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Hydronic Heated Pavement System Using Precast Concrete Pavement for Airport Applications

Hesham Abdualla
Iowa State University, abdualla@iastate.edu

Halil Ceylan
Iowa State University, hceylan@iastate.edu

Sunghwan Kim
Iowa State University, sunghwan@iastate.edu

Peter C. Taylor
Iowa State University, ptaylor@iastate.edu

Kasthurirangan Gopalakrishnan
Iowa State University

See next page for additional authors

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Abstract
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Disciplines
Civil and Environmental Engineering | Construction Engineering and Management | Structural Materials | Transportation Engineering

Comments
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Hesham Abdualla[1], Halil Ceylan[2], Sunghwan Kim[3], Peter C. Taylor[4], Kasthurirangan Gopalakrishnan[5], and Kristen Cetin[6]

[1]Graduate Research Student, Iowa State University; email: abdualla@iastate.edu
[2]Professor, Iowa State University; Phone: 515-294-8051; Fax: 515-294-8216; email: hceylan@iastate.edu (**Corresponding Author**)
[3]Research Scientist, Iowa State University; email: sunghwan@iastate.edu
[4]Director, National Concrete Pavement Technology Center; email: ptaylor@iastate.edu
[5]Research Associate Professor; Iowa State University; email: rangan@iastate.edu
[6]Assistant Professor; Iowa State University; email: kcetin@iastate.edu

ABSTRACT

The use of deicing chemical has the potential to cause environmental and safety concerns and pavement deterioration. Hydronic heated pavement systems (HHPS) have been widely used to melt or prevent ice and snow accumulation on paved surfaces. HHPS uses heated fluid circulated through pipes embedded in the concrete pavement to warm the surface of the concrete. The objective of this study is to develop a conceptual design framework and construction guidance for large-scale HHPS using precast concrete pavement (PCP) technology to expedite construction work and minimize air travel disruption. The detailed design and 3-D visualization of construction procedures has been developed for HHPS using PCP technology. The outcome of this study will help contractors and transportation agencies to envision the constructability of different components in HHPS, including tubing patterns and construction procedures.

INTRODUCTION

Ice and snow accumulation on paved surfaces has the potential to reduce pavement surface's skid resistance and thereby cause hazardous conditions that may lead to aircraft incidents and accidents (McCartney 2014; FAA 2008). The use of deicing chemical agents and deployment of snow removal equipment (SRE) to remove snow/ice has the potential to cause foreign object damage (FOD) to aircraft engines, cause corrosion to the overall airplane structure, and lead to undesirable environmental issues (Xi and Patricia 2000). The use of these methods is also typically costly and time-consuming (Anand et al. 2016).

Hydronic heated pavement systems (HHPS) have been used to melt or prevent ice and snow accumulation on paved surfaces by using heated fluid circulated through pipes embedded in concrete pavement to warm the surface of the concrete and thereby melt ice and snow. The cooled fluid is recirculated through a heat source that reheats the fluid for each cycle (ASHRAE 2015). A HHPS using a geothermal well as a heat source was constructed for the aprons at the Greater Binghamton Airport (BGM) located in Johnson City, New York. The total surface area of that project was 297 m^2 at a construction cost of $ 1,600,000 (Guney and Bowers 2016). The Oslo International Airport at Gardermoen in Norway implemented HHPS using an Aquifer Thermal Energy Storage (ATES) system able to heat the aircraft parking with a total area of 700 m^2 (Barbagallo 2013). The system was also supported by an electric and oil-fired boiler to help increase the design energy density to 248 W/m^2 since the ATES alone was not capable of providing sufficient heating energy.

