Role of EPS Geofoams in Reducing Thermal Losses from Slab-on-Grade Foundations under Freezing Conditions

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ABSTRACT

Enhancing energy efficiency for attaining net-zero homes is a crucial subject that is of great interest for advancing sustainability and addressing the issue of climate change. Almost 43% of the annual energy bill of a typical US household is known to be accounted for by heating and cooling expenses. While there have been significant works on insulating the superstructure of a home, limited research work has been performed on insulating the foundations and substructures. A research study was designed and performed to examine the role and efficacy of expanded polystyrene (EPS) geofoam in insulating a slab-on-grade foundation system, a common type of shallow foundation where the concrete slab rests directly on the ground below it. Small-scale laboratory tests were conducted on a soil box with an insulated superstructure above a slab-on-grade foundation prototype. The performance of different thicknesses and installation configurations of geofoam insulations was compared to a control section with insulated superstructure and bare slab. The tests were performed inside a temperature-controlled environmental chamber set at −18°C. Thermocouple probes were used to monitor temperature profiles within the test setup. The insulated test sections were found to have consistently warmer slab temperatures compared to the bare slab conditions, and significant variation in performance was observed between the tested configurations. The configuration with insulation around the slab perimeter showed the best performance with over 10°C warmer indoor temperatures observed compared to the control section. The test results clearly indicated that the application of geofoam has significant potential in reducing the heat transfer between the foundation and the soil/air interfaces and therefore could lower the energy losses from residential homes.

INTRODUCTION

According to the U.S. Energy Information Administration (EIA), residential buildings contributed to around 20% of the total energy consumption in the United States in 2019, with approximately 55% of that energy being utilized for space heating and cooling purposes (U.S.

Department of Energy (DOE) 2020, U.S. Energy Information Administration (EIA) 2023). Improving the thermal efficiency of residential buildings can thus have a significant impact from both the economic and environmental standpoint. Significant efforts have been made by past researchers to study the insulation of superstructure of a home (Kossecka and Kosny 2002, Al-Homoud 2004, Asdrubali et al. 2015, Dodoo et al. 2017). However, even though it has a non-trivial contribution to heat loss and inefficient energy usage, studies into insulation of building foundations for residential homes were found to be lacking (Krarti 2011, Chen et al. 2020). Particularly with slab-on-grade foundations, which are a prevalent type of foundation in residential construction, the direct contact between the slab and soil can cause a substantial exchange of heat between the building and the ground (Carmody et al. 2013).

EPS geofoams are lightweight, rigid, closed-cell foam materials with low moisture absorption and high compressive strength (Horvath 1994, 1995). In addition, the closed cell microcellular construction of EPS leads to almost 98% air by volume and therefore exhibits excellent insulation properties (Horvath 1994, Ramli Sulong et al. 2019). In recent years, EPS geofoam has come out as a versatile product suitable for many infrastructure applications like lightweight fill in roadway and pavement applications, as fill to solve settlement issues in embankments, to construct embankments atop existing infrastructure like pipelines and culverts to reduce horizontal and vertical stresses imposed on the infrastructure, as insulating layer to prevent frost heave effects, etc. (Bartlett et al. 2000, Puppala et al. 2019, Moussa et al. 2019, Özer and Akınay 2022). This versatile nature of EPS foams has also made their use increasingly popular for applications such as below-grade insulation in foundations, basements, and underground parking garages, effectively reducing heat loss and improving energy efficiency (Insulfoam 2021).

This study aims to take advantage of the versatile nature of EPS geofoam and explore its use for providing an effective means of reducing thermal losses in slab-on-grade foundations under freezing conditions. Laboratory studies were performed to determine an effective installation configuration of geofoam insulation for a slab-on-grade foundation system. To this end, test results are presented from two different insulation configurations of geofoam insulation: perimeter insulation of the slab (referred hereafter as Geofoam Around Footing or GAF configuration) and bottom insulation of the slab (referred hereafter as Geofoam Below Footing or GBF configuration). Additionally, the tests were performed for two different thicknesses of the EPS geofoam to study the influence of thickness of insulation and its contribution to the overall insulation performance as opposed to the installation configuration. The test results were then used to understand and quantify the dominating mechanism, thus determining an efficient insulation configuration for residential homes with the goal to reduce energy consumption. The following sections present the experimental setup and configurations used in the study, followed by the outcomes from each configuration, and finally a comprehensive discussion on the comparative benefits of different configurations or thickness of geofoams for effective insulation of slab-on-grade foundations.

