The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28-September 1, 2016

Hydronic Pavement Using Low Temperature Borehole Thermal Energy Storage

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ABSTRACT

Winter conditions on roads are a challenge for road administrators in cold climates and with increased public demands on safety, winter maintenance activities will increase. The most common winter maintenance activity in Scandinavia is anti-icing, which is performed when it is a risk for ice formation on the road surface. Commonly a truck is utilized for spreading freeze point depressant, like salt, on the pavement thereby lowering the freezing point and preventing ice formation on the surface. This method has been questioned for a number of reasons e.g. salts have negative effects on the local environment.

An alternative method for de-icing is to use hydronic pavement (HP). HP consists of a pipe network, embedded inside the pavement, in which a fluid is circulated. The fluid collect solar energy during summer days and transports heat back to the road surface during icy winter days. The harnessed and released energy should be in balance, otherwise an additional heat sources is needed.

This study has investigated the possibility of developing an alternative strategy to heat the pavement surface with stored low temperature fluids. By using the methodology, and software BRIDGESIM, a preliminary design of a hydronic pavement system have revealed that it is not feasible to design a system for the cold climate of Östersund (Sweden); only relying on harnessing solar energy and store the energy in a borehole thermal energy storage. However it was revealed that it is possible to design HP system for low supply temperatures of about 7 °C. Which is far below the supply temperature of about 35 °C, recommended by manufacturers of HP system. The prospect of utilizing low-temperature heat sources would make HP system more energy efficient which could make it an alternative to traditional winter maintenance methods.

1 INTRODUCTION

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Winter condition on roads has been a problem for road authorities with cold climates or high mountainous areas. Winter conditions leads to low friction on the road surface causing slippery condition which increases the risk for accidents. In order to mitigate this problems, road authorities in the Nordic countries performs a lot of snow and ice control activities, the most commonly being anti-icing for friction control. Anti-icing means the spreading of freezing point depressant, such as sodium chloride, to prevent ice formation on a road surface (Lysbakken, 2013). The usage of salt, for winter maintenance, in the Scandinavian countries adds up to about 600 000 tones each winter (Knudsen et al., 2014). This salt commonly end up in the environment along the road, causing damage to vegetation, saltification of fresh water and facilitates leaching of toxic heavy metals (Fay and Shi, 2012). Furthermore, salt causes corrosion on infrastructure, leading to high cost for the society to repair e.g. damaged bridges. Additionally, it is known that there are parts of the road infrastructure that are prone to freeze earlier and more often than the rest of the road network. Those location could be bridges or highway junctions, because those structures lacks the thermal heat flow from the ground. If those location could be ice controlled by alternative means, the CO_2-emission from winter maintenance could be reduced (Nordin, 2015). Alternative ice and snow control methods for fixed location could be FAST-systems (Fixed Automated Spray Technology) or using thermal energy. FAST-system are fixed systems that through spray nozzles spreads a freeze point depressant on the road surface, mitigating ice conditions (Ye et al., 2013). Thermal methods refers to utilizing pipes or electric cables, embedded in the pavement to heat the road surface above 0 °C. Electric cables are limited to using electric energy, while the pipes could use any heat source with sufficient temperature, making pipes a more flexible system regarding energy sources. One of the first pipe systems or hydronic pavements (HP) was installed Oregon, US as early as 1948 (Pan et al., 2015). HP system, normally used to day, use plastic pipes and are designed for a supply temperature of about 35 °C (Uponor, 2013). Those high temperatures requires the need for heat pumps or boilers limiting the possibility of utilizing renewable energy source like solar or geothermal energy directly. Design of system that utilize solar energy has been done previously in Switzerland for the SERSO project. In the SERSO project, energy is collected during sunny days through pipes and the fluid in the pavement. The energy is stored using BTES (Borehole Thermal Energy Storage) and recovered during icy conditions (Pahud, 2007).

1.1 Aims and method

This paper studies the possibility of using a hydronic pavement heating system with energy harnessing for the climate of Östersund in the central part of Sweden where a HP test site will be constructed. A methodology will be presented that reveal the most important design parameters. The methodology is based on the TRNSYS application BRIDGESIM developed by Pahud (Pahud, 2007).