Precast concrete pavement (PCP) has demonstrated satisfactory performance in bridges, pavements, buildings, and airfield construction. It provides high strength, low permeability, and low cracking potential; these features are consequences of preparing the panels off-site where quality control can be more effectively implemented. Using a PCP technique instead of cast-in-place for construction of pavements can expedite the construction process by eliminating the need for concrete strength-gaining time from the on-site construction procedure (Merritt et al. 2004; Priddly et al. 2013). PCP technology enables rapid repair of pavement facilities and can be beneficially applied in situations where extended road closures could increase road congestion and result in increased lost work time, fuel consumption, and user-delay costs (Kohler at al. 2004). A study has shown that estimated daily user-delay costs for a four-lane divided facility carrying 50,000 vehicles per day can be as high as $383,000 per day for 24-hour lane closure, compared to only $1,800 per day for nighttime lane closure only (Priddly et al. 2013). Since it is important that flight operations be resumed in the shortest time possible, often allowing only 4 to 6 hours to complete repairs, the PCP technique can also be a good choice for minimizing airport pavement facility downtime (Bly et al. 2013).

While PCP construction in the U.S. began between 50 and 80 years ago, it did not appear to be a cost-effective technique at that time because of a lack of technical information which resulted in an increased labor requirements for installation. While many US highway agencies did not implement PCP technology for a long time, during the last 10 years, several U.S. highway agencies began implementing the technology and consequently the installation price has dropped by more than 50%. The Strategic Highway Research Program 2 (SHRP2) project R05 provided a guideline for design and construction of different PCP applications, and developed specific guidelines for project selection, design, fabrication, installation, and rehabilitation of PCP systems (Tayabji et al. 2013). PCP can be used to repair distressed areas of existing pavement that represent either small areas of localized distress or extended long-distance distressed areas in the pavement.

Because of increased use of PCP implementation, several agencies have participated in developing specifications and guidelines for such systems. The American Association of State Highway and Transportation Officials (AASHTO) established a Technology Implementation Group (TIG) during 2006 that developed a specification for fabrication and construction of PCP and guidelines for the design of PCP systems (Tayabji et al., 2009). Various PCP types have been assessed and compared to conventional concrete pavement systems in terms of design concepts, field installation procedures, advantages, limitations, and costs (Chang et al. 2004).

The specific PCP types evaluated include Super-slab, Full-depth repair, Stitch-in-time, and Uretek methods (Chang et al. 2004). While PCP has been used both in Europe and in the US for rapid repair, rehabilitation, and reconstruction of asphalt and concrete pavements, no guidance has been established for using PCP for large-scale heated airport pavements.

OVERALL CONCEPTUAL DESIGN OF HHPS

HHPS are typically closed-loop systems, as shown in Figure 1. After the fluid releases heat into the pavement, it returns to the heat source to be sent back through the pipes (Barbagallo 2013). The fluid can be heated by different types of fluid heaters, including geothermal hot water, underground thermal energy storage (UTES), boilers, and heat exchangers (FAA 2011), and the selection is based on availability at the project site. Geothermal water would be considered efficient in locations with good geothermal potential (Joerger and Martinez 2006). Geothermally heated hydronic systems often incorporate heat pumps to obtain greater heating capacity, because in many places ground temperatures are not high enough to heat the concrete sufficiently to melt the snow (Minsk 1999). The efficiency of HHPS in melting ice and snow depends on different factors, including fluid temperature, pavement conductivity, pipe depth, and pipe spacing (Ceylan et al. 2014).