EXPERIMENTAL SETUP

Soil Box and Superstructure. A 3 ft. × 3 ft. × 3 ft (0.9 m × 0.9 m × 0.9 m) soil box, made of plywood, was constructed as a test setup (Figure 1a). This box was insulated on all sides with 0.2 m thick, geofoam with R-value 0.4 K.m^2/W to limit the heat lost through the box boundaries. Small gaps were carefully sealed using an insulating foam sealant to prevent heat loss. The box was then filled to the 0.6 m mark with a locally available lean clay and compacted to 95% of standard proctor density and approximately 13% moisture content. Quality checks using core sampling was performed to ensure uniform density and moisture condition in the box.

A 0.5 m × 0.5 m × 0.1 m concrete slab was used as a model of slab-on-grade footing. A superstructure was made on top of it using the same grade of geofoam as the insulation on the walls. The final indoor dimensions for the superstructure were approximately 0.4 m × 0.2 m × 0.5 m. A 1500W space heater was used to heat the indoor space at the beginning of the test. After initial tests on the setup, additional insulation using a roll of insulated duct wrap was placed around the superstructure to further reduce the amount of heat lost from the indoors to the atmosphere.

Instrumentation and Data Acquisition. The setup was extensively instrumented using Type K thermocouple probes having a functional temperature range between -200°C to 1260°C. Figure 1(b) shows the instrumentation plan used for the control test i.e., test on the uninsulated slab. Thermocouple probes labeled T-0 to T-15 were placed in different locations within the soil body. This aimed to understand the temperature contour within the subsurface. Nine of the probes were placed around the slab to monitor temperature in different locations for different insulation configurations. An additional probe was used (T-3) to measure the indoor temperature and a probe (T-4) was left outside of the setup to measure the ambient temperature. Table 1 summarizes the naming conventions used for the tests as well as their respective locations. A 16-channel thermocouple card on a chassis with an ethernet connector was used for data acquisition. Temperature readings were recorded for every one second during the test to monitor the temporal variation of the heat flux in the system.

Table 1: Sensor label and locations

Control Test	GBF Tests	GAF Tests	Location
T-4	T-11	T-11	Ambient
T-3	T-3	T-3	Indoor (air)
T-7, T-12, T-14	T-7, T-12, T-14	T-7,T-12,T-14	Indoor (slab)
T-6, T-8, T-9, T-10, T-13, T-15	T-9, T-8, T-6	T-8, T-5, T-6	Slab-soil interface
-	T-10,T-1,T-2,T-13	T2, T-10	Foam-soil interface
-	T-5	T-9, T-13	Foam-slab interface
T-2	T-15	T-15, T-4	Side boundaries
T-0	T-0	T-0	Bottom boundary

Experiment Configurations. This study examines three experimental configurations to evaluate the effectiveness of EPS geofoam for insulating slab-on-grade foundations under freezing conditions. Each configuration was designed to provide necessary insights into the overall thermal performance of the system, both with and without foundation insulation. A detailed description of the three configurations is presented in the following sections.

Control Test. The control test served as a baseline for comparing the thermal performance of the other setups. It consisted of an insulated superstructure above the slab-on-grade foundation prototype, without additional foundation insulation. This test aimed to measure the heat transfer and temperature distribution behavior in a typical slab-on-grade foundation system. The instrumentation configuration for the control test is shown in Figure 1b.

