions in the mentioned traffic areas. In the end, a two-year evaluation of the

facility was conducted, continuously recording flow, temperature, and image data. This operation was performed in different modes in summer and winter.

Besides the consideration of the concept and design principles of tunnel geothermics in general, this paper examines the Grenztunnel Füssen as a case study to point out opportunities and performance of a hydronic pavement system. Furthermore, the empirical data accrued from the project are evaluated to derive findings about the effectiveness of the pilot plant and the future deployment of hydronic pavements.

2 TUNNEL GEOTHERMAL ENERGY

Based on their large area of air and soil contact, tunnels belong to the best-suited geotechnical structures for thermal energy extraction. This energy derives from both vehicle exhaust and geothermal heat. Nevertheless, tunnels as energy structures are still only slightly investigated (Barla & Perino, 2014). The following provides an overview of tunnel geothermics as well as specified design concepts.

2.1 Overview

The heat transfer in tunnel structures is a complex issue. These processes contain convective parts, deriving from air and groundwater flow, as well as conductive components, such as the geothermal heat flux. In Germany, the amount of temperature increase normally consists of 3 K per 100 m depth (Bauer et al., 2008). This enhances the thermal potential of tunnels, especially when considering the high overburden of alpine infrastructure. Additionally, the convective component at the interface between air and the tunnel shell, deriving from engine and braking waste heat, increases the amount of transferred thermal energy significantly. For this reason, the share of this element in the yield of a closed-system tunnel geothermic facility can be quantified as up to 70 % (Buhmann, 2019).

The following section focuses primarily on hydro-geothermal (open) systems. Information on absorber technology (closed) can be found in Adam & Markiewicz (2009), Schneider (2013), and Buhmann (2019).

2.2 Hydro-geothermal systems

Hydro-geothermal systems, in contrast to absorber–heat pump systems, use the mountain water discharge as a heat source and convector fluid at the same time. For this reason, no separated circuits are required. Furthermore, the thermal energy transported by the drainage water is either extracted by a heat pump or employed for passive heating or cooling. In the end, the utilized water is discharged to natural or artificial receiving waters, in compliance with official regulations regarding permissible discharge temperatures.

$$P = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \quad (1)$$

The performance of hydro-geothermal plants depends on a number of boundary conditions. These mainly include the mountain water flow rate and temperature, the surrounding soil properties, and the construction depth of the tunnel. The former tends to be constant with increasing overburden, which is mainly fulfilled for alpine tunnels. In less mountainous regions, particularly, flow rates can show a distinct variance (Stemmler et al., 2022). The output power P supplied by the drainage water flow is depicted in Equation (1). In addition to the flow rate \dot{V} , the thermal capacity c_p and the density ρ of the mountain water, the temperature gradient ΔT , which is calculated as the difference between inflow and outflow, significantly influence the yield of the facility.

For an effective usage of a hydro-geothermal plant, the distance between the tunnel portal and the heat consumer must be kept low. Therefore, many sample projects in Europe deploy the mountain water for thermal conditioning of service buildings located adjacent to the source. For instance, the mountain water discharge of the Rennsteigtunnel, located in central Germany, with a temperature of 7 °C to 7.7 °C and an average flow rate of 6.3 l/s to 13.0 l/s, is applied to cool various road maintenance service installations (Buhmann, 2019).

3 OPEN-SPACE PAVEMENT HEATING

Open-space pavement heating is a promising field of application for hydro-geothermal energy. For the purposes of de-icing, snow removal, and summer overheating prevention of traffic areas, this system can be operated by mountain water directly, without the necessity of a heat pump. The following provides basic technical information about this technique.

3.1 Basic concept: Direct passive geothermal surface heating

A common designation for open-space heating and cooling facilities of traffic areas is Hydronic Asphalt Pavement (HAP). Although this paper additionally focuses on alternative pavement materials, such as concrete, HAP will be used as an abbreviation in the following.

HAPs have been proven as a functional and environmentally friendly concept for both surface heating and cooling in projects worldwide. Ghalandari et al. (2021) provide a comprehensive overview of various examples, operating with both conventional and renewable energy sources. Designed as a heat collector and emitter combined, a distinct number of HAPs are equipped with a thermal storage unit. Solar energy harvested in summer is then accumulated in geothermally exploitable underground layers. During winter, this energy can be released, primarily to keep traffic areas ice- and snow-free. This method is particularly reasonable for spaces difficult to access for snow ploughs or sensitive to chemical de-icing agents. Furthermore, solar energy extraction, especially from asphalt pavements, can significantly reduce the surface temperature and consequently prolong the service life of the

structure (Wendel, 1979). Potentially, the harvested thermal energy can additionally be used for residential building and domestic hot water heating.

