Applicability of insulation layer on thermal performance of energy slab

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ABSTRACT: The energy slab encases heat exchange pipes as a heat exchanger inside a slab structure of a building to utilize the geothermal energy for heating and cooling buildings. In the energy slab, heat exchange is induced with the surrounding ground by circulating a working fluid through the heat exchange pipes. The heat exchanger should be arranged with a horizontal layout, which are adjacent to underground space, to install in the energy slab. Therefore, when the heat exchanger is assembled in the energy slab, it is important to thermally insulate the heat exchanger from adjacent indoor air, because air temperature inside the underground building space significantly affects the thermal performance of energy slab. In this study, thermal performance of the energy slab was experimentally evaluated with consideration of a thermal insulation layer. Then, an optimal thermal insulation material was proposed from the results of parametric study of CFD analysis. First, two field-scale energy slabs (i.e., floor-type energy slab and wall-type energy slab) consisting of both the thermally insulated and non-insulated slabs were constructed in a test bed. In order to evaluate the effect of air temperature on the thermal performance, a series of Thermal Performance Tests (TPTs) was carried out with consideration of existence of a thermal insulation layer. A CFD model was then developed by calibrating with the TPTs results to estimate the effect of thermal conductivity of the thermal insulation material. The thermal insulation layer can relieve the effect of surrounding thermal environment. Moreover, the thermal performance of energy slabs increased as the thermal conductivity of the thermal insulation material decreased. Note that thermal insulation materials with the similar thermal conductivity to a Phenol Foam (PF) board is most efficient for thermally insulating the energy slab.

Keywords: Energy slab, Thermal insulation, Computational Fluid Dynamics (CFD), Thermal performance test (TPT), Phenol Foam (PF)

1 INTRODUCTION

The Ground Source Heat Pump (GSHP) system is usually coupled with Ground Heat Exchangers (GHEXs) to utilize geothermal energy. In general, a closed-loop vertical GHEX is a conventional type of GHEX, which is most popular in practice. However, the conventional closed-loop vertical GHEX requires a high initial investment cost because of the additional drilling of borehole and need for the construction area (Boënnec 2008). Note that the drilling cost occupies more than 50% of the total construction cost. Therefore, to reduce the construction cost, novel types of GHEX have been developed, which are fabricated in underground structure components, e.g., energy textile (Lee et al. 2012), energy pile (Brandl 2006, De Moel et al. 2004, Morino and Oka 1994), etc.

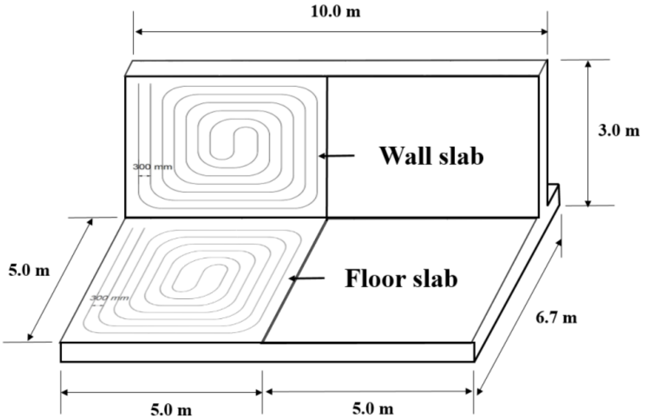
An energy slab is installed as a floor slab layer to utilize the building structure as a hybrid energy structure (Choi 2012, Choi and Sohn 2012). Application of energy slabs is an effective strategy for reducing the construction cost without additional drilling, because it is buried underground with a horizontal layout, and can be constructed not only in new buildings but also in existing structures. However, the energy slab should show poorer thermal performance than other conventional GHEX because it is constructed at a shallow depth where can be affected by ambient temperature and have the low thermal conductivity.

Even though the energy slab is constructed in the underground structure, the distance between the heat exchanger and underground space is close enough to thermally influence each other because the heat exchanger is installed in the concrete slab with a horizontal layout. For example, the repeated temperature change in the heat exchanger during heating/cooling operation can influence air temperature in the underground space, which can degrade the indoor HVAC efficiency. On the contrary, the thermal performance of heat exchangers is reduced due to indoor air temperature in the underground space. Conceptually, during the heating/cooling operation, the indoor air temperature of underground space, which is maintained at a target heating/cooling temperature, is different from the that of the working fluid in the heat exchange pipes. Heat exchange between the indoor air and the heat exchanger can take place in case no thermal insulation is installed over the heat exchanger, which reduces the thermal performance of heat exchanger. Therefore, thermal insulation between the heat exchanger and ambient thermal environments is the most critical issue in application of the energy slab even when the energy slab is installed in the underground structure.