1.2 Project description

As an extension to the project *Ice-free roads*, at Chalmers University of Technology funded by the Norwegian road administration, a test site will be built to study different kinds of components and pavement materials. Founding parties are the Swedish and Norwegian road administration which has supported research in this area (Sundberg and Lidén, 2014). This test site will be located outside the Swedish town

Östersund (63.18 N, 14.5 E) selected since it is an area with long and cold winters with an annual mean temperature of about 2.5 °C.

The test site will consist of three pavement surfaces, one heated with a hydronic heating system and two with electric heating. Figure 1 presents the principal layout of the test site with the major part as the pavement sections, the BTES, the road weather station and the service house with auxiliary heaters and control systems. The electric system for heating is used in order to insure an accurate measurement of energy and power demands. Two different pavement materials will be tested; one with standard concrete, surface 1, and the other with a modified asphalt concrete, surface 2, having enhanced thermal properties than a standard asphalt. Having two different pavement material makes it possible to determine the influence of thermal property of pavement on the performance of a hydronic pavement system.

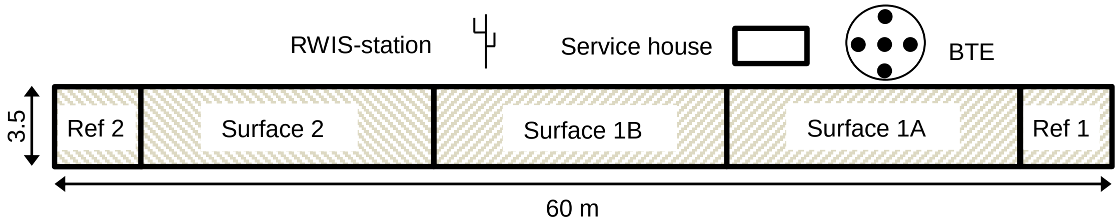

Figure 1. Principal layout of the planned test site outside Östersund.

2 BRIDGESIM DESCRIPTION

BRIDGESIM is a software that is based on TRNSYS and combines a number of components into a system model. The major modules are presented in the following sections.

2.1 System model

The system model consists of three major components: the road model, a short term thermal energy storage and a borehole thermal energy storage as well as minor components like valves and pumps, see Figure 3. The model is an energy balance model, which calculates and maintains the energy balance by using TRNSYS solver. Each of the components is added to the system model as separate types that previously has been validated, except the road model which is further described in section 2.2. For further descriptions of the individual components see the manual for TRNSYS 16.

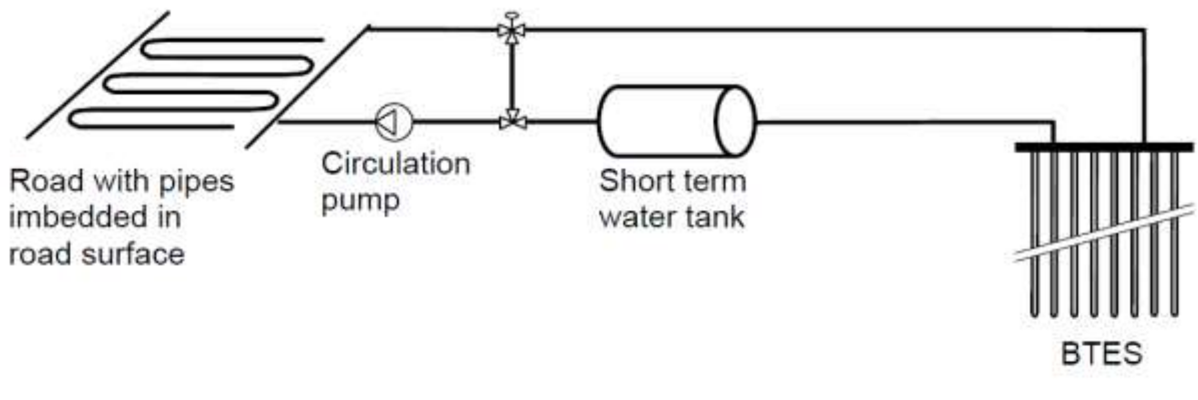

Figure 2: System layout simulated by BRIDGESIM containing the major components.(Pahud, 2008)

2.2 Road model

The road model used in BRIDGESIM is based on the work done by Koschenz and Dorer (1996) and was originally used for simulating thermally activated building systems or floor heating systems. The model simplifies the 2-D cases of pipes