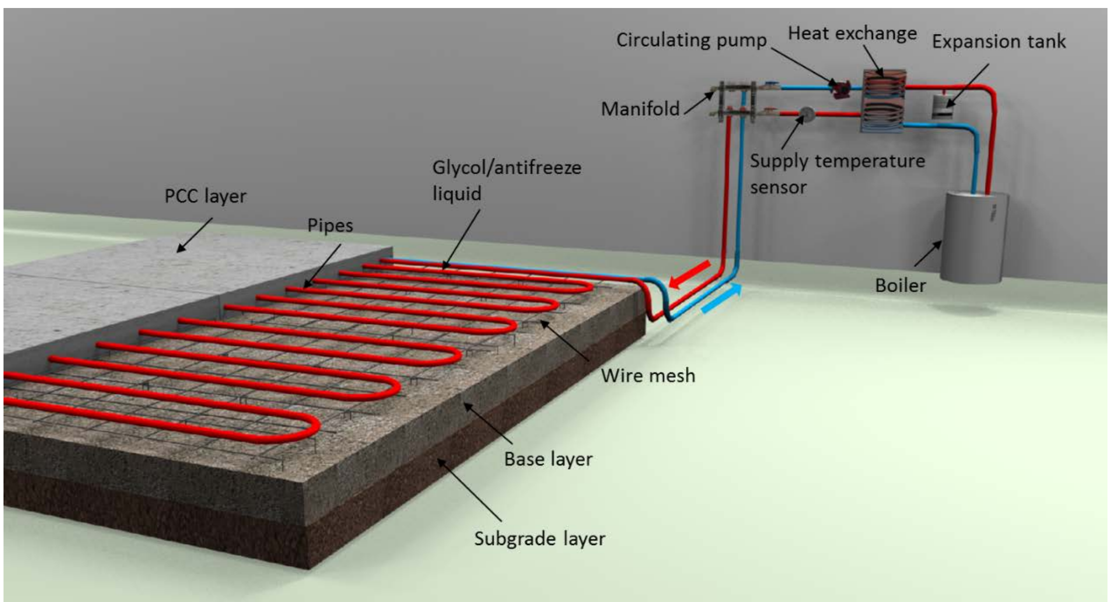


Figure 1. Schematic of HHPS.

Construction materials. The components of HHPS include heat transfer fluid, piping, a fluid heater, pumps, and controls (ASHRAE 2015). Pipes can be made of metal, plastic, or rubber, but a drawback of steel pipes is their susceptibility to rusting, so the use of steel embedded in pavement is not a common practice. An attractive alternative to steel pipe is plastic pipe such as polyethylene (PE) or cross-linked polyethylene (PEX) because it is corrosion-resistant and has a lower material cost. Polyethylene and cross-linked polyethylene withstand fluid temperatures up to

60°C and 93°C, respectively (ASHRAE 2015). A common practice is to use propylene glycol-water as a heat transfer fluid because of its moderate cost, high specific heat, and low viscosity.

Piping design pattern. A hydronic slab's piping can be arranged into different patterns – for example, serpentine or slinky – to provide uniform heat on the hydronic slab surface and prevent ice and snow accumulation. A serpentine pattern (Figure 2) is commonly used in melting snow and ice on paved surfaces (Spitler and Ramamoorthy 2000). In the serpentine pattern, straight pipes are evenly spaced and connected to a manifold that uses U-shaped pipes. The slinky pattern is formed by configuring pipes into a circular shape, with each circle overlapping the next adjacent one. An HHPS was constructed into a 44.5 m long and a 17.7 m wide bridge deck in Amarillo, Texas using a serpentine pipe pattern (Minsk 1999). The detailed pipe pattern can be designed using industrial software such as LoopCAD 2016 (Avenir Software Inc. 2017) to generate the circuit layout drawings and zones for the HHPS project site, as well as perform detailed calculations such as energy density based on ASHRAE methods (ASHRAE 2015). LoopCAD software offers flexible tools for adjusting pipe layout drawings and generating loop lengths.