In this paper, experimental and numerical studies for the energy slab were carried out to evaluate the effect of a thermal insulation layer on the thermal performance of energy slab. First, two types of field scale energy slabs were constructed in a test bed with different thermal insulation conditions. Then, for evaluating the thermal performance of each energy slab, Thermal Performance Tests (TPTs) were conducted. Finally, a parametric study was carried out with consideration of various thermal insulation materials using the developed CFD model.

2 SUMMARY OF ENERGY SLAB CONSTRUCTION

A field-scale energy slab was constructed in a test bed as shown in Figure 1. The energy slab was constructed on the floor and wall with the same interval of heat exchange pipes to expect similar heat exchange amount per unit pipe length. The backfill material on the back side of the wall-slab resembles the in-situ ground condition.

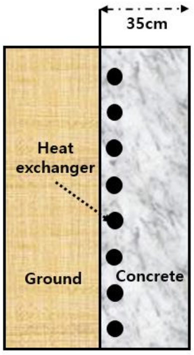


(a) Schematic of energy slab

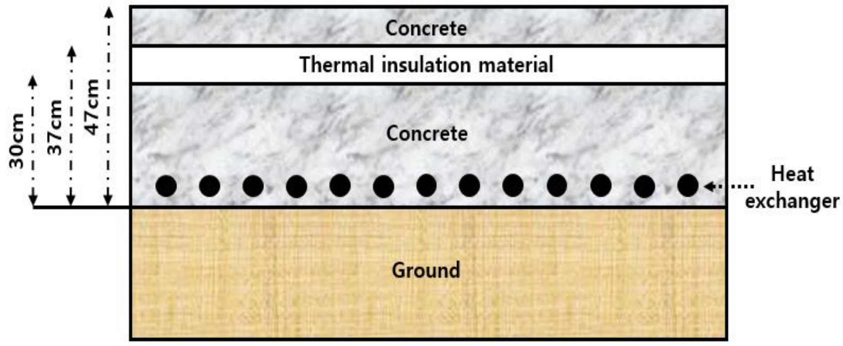
(b) Overview of test bed

Figure 1. Schematic and overview of constructed energy slab

Figure 2 shows the sectional view of the constructed energy slabs. In this experiment, since the energy slab was exposed to ambient air, seasonal air temperature changes considerably affect the thermal performance of energy slab. Moreover, even though the energy slab is constructed in the underground structure, repeated temperature changes by the cooling/heating operation may affect the indoor air temperature of the underground space. Consequently, it is of importance to relieve such mutual influence along with a thermal insulation layer installed within the energy slab. In the test bed, two types of energy slabs were installed with different thermal insulation conditions to evaluate the effect of a thermal insulation layer on the thermal performance of energy slab. In floor-type energy slab, a Phenol Foam (PF) board with the thermal conductivity of 0.018 W/mK was adopted as a thermal insulation layer, which is expected to hinder the thermal interaction between the air and heat exchanger efficiently. On the other hand, the thermal insulation layer was not inserted in the wall-type energy slab. Table 1 shows the specification of each energy slab.



(a) Wall slab



(b) Floor slab

Figure 2. Sectional view of energy slab

Table 1. Specification of each energy slab

Type	Material	Thermal conductivity of Thermal insulation material	Pipe length	Pipe interval
Floor-type energy slab	High density polyethylene (HDPE)	0.018 W/mK (PF board)	85 m	30 cm
wall-type energy slab		-	58 m	30 cm

3 FIELD TEST FOR EVALUATING INFLUENCE OF THERMAL INSULATION LAYER

The TPT is one of the effective tools to evaluate the thermal performance of GHEXs because it is simulated under real operation conditions of the GSHP system. In this test, an artificial heat load is applied by maintaining a target inlet fluid temperature in a constant-temperature water bath. From the TPTs, the heat exchange amount is calculated from Eq. (1).