Basically, HAPs consist of either serpentine or spiral-counterflow arranged tubes installed in the pavement. While being flowed through, these conduits work as heat exchangers. In addition to solar and thermal radiation, the possible transferable heat flux depends in particular on the surface air flow conditions as well as evaporation or condensation (Bobes-Jesus, 2013), while the influence of the geothermal heat flux is considered to be very small in comparison, which is caused by a strongly surface-near installation depth (Kugler et al., 2025).

3.2 Hydronic pavement design

In the following, fundamentals and details of HAP design are described, where a preliminary thermal analysis — specifically an energy balance at the road surface — is essential.

One key consideration is that the earth's surface temperature is determined by evaluating heat exchange processes at the air-touching interface. This equilibrium consideration, which comprises the components mentioned in the last paragraph, can be seen as a well-established tool in the study of snowmelt and evaporation.

Slaughter (1970) summarizes various energy balance models applied for this purpose. Extended by further components, elaborated for HAP design, an overview of the acting thermal influences is given in Equation (2) and visualized in Figure 1.

$$\dot{q}_{in} = \dot{q}_{NR} + \dot{q}_{conv} + \dot{q}_{lat} - \dot{q}_{rain} + \dot{q}_s - \dot{q}_{Geo} \quad (2)$$

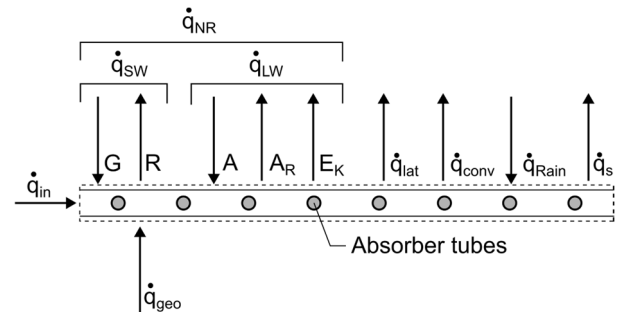


Figure 1. Visualized HAP heat fluxes from Equation (2), adapted from Kugler et al. (2025)

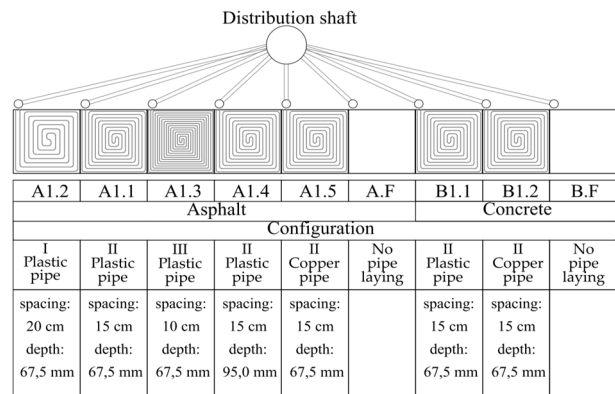


Figure 2. Testing plant parking lots (A1.2 - B.F.), different configurations, adapted from Kugler et al. (2025)

Equation (2), which is visualized in Figure 1, contains latent heat fluxes resulting from evaporation and condensing \dot{q}_{lat} , the geothermal heat flux \dot{q}_{Geo} , convection caused by air movement \dot{q}_{conv} , thermal influence by falling rain \dot{q}_{Rain} as well as the

required snow melting energy \dot{q}_S . The radiative heat flux \dot{q}_{NR} , comprising short- and longwave radiation \dot{q}_{SW} and \dot{q}_{LW} , is given by the sum of incoming and reflected global radiation G and R , atmospheric back radiation A , reflected atmospheric radiation A_R and surface-emitted longwave radiation E_K . As an artificial element, the thermal energy transferred by the HAP inflow (\dot{q}_{in}) has a decisive influence on the performance of the facility. It firstly depends on the working fluid temperature and secondly on its flow conditions regarding laminar or turbulent states. Turbulent pipe flows provide significantly increased heat transfer properties compared to laminar flows. As the geometry is comparable with shallow geothermal collectors, technically reasonable recommendations for a target flow condition are derived from the VDI 4640 guideline (VDI, 2019). For sufficient energy harvest, VDI 4640 recommends a turbulent flow state with a Reynolds number of $Re > 3,500$. A detailed description of all equilibrium components, focused on open-space heating design, is given by Kugler et al. (2025).