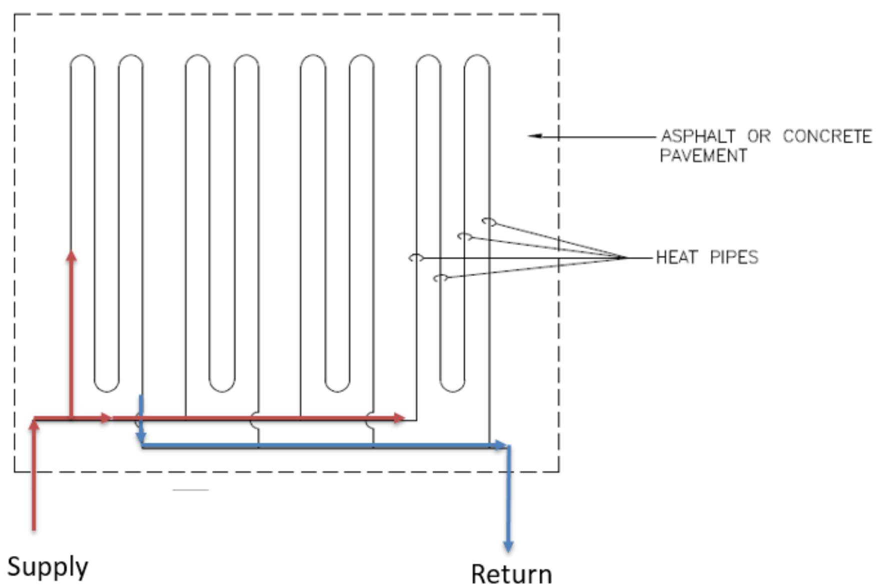


Figure 2. Hydronic pipe pattern.

Heat requirements. The minimum design requirement of a heated pavement system (HPS) is that it must be capable of keeping a surface condition of "no worse than wet" and maintain a surface temperature above the freezing point both before and during snow accumulation (FAA 2011). The heating requirement for snow melting depends on the rate of snowfall, the air temperature, the relative humidity, and the wind speed. Equation 1 is the steady-state energy-balance equation for required heat flux (q_O), expressed in (W/m^2)

$$q_o = q_s + q_m + A_r(q_h + q_e) \qquad (1)$$

where q_s, q_m, A_r, q_h, q_e are sensible heat flux (W/m^2), latent heat flux (W/m^2), snow-free area ratio, convective and radiative heat flux from a snow-free surface (W/m^2), and heat flux of evaporation (W/m^2), respectively. The detailed equation definition and parameters are available in the ASHRAE 2015 HVAC Applications Handbook (ASHRAE 2015) and the FAA advisory Circular AC 150/5370-17 (FAA 2011). Equation (1) does not account for back and edge of the slab heat losses that increase the total heat slab output (q_o); these can vary from 4 to 20% depending on factors such as pavement construction, operating temperature, ground temperature, or back exposure (Abdualla, et al. 2016). A finite-element (FE) method can also be used as a tool for estimation of the required heat flux and the snow/ice melting time for HHPS (Mallick et al. 2012).

The heat requirements for a snow-melting installation are based on system classifications I, II or III. Class I (minimum): residential walks or driveways, class II (moderate): commercial sidewalks and driveways, and class III (maximum): toll plazas of highways and bridges; aprons and loading areas of airports; hospital emergency entrances (FAA 2011). These classifications are correlated with snow-free area (A_r) values. Class I has a snow-free area ratio of 0 and the surface and can be covered with a sufficient thickness of snow before beginning to melt the snow. Class II has a snow-free area ratio of 0.5, the surface must be kept clear of snow accumulation, and a wet surface is acceptable. Class III has a snow-free area ratio of 1, the surface must melt falling snow quickly, and the surface must remain dry.

SYSTEMATIC DESIGN AND CONSTRUCTION CONSIDERATION FOR LARGE-SCALE HHPS USING PCP

Figure 3 shows the construction steps required for constructing a HHPS using PCP. The major difference between the construction of HHPS using PCP and typical PCP installation is that a HHPS using PCP requires installation that allows hot fluids to run through the pipes and thereby release heat to warm the paved surfaces and melt ice and snow. The construction sequence for a HHPS using PCP involves the following three major steps:

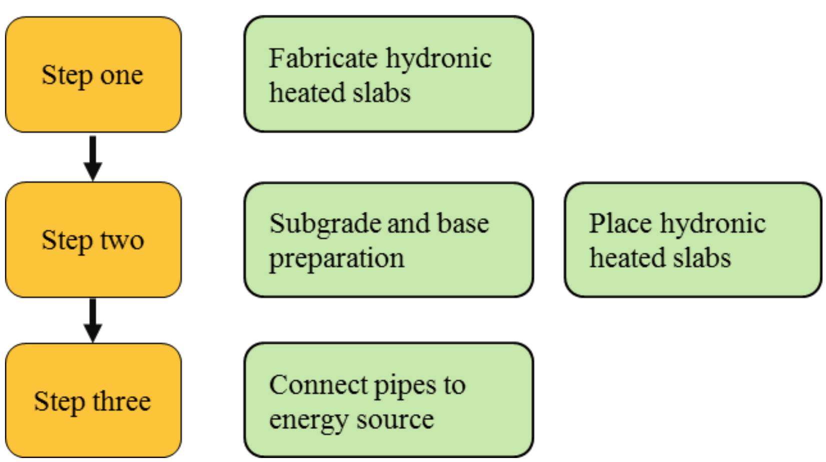


Figure 3. Work sequence.