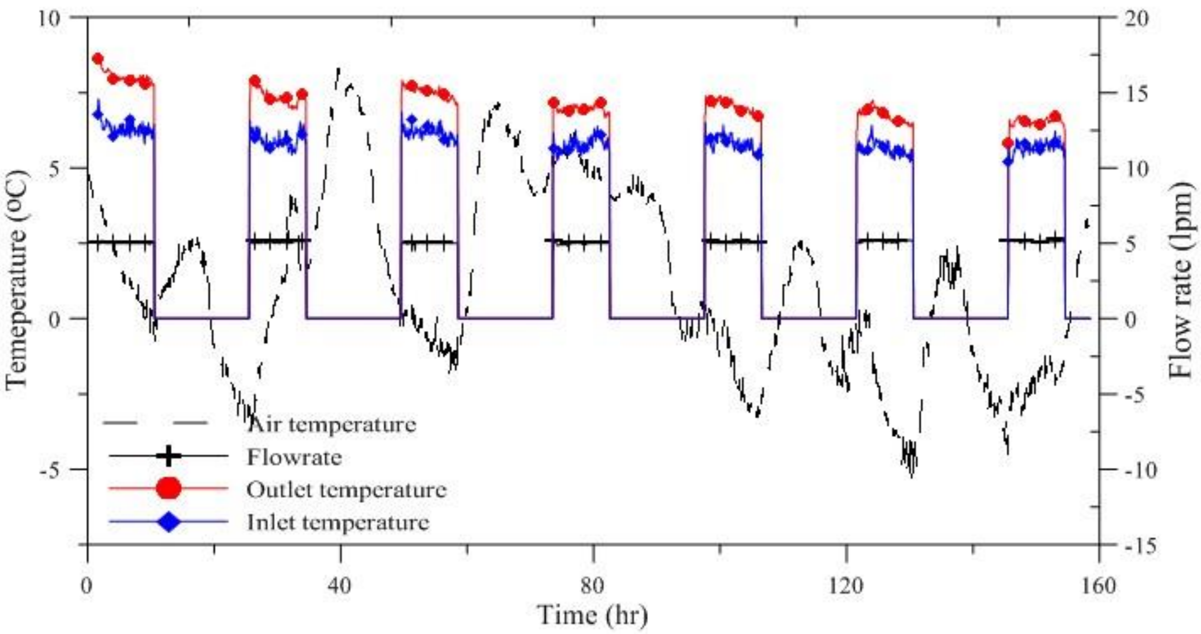
$$Q = C\dot{m}\Delta T = C\dot{m}(T_{in} - T_{out}) \tag{1}$$

where Q = heat exchange amount (W), T_{in} = inlet fluid temperature (℃), T_{out} = outlet fluid temperature (℃), $\dot{m}$ = mass flux of circulating fluid (kg/s) and C = specific heat of circulating fluid (J/kgK).