4 GRENTUNNEL FÜSSEN PILOT PLANT

The Grenztunnel Füssen is a single-tube road tunnel with a length of 1,284 m. It is located at the German–Austrian border and underpasses the Falkensteinkamm, which is part of the northern Limestone Alps, with a maximum overburden of 210 m. The following describes the project development, test scenarios, and monitoring results.

4.1 Introduction

As already mentioned, the Grenztunnel Füssen has been identified as an optimal candidate for a mountain water-powered open-space heating pilot project in a preliminary study by Moormann & Buhmann (2017). Its results indicate that the flow rate at the northern portal remains relatively stable, varying between 11 and 23 l/s, while the corresponding water temperatures range from 8.3 to 12.1 °C.

According to VDI guideline 4640 (VDI, 2019), the temperature of water discharged into the receiving waters should range from 5 °C to 20 °C. This leads to a theoretical minimum geothermal potential for heating of 152 kW, while for cooling, it is estimated at 438 kW.

In addition to its thermal characteristics, the area around the Grenztunnel Füssen offers ideal conditions for a pilot plant, due to the presence of a road maintenance facility located adjacent to the northern portal. On this traffic area, nine parking lots with varying pipe materials, installation depths, pipe spacings, and pavement materials were installed.

4.2 Design

As depicted in Figure 2, two of the nine parking lots were executed as dummy areas for comparison purposes, without heating loops or sensors. The HAPs were designed for three operating modes: snow and black ice removal in winter, as well as pavement cooling during summer operation. The aim was to find the most efficient configuration for open-space heating based on variations in geometry and materials.

The testing areas were designed conservatively, considering a mountain water flow rate of 11 l/s with a temperature of 8.3 °C. Fulfilling the precondition of a minimum surface heat flux of 400 W/m² for black ice and snow-free maintenance, the dimensions of the HAPs were derived from transient simulations using a hydro-thermally coupled finite element model in COMSOL Multiphysics®, as shown in Figure 3 (Kugler et al., 2025).

Each of the test areas is equipped with numerous temperature sensors, which are arranged vertically in the pavement cross-section as well as in the inflow and outflow.

The cross-sectional sensors have vertical distances from the surface of 6 mm, 46 mm, 89 mm, and 129 mm. Additionally, the working fluid flow rate and pressure are measured and centrally recorded for each test field.

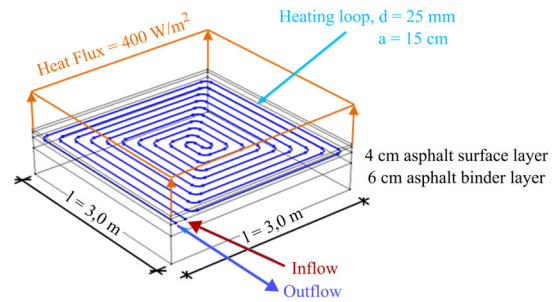


Figure 3. HAP design in finite element simulation (Kugler et al. 2025)

Also, the processing of weather forecasts and current ambient climatic conditions allows the facility to start up when a snow or black ice event is likely to occur. Moreover, when the conduit is in danger of freezing, an automatic blowout is triggered using compressed air.

The flow direction was maintained during all test runs. In various preliminary tests, a comparison was made between laminar and turbulent flow conditions. Finally, the resulting flow rate for $Re > 2,300$ (turbulent flow state) was maintained at 1.5 l/s during all main tests.

5 TEST SCENARIOS AND MONITORING RESULTS

In the following, the monitoring results of three selected, meaningful test operations during winter and summer are presented and evaluated.

5.1 Test scenarios: Winter mode

During winter, various test runs were conducted. Two key events were a snowfall that occurred during system operation and a cold-start scenario involving black ice and snow.

Figure 4 shows the temperature measurements for both scenarios along the HAP cross-section, with the heating pipe installed at 67.5 mm. During the first scenario, a heavy snowfall event occurred while the system was operated in normal mode, with an average ambient temperature of 2 °C.

While the snowfall lasted for over 9 hours, an operational pause was taken, allowing a snow cover of up to 10 cm to form on the parking lot surfaces. After restarting the system, the HAP configuration with concrete and copper pipes B 1.2 (red line in Figure 4) was able to remove the snow cover first. The worst-performing configuration was the asphalt and plastic pipe composite A 1.2 (green line in Figure 4), which proved insufficient to melt the snow cover.