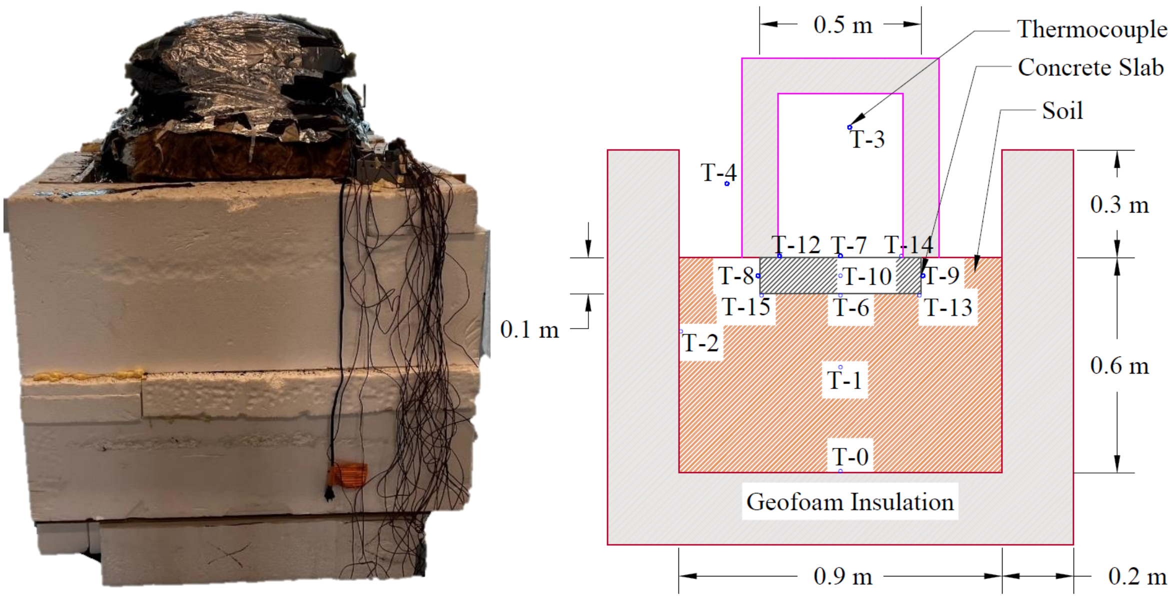

Figure 1. (a) Test setup and (b) instrumentation plan for Control test on bare slab

Geofoam Below Foundation (GBF) Tests. The GBF tests incorporated EPS geofoam insulation beneath the slab-on-grade foundation prototype. Tests were performed with two different thicknesses (0.2 m and 0.05 m) of geofoam insulation. These tests aimed to evaluate the impact of placing geofoam at the soil-foundation interface on the overall heat transfer and temperature profiles of the system, i.e., the difference in thermal performance when the heat transfer from the foundation slab to the deeper ground is attenuated by geofoam. Since the overarching phenomenon of interest was an improvement in indoor temperature retention, the primary variables of interest were indoor air and slab temperatures. The instrumentation details for this configuration are depicted in Figure 2a.

Geofoam Around Foundation (GAF) Tests. The GAF tests involved setting up EPS geofoam insulation around the perimeter of the foundation slab. Figure 2b illustrates the instrumentation plan used in this set of tests. This set of tests was also performed using the same two thicknesses (0.2 m and 0.05 m) of geofoam insulation as the GBF test case. As opposed to the GBF set of tests, these tests study the difference in thermal performance of the system when the heat transfer between foundation and ambient air, through the shallow soil layer is countered by the presence of geofoam on the perimeter. Therefore, the two sets of tests were used to compare different mechanisms of heat transfer and should help to determine which of the two is the principal controlling mechanism.

Each of the three sets of tests was subjected to the same temperature-controlled environmental chamber with an ambient temperature of -18°C. Data collection was started once the setups were placed inside the environmental chamber, and the temperature fluctuation within the setup was measured for the next 70 hours. The setup was periodically monitored for the test duration to ensure the required ambient conditions were maintained. The next section presents the outcomes from the experimental studies to provide an exhaustive understanding of the influence of geofoams in insulating slab-on-grade foundation systems.