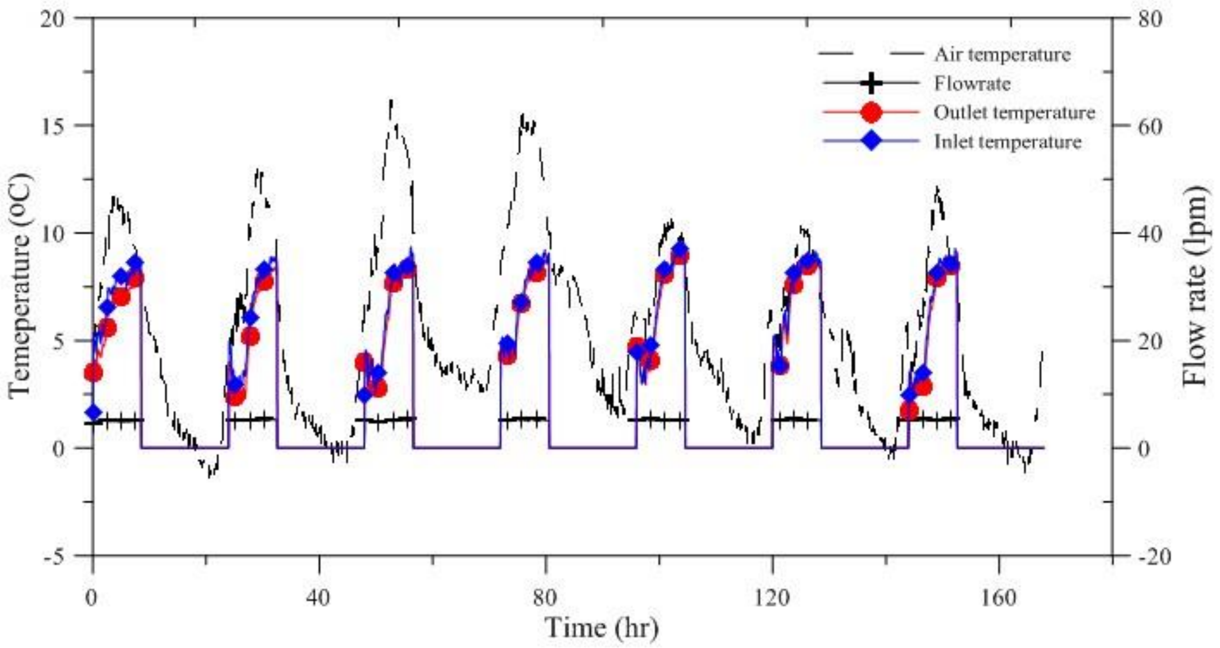
The test conditions are summarized in Table 2. As shown in Figure 3, the difference between the inlet and outlet temperature was not observed in the wall-type energy slab. Note that, the tendency of both inlet and outlet temperature change was similar to that of the ambient air temperature. Because no thermal insulation layer was installed in the wall-type energy slab, the ambient air signficantly influenced the temperatuer of heat exchanger. On the contrary, in case of the floor-type energy slab, heat exchange occurred stably during the entire test irrespective of the ambient air temperature. This result indicates that a thermal insulation layer should be inserted in the energy slab to stimulate heat exchange by cutting off the ambient air.

Table 2. Operational condition of in-situ TPT

Type	Condition
Operation type	Activating 8 hours – Deactivating 16 hours (intermittent operation)
Flow rate	5 L/min
Inlet temperature	5℃ (heating condition)
Sample interval	5 min
Total test duration	7 days



(a) Floor-type energy slab (with thermal insulation layer)



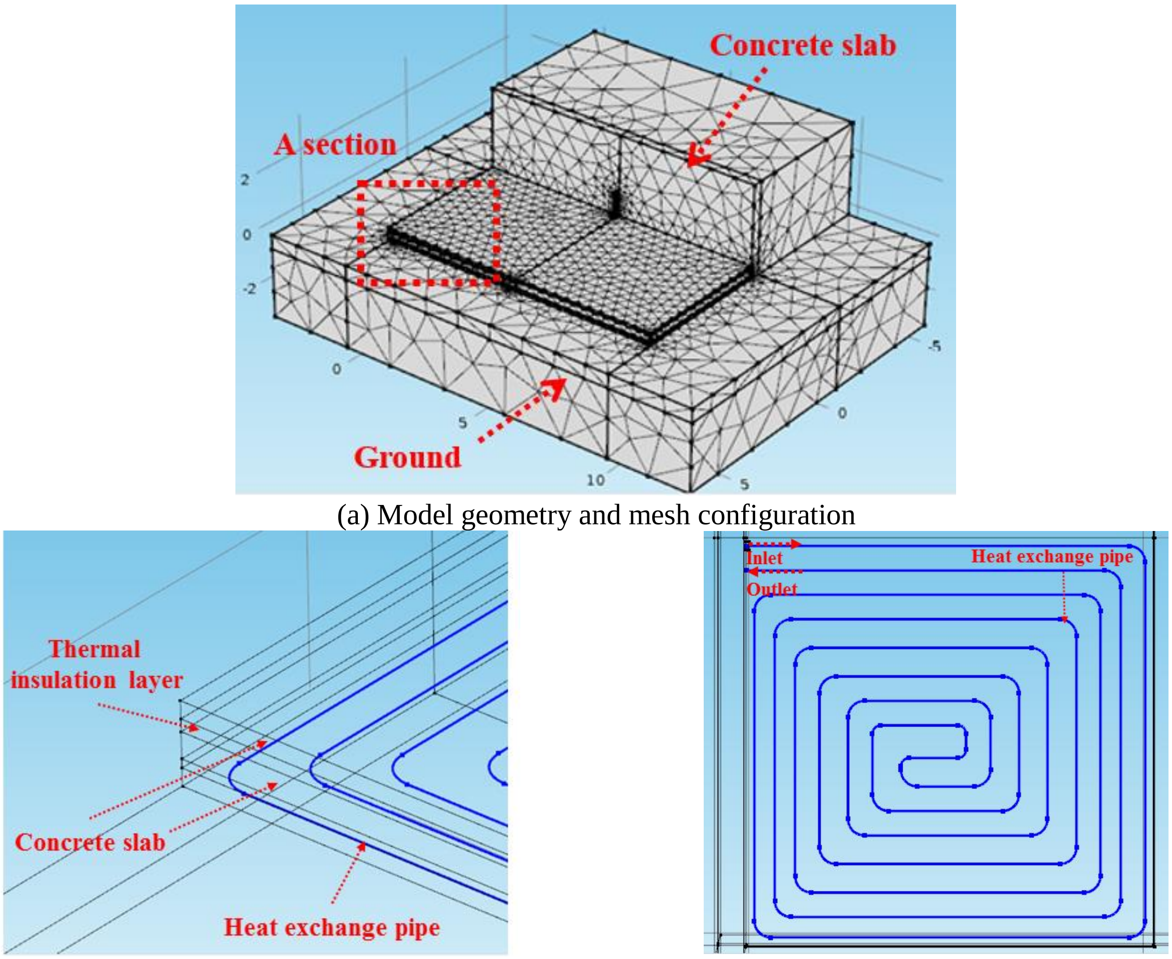
(b) Wall-type energy slab (without thermal insulation layer)