Step 1: Fabricate hydronic heated slab off-site. Figure 4 presents a 3D visualization for hydronic heated slab fabrication using PCP with connected pipes placed inside each panel. A hydronic heated slab can be fabricated off-site using PCP (Figure 4) with formwork designed to facilitate placement of the pipes, wire mesh, dowel bars, and slots (Figure 4a and Figure 4b). The formwork has open areas to permit inlet and outlet pipes to be connected to other hydronic slabs. The pipe is placed on top of wire mesh to elevate it closer to the surface and hold it there while the concrete is poured. A minimum of 50 mm of concrete cover extending above the top of the pipe is typically required (ASHRAE 2015). The pipe pattern can be designed for a particular job site to provide sufficient heat for melting ice and snow. After securing the pipe, concrete is poured into the formwork and then is screeded and cured before transferring the final product to a construction site (Figure 4c and Figure 4d).

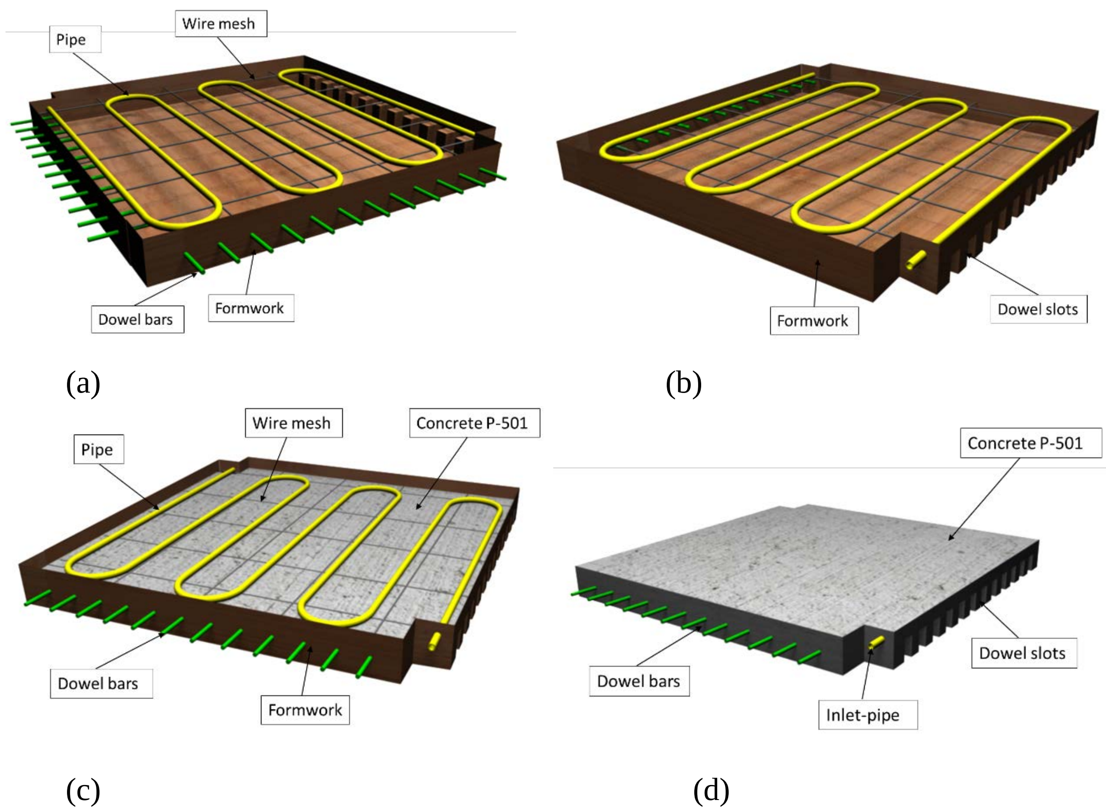
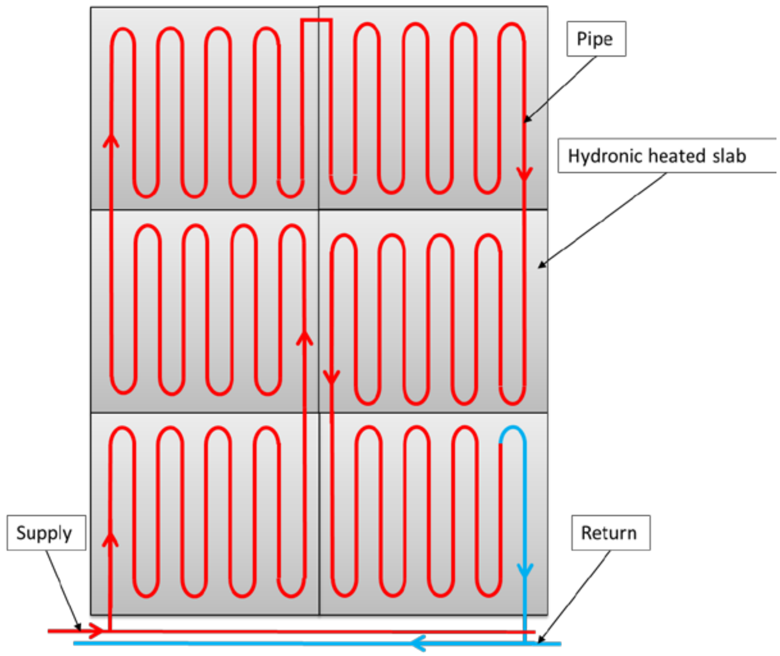
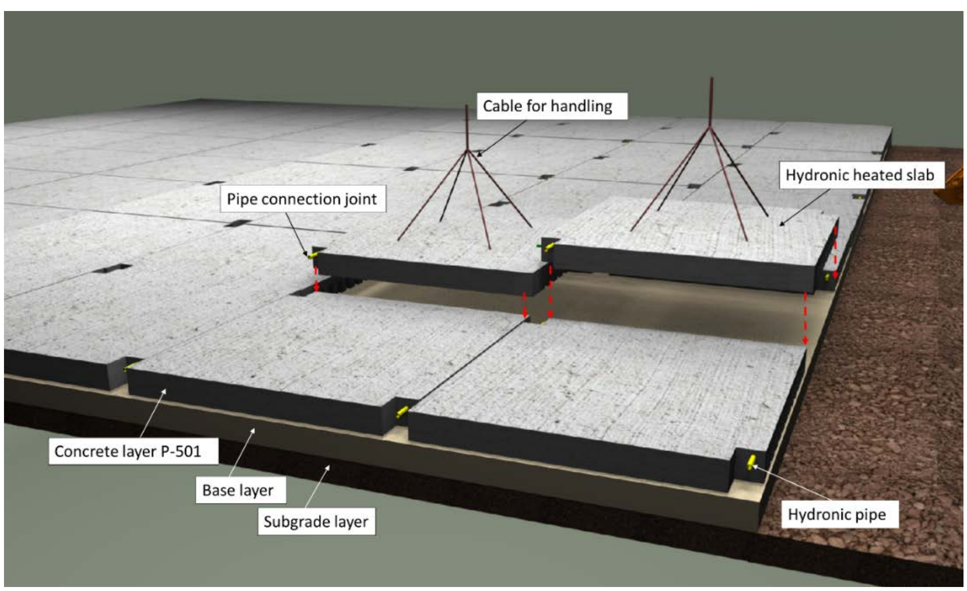


Figure 4. Hydronic heated slab fabrication using PCP.