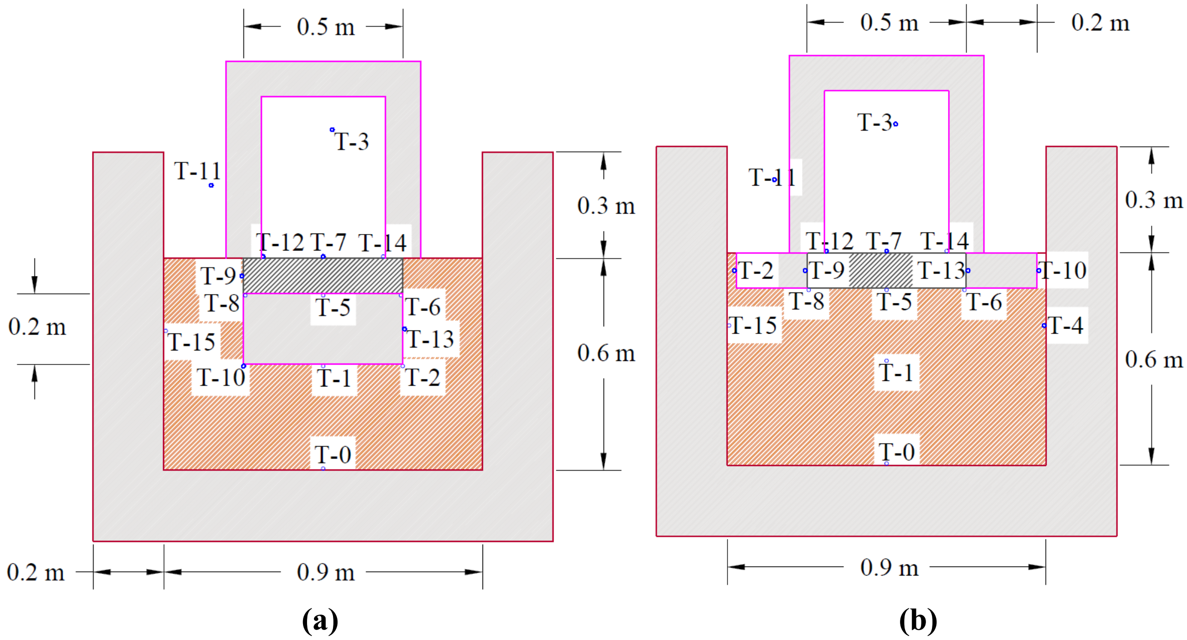

Figure 2. Instrumentation plan for (a) Geofoam Below Foundation, and (b) Geofoam Around Foundation configurations

RESULTS AND DISCUSSION

The overall temperature profile obtained over the duration of the test for the control test is shown in Figure 3. The periodic spikes in temperature observed throughout the test represent the times when the compressor of the environmental chamber shuts off and restarts to maintain the required ambient temperature. Following the initial transitionary period of the test (approximately 10 hours), specific zones of similar temperature emerged corresponding to probe location and type of substrate (concrete, soil, or wall). The indoor air (T-3) and slab surface (T-7, T-12, and T-14) were consistently about 2°C warmer than the slab surface in contact with the soil (T-15, T-6, and T-13). Additionally, T-15, T-6, and T-13 displayed the lowest temperature within the experimental setup. Beyond the top 0.5 m (T-1 and T-0), the temperature variation with depth was negligible and these were the warmest locations in the setup after the transitionary period. This suggested that a significant heat exchange occurred closer to the surface. An overall decline in temperature over time was observed throughout the experiment. The temperature gradient observed between the top and bottom surfaces of the slab suggested that heat was lost from the interior to the soil. Although the exact contribution of the slab-soil contact to this loss cannot be easily isolated due to the contributions of the atmosphere and heat transfer at the superstructure boundaries, the results illustrated the necessity for an insulation system.

The two GBF tests showed a similar decreasing trend as observed in the control test (Figure 4). However, adding a geofoam insulation to the bottom of the slab reduced the temperature variation between the zones observed in the control test, across all test cases, leading to smaller temperature gradient which implies lower energy losses. The slab temperature for 0.05 m thick insulation got to cooler temperatures than the control case after approximately 40 hours of testing (Figure 4a). GBF with 0.2 m thick geofoam layer, on the other hand, maintained the slab at approximately 2°C warmer temperature than the control case while also reducing the temperature difference to less than 1°C between the indoor and slab temperatures (Figure 4b). Additionally, unlike the control test, the coolest zones in the setup were found closer to the side walls of the setup. The presence of geofoam directly beneath the footing hindered the transfer of heat from the warmer zones at the middle and bottom of the soil body to the cooler zones closer the box boundaries. While this reduced the heat transferred to this area, heat was still lost through the side boundaries. This then resulted in a cooler soil temperature as compared to the control test as well as other locations within the GBF tests.