Figure 3. Results of TPTs (change in inlet and outlet temperature and heat exchange amount)

4 PARAMETRIC STUDY FOR THERMAL INSULATION LAYER

4.1 *Development of CFD model*

A CFD model was developed using COMSOL Multiphysics for evaluating the effect of a thermal insulation layer in the energy slab. Figure 4 shows the entire geometry and mesh configuration of the CFD model. The mesh configuration is composed of the 3-D tetrahedral element, and the number of meshes is set to about 50,000 to improve the accuracy of the numerical model.



(a) Model geometry and mesh configuration

(b) Enlargement of section A (c) Configuration of heat exchange pipe

Figure 4. Geometry and mesh configurations of developed numerical model

Thermal properties of each component are summarized in Table 3. The thermal conductivity of concrete slab and ground formation were directly measured with QTM-500 and KD2-pro, respectively (ASTM C 1113-90, ASTM D 5334). The thermal properties are referred to the literature and product specification (engineering toolbox, 2017).

Table 3. Applied material properties of energy slab

Type	Ground	Concrete slab	HDPE (Pipe material)	Water
Density (kg/m^3)	1,820	3,640	950	998.2
Specific heat (J/kgK)	1,480	840	1900	4,182
Thermal conductivity (W/mK)	1.30	2.050	0.4	0.6
Viscosity (kg/ms)	-	-	-	0.001

The developed CFD model was verified by comparing with the TPT result for the floor-type energy slab. The operating conditions applied to the numerical analysis are identical to the actual field test (refer to Table 2). In order to validate the model, the inlet fluid temperatures measured in the TPTs were applied to the boundary as a transient boundary condition. Then, the outlet fluid temperatures calculated through the numerical analysis were compared with the measurement in the TPT. Especially, because the test bed is exposed to the atmosphere, the thermal performance of energy slab should be largely affected by the variation of air temperature. Therefore, the recorded variation of ambient air temperature with time was applied to the outside boundary of the energy slab in the numerical model (refer to Figure 3(a)). The comparison between the numerical analysis and the TPT result is shown in Figure 5. As a result, it is proved that the numerical model can accurately simulate the field TPT within the average error of 4.01 % and Root Mean Square Error (RMSE) of 0.41℃.

