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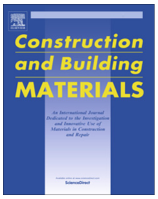

Experimental and numerical study on heating performance of the mass and thin concrete radiant floors with ground source systems

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HIGHLIGHTS

- Heating performance of mass and thin concrete radiant floors.
- Comparing the temperature variation in both radiant floors.
- Storing considerable thermal energy in the mass floor by three heating cycles.
- A 3D finite element (FE) model for temperature profile in the mass concrete radiant floor.
- Good agreement between FE modeling and experimental results.

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ABSTRACT

The thickness of the slabs is imperative when considering the method of heating system due to the thermal mass and thermal lag properties. Thermal properties of concrete allow thermal energy to be stored in the mass floor after heating cycles. In this study, the experimental heating performance of a 1.22 m-thick mass concrete radiant floor and a 0.18 m-thick concrete floor is investigated. In addition, a full 3D finite element model of the mass concrete radiant floor is performed and validated by the full-scale building measurements. The mass floor simulation contains embedded pipes, vertical steel anchors, and horizontal reinforcing steel grids at the top and bottom. The experimental results show that the initial temperature of the thick concrete slab is increased by a few cycles and the mass heated concrete floor acts as a thermal storage battery for the building. Also, the modeling results are in good agreement with construction site measurement. This model is further expanded to simulate different thermal loadings on the pipes to predict the temperature development inside of the mass floor. Furthermore, importance of the vertical steel anchors in conduction the generated heat to the surface of the floor would be seen in the modeling results.

1. Introduction

Concrete slabs with a heating/cooling pipe system have been extensively used for heating and cooling buildings. Nowadays, to increase efficiency, concrete slabs with heating and cooling pipe systems are an essential element of modern buildings. The recent researches indicated that radiant floor system can provide thermal comfort and low energy consumption, and quiet operation [1–4]. The heated and (or) chilled fluid in the radiant floor system that originates from a ground source will substantially increase the energy efficiency. However, the thin or thick concrete radiant floors can perform differently because of the thermal mass and the thermal lag properties of concrete.

The possibility of storing thermal energy in the mass concrete floor will have a major impact on stabilizing the temperature in the building floor. The thermal performance and energy storage density of a system could be optimized by controlling the storage-restitution periods, thickness of slab and surface radiative properties which the most practical choice is slab thickness [5–8]. Concrete has a high volumetric heat capacity and low thermal conductivity properties which allows it to charge and discharge effectively for 24 h period [9]. The specific heat capacity $C_{p,}$ of the material is ability of the material to absorb or radiate heat defines the effective thermal capacity of a material [10]. The material with higher heat capacity such as concrete can store the generated heat (hydration heat in mass concrete or heat from radiant heating).

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However, thermal cracks in the concrete elements should be prevented due to huge temperature change [11–13].

Part of the thermal energy is stored by the mass concrete slab and its' temperature increases. When the concrete floor is covered by a roof, the indoor temperature is mostly affected by radiant heat floor. Using the mass heated floor in the covered structures such as offices and laboratory with controlled condition of internal air temperature can moderate the heating need at cool seasons. The slab temperature could be used as a controlled parameter to increase energy efficiency or prevent discomfort [14,15].

Due to complicated nature of heat transfer through the concrete and reinforcement combination, some software engineering and technology may result in higher accuracy temperature distribution for the modeling. Therefore, modeling the all elements involved in heat transfer modeling is necessary. Disregarding the steel role in the heat transfer of the reinforced radiant floor system would cause inaccurate results. Therefore, simplifying the model should be reasonable in the accurate range of results. Some numerical methods such as finite difference and finite element have been used for modeling the heat transfer in different materials [16–18]. However, the model validation needs to be verified by the physical experiment. Jin, X et al. [19] has studied a finite volume model for a radiant floor cooling system regarding the effects of the pipe thermal resistance and water velocity on the performance of the system. It was noted that the effect of water velocity in the radiant floor system is not great and the performance of radiant floor will be affected by low thermal conductivity of the piping system. Sattari and Farhanieh [20] studied a finite element model of radiant floor system and they concluded that thickness of the radiant floor system are the most important parameters in the radiant floor design.

In this study, the heating performance of thick and thin radiant concrete floors is presented by temperature measurement of slabs in a covered laboratory building. Steady state heat transfer analysis of the heated slab with heating pipe systems is completed by a widely finite element software [21]. A three-dimension full modeling of concrete, steel, and pipes is selected to study the thermal behavior of mass heated concrete floor as well.