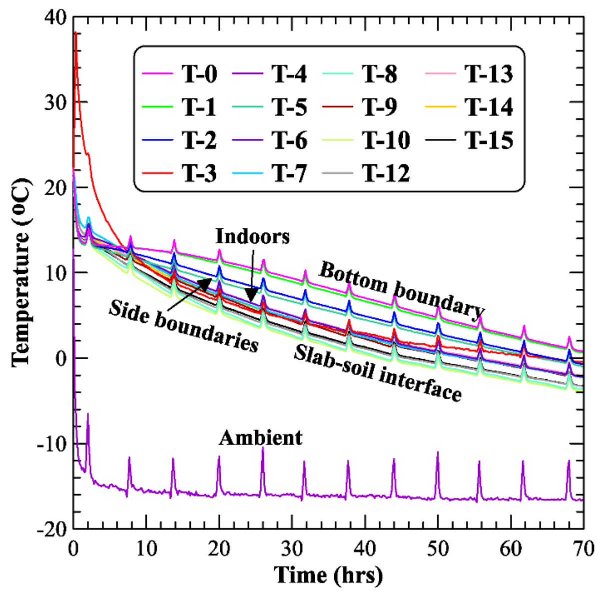

Figure 3. Temperature profile for Control Test

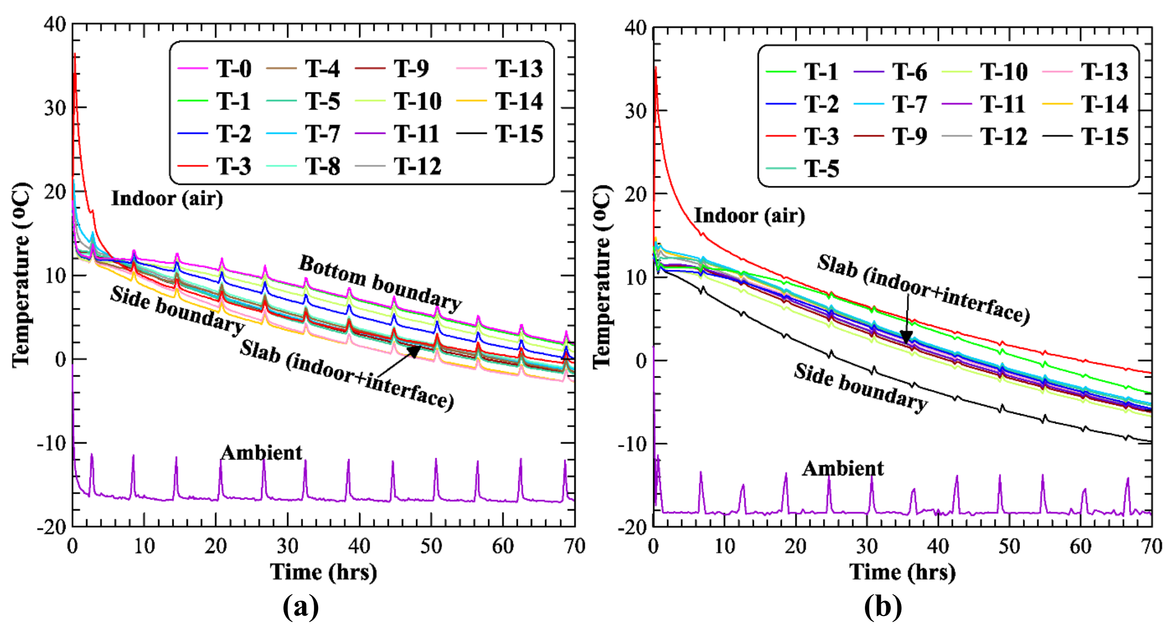

Figure 4. Temperature profile from a) 0.2 m GBF Test and b) 0.05 m GBF test

A similar trend was also observed in GAF tests in that the temperature zones observed in the control test were not as obvious now (Figure 5). Similar to the GBF tests, temperature probes close to the side walls and 0.05 m below the surface showed the coldest temperature and the rest of the monitored locations were consistently warmer than this zone. The temperature difference between these two zones (walls and the rest of the setup) increased with increasing geofoam thickness. The indoor and soil sensors retained warmer temperatures with increasing insulation thickness. GAF insulation showed observable improvements in indoor air and slab temperatures as compared to the control tests, with a consistent 10°C warmer temperature than the control section. However, no major difference was observed between 0.05 m and 0.2 m thick GAF insulation. The improvement in performance for the retention of indoor air and slab temperatures clearly exhibits the efficacy of GAF insulation for reducing heat loss from the indoor environment, thus leading to significant savings in terms of energy costs. However, the minor difference observed between the two thicknesses of the geofoams suggested that using a thin insulation system might be a potential cost-effective solution for effective insulation of the slab-on-grade foundation.