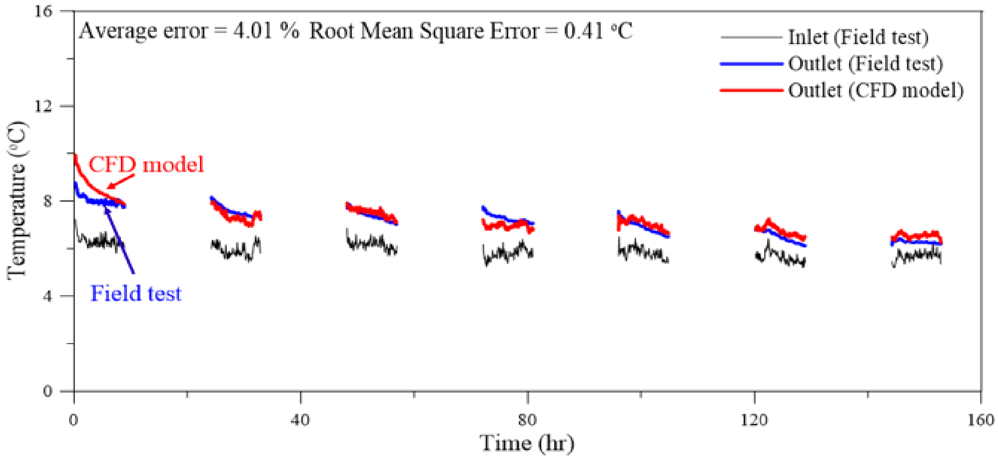


Figure 5. Comparison of outlet temperature between field test and CFD model

4.2 *Results of parametric study*

The parametric study was performed on different materials for the thermal insulation layer, which are summarized in Table 4. The thermal conductivity of each material is referred to the product specification. Note that as the air temperature suddenly increased from the 3rd day of the field test for the floor-type energy slab (refer to Figure 3), an abrupt increase in the average heat exchange amount was simulated around on the 4th day of the test in all cases.

Table 4. Thermal conductivity of considered thermal insulation material

Type of thermal insulation material	Thermal conductivity (W/mK)
PF board – Field test case	0.018
VIP (Vacuum insulation panel)	0.003
GFP (Gas-filled panel)	0.004
Polyurethane	0.025
Mineral wool	0.035
Bottom ash-air mixture (porosity = 0.33)	0.209

Figure 6 shows the average heat exchange amount according to the choice of the thermal insulation materials. As a result, an increase in the thermal conductivity of insulation layer reduced the thermal performance of energy slab due to the influence of ambient temperature. Especially, from the 6^{th} day, the average heat exchange amount of the energy slab in case of using the bottom ash-air mixture showed a negative value because the temperature in the concrete slab became lower than that of the inlet temperature (refer to Figure 7).

In order to evaluate the performance of the thermal insulation layer, a relative thermal conductivity (RTC) and relative heat-exchange amount (RHA) are considered in this paper. In this case, the RTC and the RHA are normalized by the PF board (Eq. (2)).

$$\mathrm{RTC} = \frac{Thermal\ conductivity\ of\ material}{Thermal\ condcutivity\ of\ PF\ board} \quad (2\text{-a})$$

$$\mathrm{RHA} = \frac{Heat\ exchange\ amount\ of\ each\ material\ case\ (7^{th}\ day)}{Heat\ exchange\ amount\ of\ PF\ board\ case\ (7^{th}\ day)} \quad (2\text{-b})$$

The performance of the thermal insulation materials was indirectly evaluated by comparing the inverse of RTC, which indicates the thermal insulation performance, and the RHA value. Figure 8 shows a non-linear relationship between the inverse of RTC and the RHA value. In other words, the application of thermal insulation layer with the thermal conductivity less than that of the PF board can increase the thermal performance of the energy slab, but the amount of increase is insignificant. Therefore, the thermal conductivity of the PF board shows suitable thermal insulation that leads to the optimum thermal performance of energy slab.

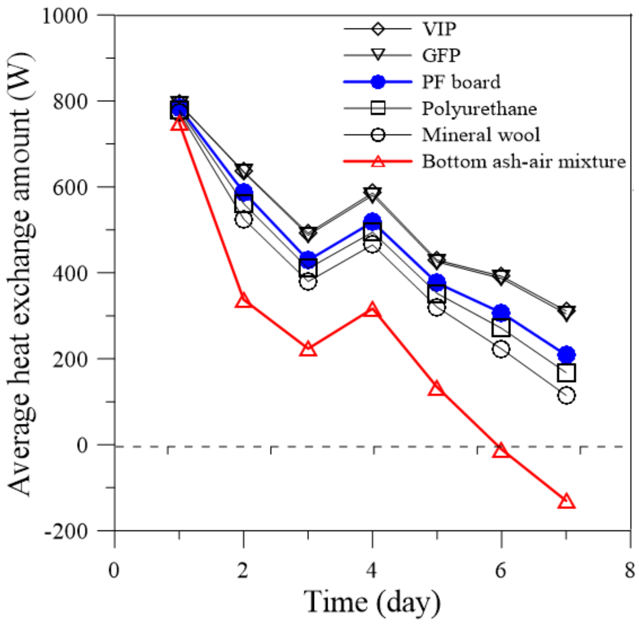


Figure 6. Average heat exchange amount according to thermal conductivity of thermal insulation material