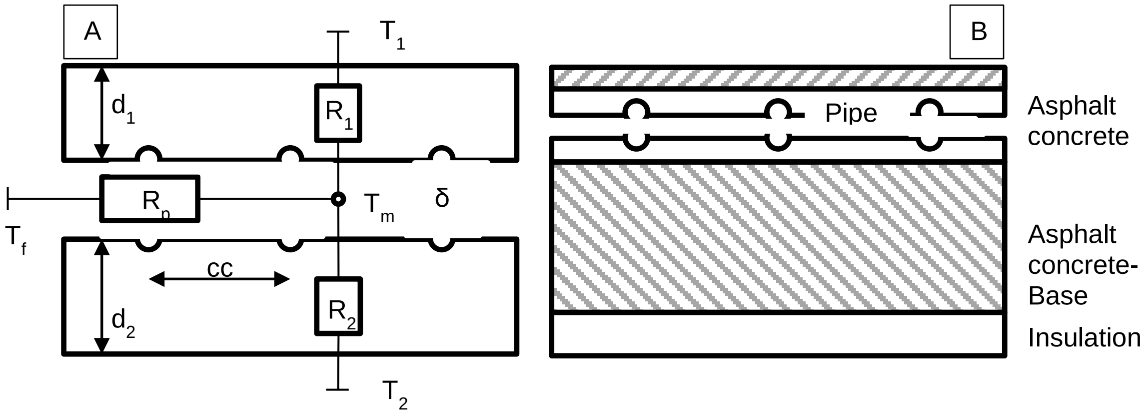

Figure 3: A, simplified 1-D thermal network for the road model. B, simplified 2-D case describing the original problem.

embedded in the pavement into a simplified 1-D case which could be seen in Figure 4.

In Figure 4A the temperatures T_1, T_2, T_f and T_m respectively refers to: the upper and lower surface temperature, the mean fluid temperature and the mean temperature at the depth of the pipes. The thermal resistances R_1, and R_2 represents the thermal resistance between the upper and lower boundaries to the depth of the pipes. R_p is the thermal resistance between the fluid in the pipe and the temperature T_m. R_p takes into account the resistance from the fluid through the pipe material as well as the geometrical influence of the pipe diameter δ and the spacing between the pipes i.e. the distance cc. Furthermore, d_1 and d_2 represents the distance from the boundaries to the mean pipe depth. In Figure 4B the different material layers in the model are presented, variations could be done one the thickness and thermal properties of each layer. The insulation layer could be removed by setting the thickness to zero. A detailed description of the road model together with and evaluation could be found in (Pahud, 2007).

The surface model in BRIDGESIM uses a simplified approach taking convection, shortwave radiation and longwave radiation into account. However, it neglects wind, precipitation and latent heat due to condensation. (Pahud, 2007)

2.3 Control system

The control system consist of two different parts, one function controlling the supply temperature to the road at different air temperature and a function controlling the circulation pump for harnessing of solar energy.

2.3.1 Heating of the road

The supply temperature, in the above mentioned model, to the road is controlled according to a heating curve similar to the one seen in Figure 5. The system is started when the air temperature is below TE3 and the supply temperature is then adjusted according to the curve confined by TS1-TS3. When the air temperature is below -8 °C the system is stopped. The reason for this is the low likelihood of ice formation at those temperatures due to the low humidity content of the air (Pahud, 2007).

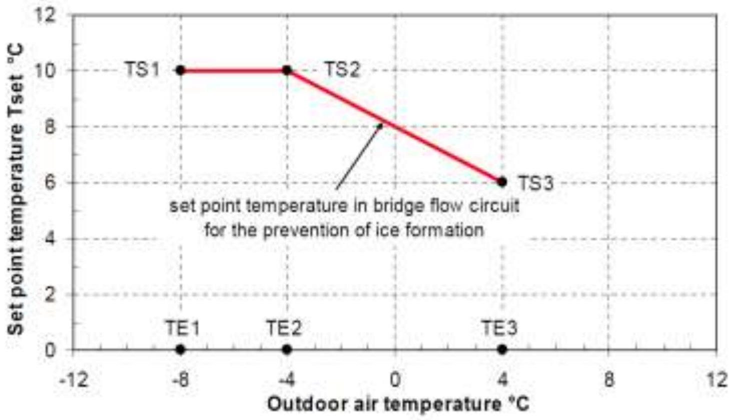

Figure 4: Heating curve controlling the supply temperature to the bridge at different air temperatures. *(Pahud, 2008)*