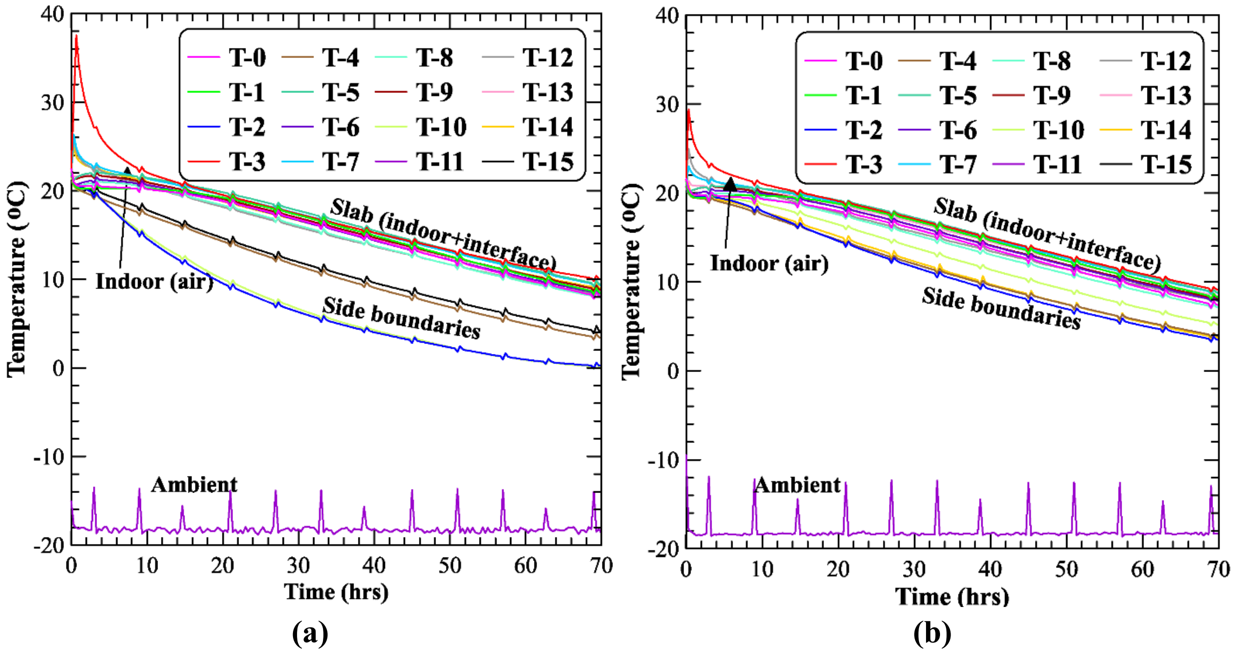

Figure 5. Temperature profile from a) 0.2 m GAF Test and b) 0.05 m GAF test

Figure 6 illustrates the temperature variation at the indoor slab surface (T-7) for all test cases at the beginning of the test and after 70 hours of testing. GBF test with 8 in. thick insulation showed a decent increase in indoor slab temperature compared to the control test (approx. >2°C). However, even though the test started out at similar temperatures, 0.05 m thick geofoam insulation reached a cooler temperature than control section at the end of the test period indicating a limited efficacy of thin insulation layer in the GBF configuration. On the other hand, the 0.05 m thick GAF insulation showed a significantly good insulation behavior (> 10°C warmer than the control test) and significantly outperformed the 0.2 m thick GBF insulation. However, the gain in performance was not as significant when comparing the 0.2 m and 0.05 m GAF options. The comparable results between the two thicknesses suggested that the configuration of insulation (GAF or GBF) is more decisive as compared to the thickness of the insulation for obtaining an efficient insulation system. As such, a 0.05 m geofoam could be more economical alternative than the 0.2 m geofoam, resulting in an effective insulation performance.