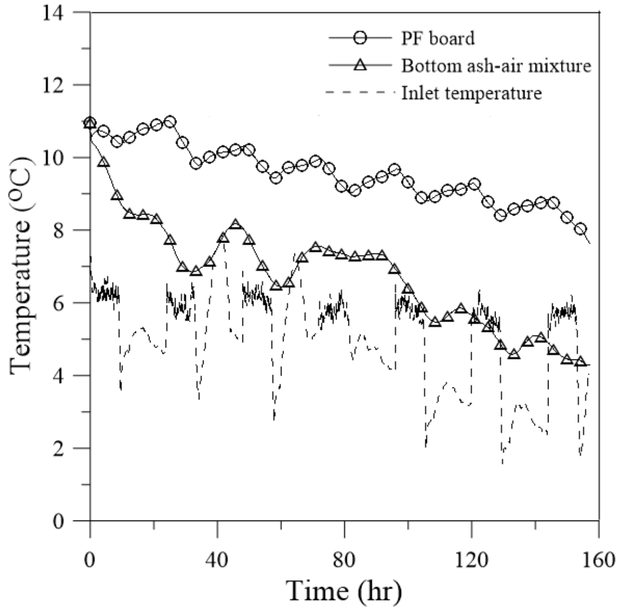


Figure 7. Temperature variation in concrete slab (below thermal insulation layer) and inlet temperature during TPT (PF board and Bottom ash-air mixture

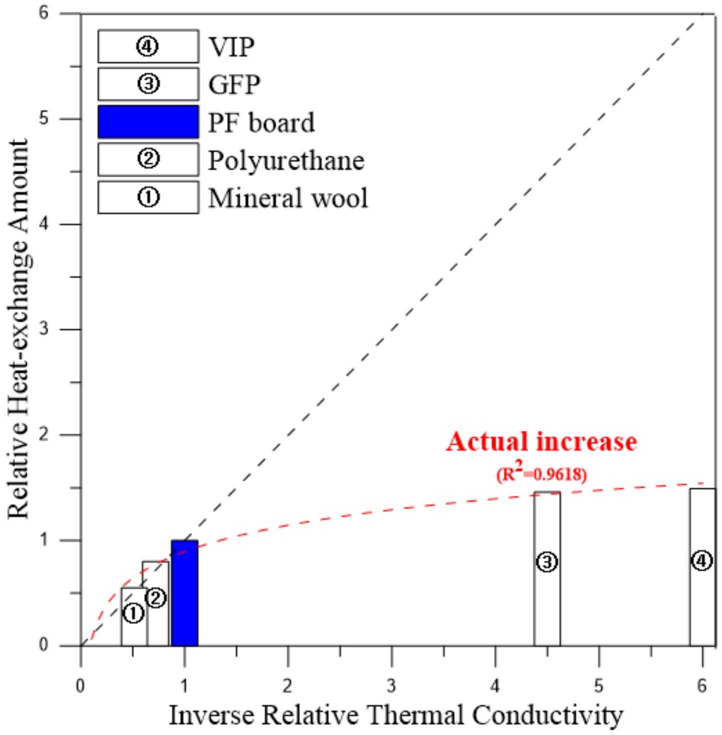


Figure 8. Nonlinear relationship between inverse RTC and RHA

5 CONCLUSION

In this paper, the field experiments and numerical analysis were conducted to evaluate the effect of a thermal insulation layer on the thermal performance of energy slab. In order to preserve the thermal performance of energy slab from air temperature change, the thermal insulation layer should be inserted in the energy slab. Additionally, the thermal performance of energy slab becomes increased by installing the thermal insulation layer of lower thermal conductivity. However, the thermal conductivity of the PF board shows suitable thermal insulation that leads to the optimum thermal performance of energy slab.

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