2.3.2 Harnessing of solar energy

The system utilize the heat absorbed by the pavement due to solar radiation during summer to recharge the BTES. Harnessing of solar energy is controlled by a simple temperature setting which controls if the circulation pump should be active or not. The circulation pump is started if the temperature difference between T_m and the temperature in the short term storage tank is above the set temperature DT1CST. The circulation pump is stopped when the same temperature difference is below the set temperature DT0CST. By varying these set point temperatures, the amount of stored energy could be controlled (Pahud, 2008).

2.4 Evaluation method

The evaluation of different system configurations must be compared in a way that is relevant. In BRIDGESIM it is done by the factor NT which is a measure of how many degree-hours the system fails to meet the prescribed demand. When the temperature of the road surface T_1 is lower than 0 °C there is a risk for ice formation on the road surface. However, when the air temperature is lower than - 4°C the frequency of snow fall is greatly reduced, as well as the moisture content in the air, which reduces the risk for ice formation. Therefore the demand for the system has been stated as $T_1 > 0$ °C if the $T_{air} > -4$ °C. Nevertheless, there will be conditions when the energy demand could not be supplied and the system should be designed to keep this time at a minimum. To calculate this amount of time and compare between systems the factor NT is defined according to Eq. (1).

$$NT = \int_0^{1\,year} (0 - T_s)dt \qquad \text{if } T_1 < 0\text{ °C and } T_{air} > -4\text{ °C} \tag{1}$$

NT is the sum of the degree-hours over a year when there is a high risk for ice formation and the system could not meet the demand. The unit for NT is K*h/year.

3 DESIGN OF TEST SITE

Simulations related to design of the system in the test site was done in a number of steps by varying different simulation parameters in order to determine the influence of each parameter on the system performance. As a first step the parameters affecting the control system was varied. Furthermore, the whole system was simulated with the BTES.

3.1 General assumptions

BRIDGESIM have a number of parameters that could be altered and the few anticipated to have major effect on the results, has been investigated in this study. The other parameters have been fixed in order to limit the amount of simulation runs and to adopt the design to criteria for the test site outside Östersund. The fixed parameters are presented in Table 1. A high fluid flow rate was selected in order to keep the fluid temperature drop low in the pipes that goes through the road. For a complete description of all parameters see the manual for BRIDGESIM (Pahud, 2008).

Table 1: Simulation parameters fixed during the simulations.

Parameter	Value	Unit
Heated bridge surface	1000	[m^2]
Road solar absorption	0.7	[-]
Surface convective heat transfer coefficient	10	[W/m^2 K]
Thermal conductivity asphalt	4	W/m K
Thermal conductivity material pipe at layer	2.4	[W/m K]
Outer diameter of the embedded pipes	25	[mm]
Thermal conductivity of the pipe material	0.41	[W/(m K)]
Thermal conductivity of the heat carrier fluid	0.48	[W/(m K)]
Fluid flow rate per square meter of heated bridge surface	77	[litre/(h m^2)]
Heat carrier fluid density	1052	[kg/m^3]
Heat carrier fluid heat capacity	3.795	[kJ/(kg K)]
Mean borehole length	200	[m]
Average spacing between the boreholes	5	[m]
Mean undisturbed ground temperature at surface	4	[°C]

3.1.1 Parameters in sensitivity analysis

The influence of the parameters, presented in Table 2, on the system performance was investigated. The selection of the parameters was based on assumption that they have a major impact on the performance of the system.

Table 2: Simulation parameters, altered during simulations.

Parameter	Explanation	Unit
TS2	Max supply temperature	[°C]
TS3	Min supply temperature	[°C]
T_2	Lower temperature boundary road	[°C]
cc	Pipe spacing in road	[m]
NBore	Number of boreholes	[-]
λ_{ground}	Thermal conductivity of the ground	[W/(m K)]
DT0CST	Harnessing stop temperature difference	[°C]
DT1CST	Harnessing start temperature difference	[°C]
Nserie	Number of boreholes connected in series	[-]
Wvol	Water volume in short term storage	[m^3]

4 RESULTS AND DISCUSSION

The design of system parameters was divided in two tasks. The first task is to determine the energy demand for the whole system and the second task deals with adding energy harnessing and thermal storage system.