Step 2: Prepare the base layer and place hydronic heated slabs. Prepare and compact both the subgrade and base layers to satisfy density requirements and identify the location of manifolds to define pipe circuit length and pattern. The pipe pattern and pipe spacing can be adjusted based on the project site, geometry, size, required energy, and locations. The slab has dowel bars and slots to provide load transfer like a traditional PCP structure, and can be transported and placed into position at the project site. The pipes can be connected to each other at the joints after placing the hydronic slabs and filling the voids of the dowel slots and ensuring that the desired panel elevation is achieved. Figure 5a and Figure 5b show the pipe pattern and the connections between hydronic-heated slabs, respectively.



(a)



(b)

Figure 5. Hydronic heated slabs assembly.

Step 3: Connect pipes to energy source. After identifying and connecting the manifold to the pipes, the manifold should be connected to the heat source to permit fluid to circulate in the embedded pipe through a heat source (Figure 6). A HHPS can be operated automatically using a control system to turn the system on and off based on a set-point temperature value that can be measured by temperature sensors embedded in the concrete. To provide satisfactory operation the HHPS should be warmed up before snow and ice accumulates on the surface (ASHRAE 2015).

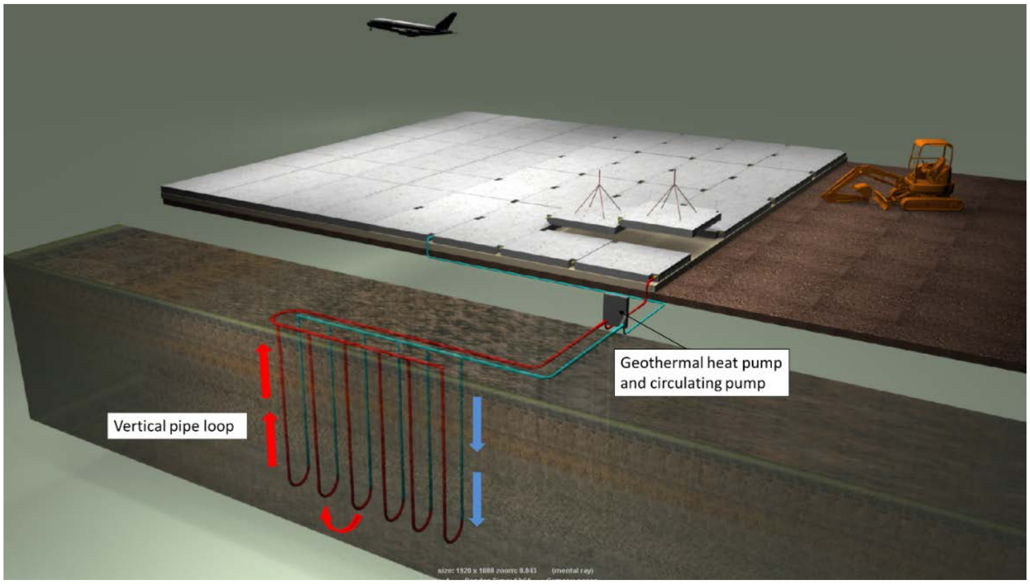


Figure 6. HHPS with geothermal wells as heat source.

CONCLUSIONS

The goal of this study was to create a conceptual design framework and provide construction guidance for a hydronic heated pavement system (HHPS) using precast concrete pavement (PCP) technology. The results of this work can be listed as follows:

- Construction considerations and 3D visualization for HHPS using PCP technology were developed to ensure that the system would perform as desired and to develop more robust construction schemes, high-performance heated airport pavement systems, and good construction practices.
- A HHPS using PCP is a viable option for accelerating construction procedures, reducing labor costs, and minimizing traffic disruptions. HHPS PCP technology also enhances heat distribution to the pavement surface since the HHPS slabs are fabricated offsite where construction quality and workmanship can be better controlled.
- Heat generation and performance of HHPS using PCP can be tested before transporting and placing it at the project site.
- The bedding support materials used under PCP could be modified to behave as an insulation layer by adding admixtures to mitigate heat loss, and HHPS using PCP would then provide better performance and reduce the operational cost of HHPS during the design life of the heated slabs.
- HHPS using PCP has the potential for installation in small areas such as gates to prevent snow and ice accumulation within a short time to minimize flight delays and/or cancellations.

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