2. Experiment

The experimental part of this research has been conducted in a new full-scale laboratory building over 3000 m^2 area [22–24]. The concrete slabs with embedded pipes were placed as the foundation of the building. The slabs include the 1.22 m-thick mass concrete floor (570 m^2 area) with heat tube located 0.15 m under the surface of the slab and the 0.18 m-thick slab (570 m^2 area) with embedded heat tube at the bottom. The mass concrete floor has four sets of vertical steel anchors with diameter of 0.04 m located at every 1.22 m in X, Y direction. There is 0.025 m of polystyrene insulation under the thin slab and all-around of the mass floor perimeter to increase the thermal storage capacity of the radiant floor. The mass concrete floor was cast on the 0.075 m mud slab with no insulation underneath.

Before casting the concrete slabs, T-type thermocouples have been installed at the positions all through the height of the slabs to measure the temperature at different elevations. T-thermocouple wire temperature range is −40 to 80 °C with accuracy of ±0.1 °C. All thermocouple wires are connected to a data logger to record the data over time. Data logger was selected with thermocouple measurement accuracy of ±0.3 °C (−25° to 50 °C), ±0.8 °C (−55° to 85 °C). The thermocouple measurement was recorded with ±0.01 °C accuracy in the data logger. The aim of setting thermocouples in various elevations is to measure the thermal profile along the concrete depth when the radiant floor is applied. The thermocouples are located at 0.05 m, 0.15 m, 0.3 m, 0.52 m, 0.82 m, and 1.22 m below the surface of the mass concrete. One thermocouple is located under the mud slab to measure soil temperature. Thermocouples are concentrated at the top of the slab to measure more precisely the heat from the radiant pipe system. It means when the radiant floor system working, the greatest variations in temperature are expected at the top of the mass floor around the pipes. There are fewer thermocouples in 0.18 m slab to record the temperature profile. Thermocouples are located at 0.05 m below the surface, at middle of the slab, and the bottom of the thin slab. The thermocouples' position at the 1.22 m floor and 0.18 m slab are shown in Figs. 1 and 2, respectively.

The average of two thermocouple readings at each location is used for collecting the temperature data to verify the accuracy of the results. In addition, there are two sets of thermocouple column for each slab including the "edge point" (0.3 m from the building façade) and the "center point" (5m from the building façade). The temperature in the radiant floor system is important because source of heating system in the building is the key to control the indoor air temperature.

In this case study, radiant floor system works with ground source heat pump (GSHP). The supply temperature and return temperature of the radiant piping system are measured over time to control the radiant floor system. An ultrasonic flow meter was used to measure the flow rate of fluid through the pipes. Pressure gauges were inserted to the p-t ports of pipes to measure the return fluid. These measurements over step time of 15 min were used as input parameters for the modeling of the radiant floor system.

3. Heat transfer analysis

The in-situ temperature gradient by a piping system can be simulated with a comprehensive finite element modeling. A three-full modeling of concrete, steel, and pipes is selected to study the thermal behavior of heated concrete floor. Several researches show that the 3D finite element analysis provides the more detailed modeling of the concrete pavements [25]. The fundamental for thermal analysis in this finite element software [21,26] is a heat balance equation obtained from the principle of energy conservation.

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + k\frac{\partial^2 T}{\partial z^2} + q = \rho c\frac{\partial T}{\partial t}$$

where c is the specific heat coefficient [J/(kg.°C)], k is the thermal conductivity coefficient [W/(m.°C)], ρ is the density [kg/m^3], q is the heat generation rate [$J/(m^3.s)$]. The q term can be neglected regarding there is no heat generation after long time of casting concrete.

The generated heat from the piping system distributes to the surrounded area by concrete, steel anchors, top and bottom horizontal mesh. The heat transfer in the slab happens through the conduction, convection processes. Then, the indoor air would be affected by the heat of embedded heat pipes by convection and radiation. The amount of transferred heat through radiation and convection from the surface of the concrete depends on a lot of parameters such as the concrete properties, indoor air temperature, air movement, building insulation, occupants, floor cover, and less on outside weather conditions. The most effective parameters are needed to simplify the model with accurate results.

Regarding the finite element modeling, a three-dimensional 8-node thermal solid element (Solid 70) was used to model concrete thermal properties. A 3D element (Fluid 3-D th-fl pipe 116) used to model the fluid with the ability to conduct heat and transfer fluid between its two main nodes. Finally, 3D conduction bar uniaxial