4.1 Energy demand

The energy demand can be determined by using a suitable control curve e.g. a control curve according to Figure 5. The simulation were performed by varying the first four parameters in Table 2, i.e. TS2, TS3, T2 and cc- distance of the pipes.

4.1.1 Variation of TS2 for different TS3

The maximum and minimum supply temperatures TS2 and TS3 have a large impact on the magnitude of NT. The parameters were investigated for fixed values of the pipe spacing cc = 10 cm and an insulated ground temperature T_2 = 4 °C. The results are presented in Figure 6 with two sets of graphs representing the required heating energy and the number of degree-hours that the system fails to meet the requirement. The arrows embedded refers to the other varied parameter, TS3, with the base of the arrow representing the first value (9 °C) in the sequence.

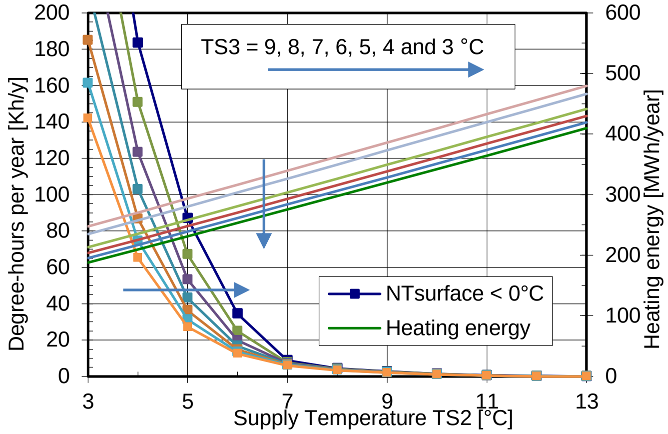

Figure 5: Variations of TS2 and TS3 for a fixed value of cc = 10 cm.

By varying TS3 it could be seen that for values of TS2 less than 7 °C, TS3 has a major impact on the NT. With TS2 above 7 °C, there was a low decrease of NT, however still an increase of the required heating energy. The aim was to reduce the value of NT at the lowest energy need. With TS2 equal to 7 °C, there was as small influence of TS3. Thus, 7 °C was chosen to be a reasonable value for TS2. In Figure 7 the results of varying TS3 for a fixed TS2 of 7 °C are presented. The results indicate that when TS3 was above 4 °C, there was no longer any large reduction of NT by increasing TS3. However for lower values of TS3 the effect on NTs were quite high. Therefore the control temperature TS3 was set to 4 °C.

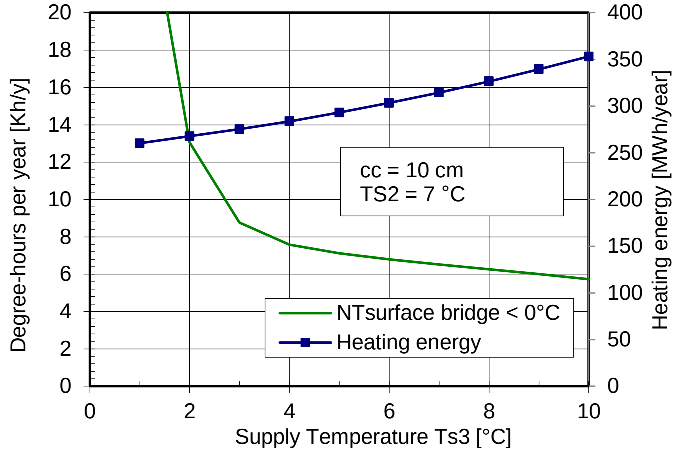

Figure 6: Variations of TS3 for fixed value of TS2 = 7 ℃, cc = 10 cm.

4.1.2 Variation of TS2 with different pipe spacing

The distance between pipes in the road (cc) is one of the major parameters in a HP system. In Figure 8 it could be seen how the spacing of pipes effects the value of NT for varying TS2. The simulation was done at a fixed fluid flow per square meter namely 77 (l/(h m^2)), as a way of keeping the temperature drop low between the supply and return flows. The results indicates that by decreasing the spacing of pipes, the value of NT will decrease. Decreasing the cc from 10 cm to 5 cm, the TS2 could be lowered by one degree to 6 °C with equal or better system performance. However, even for a spacing of 5 cm, lower values of TS2 than 5 °C would increase the value of NT substantially. Pipe spacing of 10 cm was chosen for further investigations due to the easier construction.