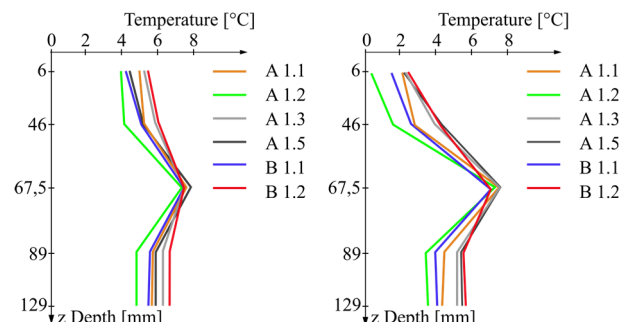


Figure 4. Temperature distribution in pavement cross-section during snowfall (left) and black ice cold-start event (right), adapted from Kugler et al. (2025)

In Figure 5, the snow-melting performance of the concrete and copper pipe configuration (left) and the asphalt and plastic pipe composite (right) is depicted. The advantage of the concrete-copper system is obvious, which can be explained by its significantly higher thermal conductivity.



Figure 5. Performance of concrete-copper (B 1.2) and wide-spaced asphalt-plastic (A 1.2) HAPs during snowfall scenario

The second scenario consisted of a cold start of the system, which was conducted shortly before a black ice and snow event was forecasted. The associated temperature distributions are depicted on the right in Figure 4. The performance ratio in terms of temperature distribution between concrete and asphalt seems comparable to the snowfall scenario (left). However, a significantly higher temperature gradient in the black ice scenario (right) is clearly visible. This phenomenon results from the insulating effect of the snow cover, which increases with decreasing snow density.

5.2 Test scenario: Summer mode

Various measurement results during the two-year monitoring illustrate the capability of the HAP to positively influence traffic area surface temperatures in summer. A comprehensive analysis of summer pavement temperatures over more than 100 measuring points is presented in Figure 6. It shows a strong correlation between a significant pavement cooling effect of at least 5 K and an operated HAP. Berdahl et al. (2008) outlined that an increase of 10 K can double the rate of thermal asphalt oxidation, a key factor in asphalt hardening. Considering the test results, a HAP can contribute significantly to prolonging the lifespan of asphalt pavements.

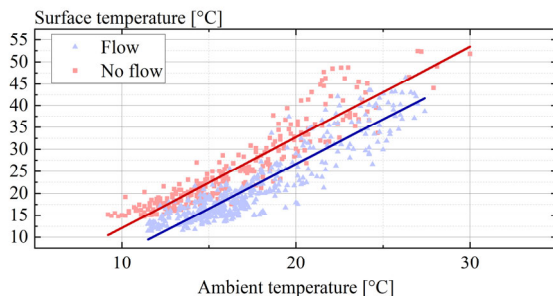


Figure 6. Asphalt pavement cooling effect through hydro-geothermal open-space heating

5.3 Numerical investigations

In addition to the experimental work, a comparative numerical study was conducted using transient, coupled thermo-hydraulic finite element simulations (Figure 3).

The objective was to numerically reproduce the thermal behavior of the system in the winter scenario, depending on the actual boundary conditions and real-time weather and mountain water data. As a result, the temperatures of all pavement sensors as well as the HAP performance were evaluated.

The results of this comparative study strongly correspond with the experimental data, despite the neglect of shortwave radiation on the pavement surface. This simplification is enabled by shadowing effects of the mountains located south of

the facility, which prevent direct solar radiation on the parking lots from October (Kugler et al., 2025).

Following this investigation, numerical parameter studies were conducted, varying geometric dimensions and materials. This examination identified the copper-concrete composite, arranged according to configuration II (Figure 2, B 1.2), as the best-performing solution. Moreover, it revealed that a pipe spacing of 15 cm boosts performance significantly in comparison with 20 cm (Configuration I), while a further reduction to 10 cm (Configuration III) leads to a disproportionately increased pipe length.

6 CONCLUSION

As a result of this research, hydronic asphalt pavements (HAPs) proved to be a well-suited application for an open, hydro-geothermal system. The experiments revealed that the mountain water is feasible to maintain snow- and ice-free conditions in most cases, especially with Configuration II. Furthermore, the system proved suitable for reducing summer pavement temperatures and prolonging its service life. Following this, hydro-geothermally powered HAPs can be seen as a promising technology for road maintenance, making a meaningful contribution to the sustainability of infrastructure, especially due to the possibility of retrofitting numerous existing structures.

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