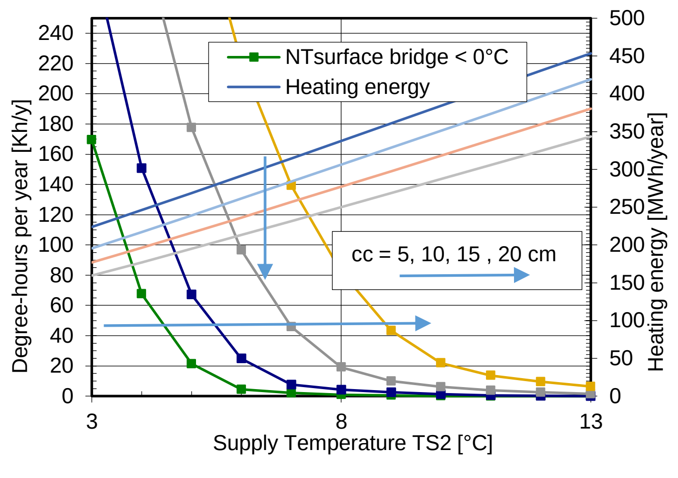

Figure 7: Varying pipe spacing for different TS2, fixed TS3 = 4 ℃.

4.1.3 Varying TS2 for different ground temperature T_2

The temperature under the road T_2 could either act in a positive or negative way for the system depending on the temperature T_2 and TS2. The simulations presented previously was made using a road model with insulation. However the influence of the ground temperature was studied by removing the insulation layer and varying T_2 for different TS2. Results from simulations with and without insulation is combined and they are presented in Figure 9. It could be seen that the effect of the ground temperature T_2 is limited and for temperatures of TS2 around 7 ℃ the effect on NT is neglect able. However, it could be seen that the required energy for an insulated ground, compared to uninsulated, is decreasing with increasing temperatures of TS2. That is, since more energy is required to heat the ground. From the results it could be recommended to avoid using insulation if the supply temperature is less than the ground temperature plus 2 °C. However further simulations with different thickness and placement of the insulation should be done to verify this conclusion.

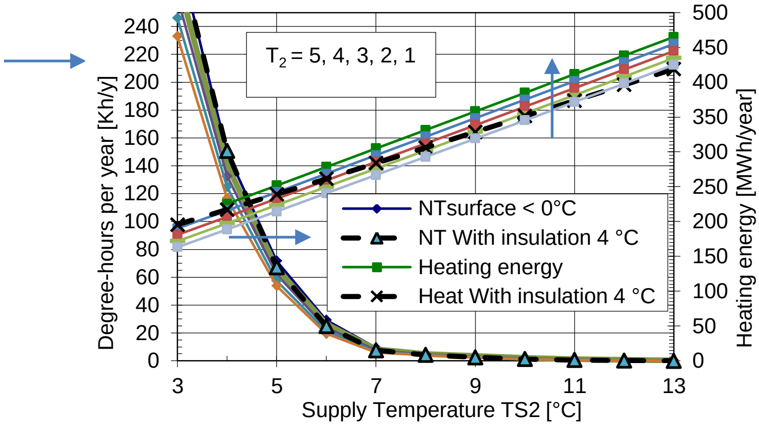

Figure 8: Varying ground temperatures T_2 for different TS2, fixed TS3 = 4 ℃, $cc = 10$ cm.

4.2 Design of BTES

The second design task was to design the borehole storage together with the controls for harnessing solar energy.

4.2.1 Varying Nbore for different thermal conductivity of the ground

The number of boreholes would directly affect the total borehole length, considering a fixed length of 200 meters for each borehole. The thermal conductivity of

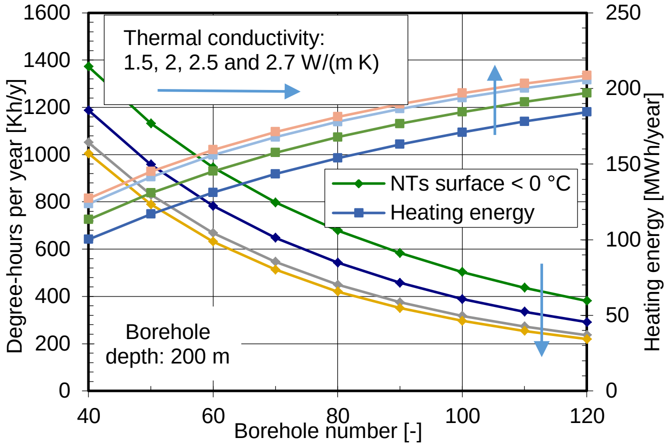

Figure 9: Varying thermal conductivity of the ground for different NBore, fixed NSerie = 3.

the ground in the area of the test site was rather low, 2 W/mK compared to the average for Sweden, about 3 W/mK. This is due to the rock type at the test site limestone and shale which have generally lower thermal conductivity than the crystalline rocks that dominate the bedrock of Sweden. However, the thermal conductivity was varied in the simulation to investigate the importance of that parameter. The results are presented in Figure 10.

The results presented in Figure 10 was done with 3 boreholes connected in series, DT1CST = 8 °C and DT0CST =4 °C. The results indicates the effect of the thermal conductivity on the value of NT, the degree-hours that the system fails to meet the demand. However, with a thermal conductivity of 2 W/m K at the test site and with these settings the required number of boreholes is approximately 100.

4.2.2 Harnessing control

The amount of solar energy stored into the BTES was controlled by the harnessing control settings. The simulations was done for a case with the borehole depth fixed to 200 m, ground thermal conductivity of 2 W/m K, NBore arbitrary selected to 90. The results of simulations are presented in Figure 11.

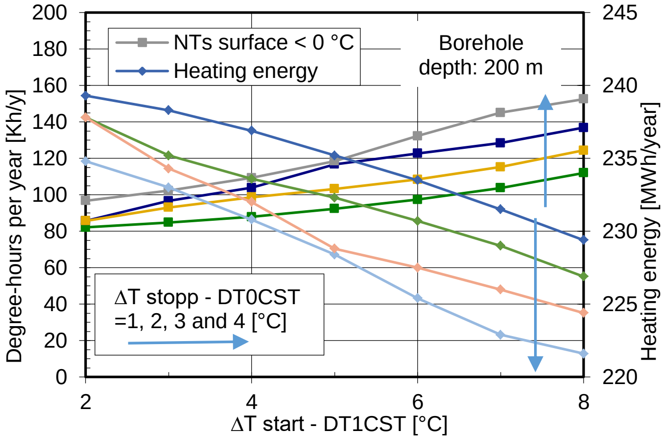

Figure 10: Varying settings for the harness control.

By increasing DT1CST from two to eight degrees Celsius it was found that the value of NT is increasing while the amount of energy for heating was decreasing. This means that less solar energy would be harnessed by increasing DT1CST. By studying the different values for DT0CST, it was found that a lower DT0CST would result in a lower value of NT and that more solar energy would be harnessed. However, by decreasing the control temperatures for harnessing, the efficiency of the system was reduced, see Figure 12. For the simulated system, DT1CST was selected to 4 ℃ and DT0CST to 2 ℃.

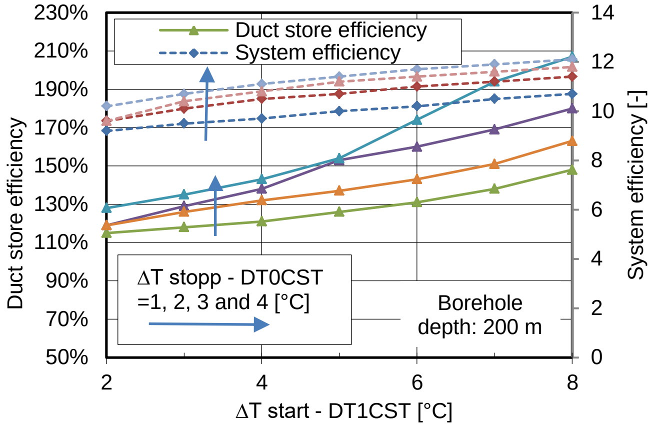

Figure 11: Efficiency for varying harness control settings.

The duct store efficiency was calculated by dividing the energy extracted from the storage by the energy injected into the storage. The system efficiency was calculated by the energy used for heating the road surface divided by the energy need for the circulation pumps. Since increasing the starting temperature DT1CST, would decrease the number of hours that the pumps will be in operation thus, the system efficiency increases. Furthermore, by increasing the starting temperature, less energy would be harnessed from the sun which leads to more energy would be coming from the surrounding ground, thus increasing the duct store efficiency. For a system with a high content of harnessed solar energy the duct store efficiency should be less than 100 %.

4.2.3 Number of borehole in series and size of water tank

The results of the simulations of increasing the number of boreholes connected in series, NSerie, was low. There was a difference on the value of NT of about 10 when changing from one borehole in series to two boreholes. Further increase of the boreholes connected in series did not decrease the value of NT. From this results it could be concluded that at the simulated fluid flows there is no need to use more than 2 boreholes in series. Furthermore, when investigating the effect of altering the volume of the short term thermal energy storage tank it was found that it had a limited effect on the value of NT. Thus, for the case study of Östersund a small water tank of about 4.4 m^3 would be sufficient.

4.3 Summary of system design parameters

The results and conclusions from the simulations above are presented as parameter values in Table 3. Results from one simulation with the parameter values presented in Table 3 are shown in Figure 13. Results in Figure 13 indicates that in order to reach low values of NT more than 120 boreholes would be needed. That is equivalent of having 24 meters of borehole for each square meter of road. The drilling cost would be in the range of 610 000 € which would be more than most projects could

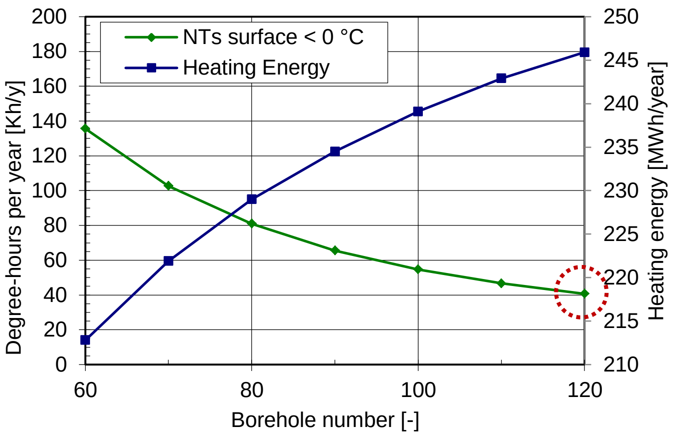

Figure 12: Varying number of boreholes for suggested system design.

support considering that the road surface is only 1000 m^2. However, the importance of designing the system could be seen by comparing Figure 10 and Figure 13. The adjustments made to the control system reduced the number of NTs from 290 to 40 for 120 bore holes.

Table 3: Input for suggested system design according to preliminary simulations.

Parameter	Explanation	Values	Unit
TS2	Max supply temperature	7	[°C]
TS3	Min supply temperature	4	[°C]
T_2	Lower temperature boundary road	4	[°C]
cc	Pipe spacing in road	0.1	[m]
NBore	Number of boreholes	120	[-]
λ_{ground}	Thermal conductivity of the ground	2	[W/(m K)]
DT0CST	Harnessing stop temperature difference	2	[°C]
DT1CST	Harnessing start temperature difference	4	[°C]
Nserie	Number of boreholes connected in series	2	[-]
Wvol	Water volume in short term storage	4.4	[m^3]

5 CONCLUSION

The methodology, presented in Pahud(2007) for using BRIDGESIM, to make a preliminary design of a hydronic pavement system have revealed that it is not feasible to design such a system for the location of Östersund; if only relying on harnessing solar energy and store the energy in a borehole thermal energy storage. It is possible to improve the model by adding other important physical phenomena's e.g. surface condensation and precipitation to the control system. Thus, decreasing the energy need. However, changes to the control system would most likely not be enough which means that supplementary energy from boilers or heat pumps would be needed.

The preliminary system design have however revealed that it is possible to design HP system for low supply temperatures of about 7 °C, considering a high thermal conductivity of the pavement. This temperature is far below the supply temperature that the manufacturers of HP system recommend, which is normally of about 35 °C. The prospect of utilizing low-temperature heat sources would make HP system more energy efficient which could make it an alternative to traditional winter maintenance methods. Usage of HP system would then be one way of making winter roads safer.

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