The two configurations tested herein tend to attenuate the heat loss from two different modes: heat lost to the deep soil layer through the exposed foundation slab (GBF) and the heat lost to the ambient air through the shallow soil layer (GAF). A common theme observed during both the GBF tests was that soil temperature below the bottom of the geofoam remained approximately constant with depth. A similar behavior was observed in the control section. However, the depth beyond which a constant temperature was observed was much higher (>0.5 m). The results showed that the presence of geofoam has attenuated the heat exchange between the slab and soil, implying a reduction in energy lost from beneath the slab to the soil. However, even for 0.2 m thick geofoam insulation, the difference in indoor slab temperature compared to the control section was not very high. This suggests that while some heat is lost from the bare slab-soil contact, it might not be the greatest contributor when it comes to energy losses.

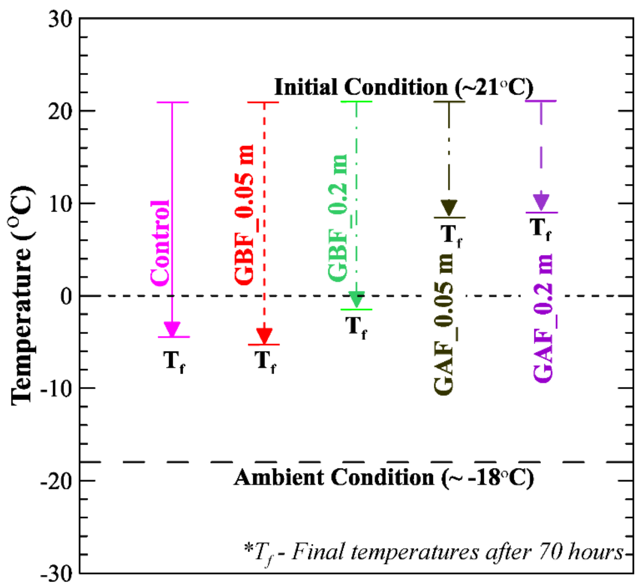

Figure 6. Comparison of indoor slab temperatures across all test cases

Since the main mode of heat transfer countered by the GAF configuration is the loss of heat from the slab to the atmosphere through the surficial soil layer, the superior performance of this configuration suggests that the amount of heat lost from the slab to the atmosphere is highly significant. Therefore, it could be concluded that the loss of indoor heat to the foundation slab is mainly controlled by the ambient temperature and the embedment depth of the footing. This suggests insulating the parts of the footing closest to the surface (i.e., its perimeter) is crucial to reduce the energy losses from the indoor heated environment through the foundation slab to the external atmosphere.

CONCLUSIONS

Two different insulation configurations of slab-on-grade foundations using geofoam were tested in a small-scale laboratory model. The two configurations tested primarily varied on the type of heat loss mechanism countered viz: heat lost to the atmosphere through the top, shallow soil layer and heat lost to the soil beneath the foundation slab and to the deeper soil layers. The findings of the studies are summarized below:

- In the absence of insulation, several distinct zones of similar temperature were observed during the test. This temperature gradient suggests not insignificant heat transfer between the different zones, which can be translated to energy losses when the only source of heat is the warm indoor air. The warmest zones were located below 0.5 m from the surface and the surface of slab in contact with the soil exhibited coldest temperature.
- In the case of GBF tests, when insulation was added to the setup the difference in temperature between the zones was significantly reduced. While the warmest zones were still about 0.3 m below the surface, the coldest zone switched to sensors close to the walls. This is attributed to both the boundary effects and the disruption in heat flow within the soil caused by the geofoam insulation.
- GAF tests showed a significant increase in indoor temperatures (>10°C) compared to the control tests. The warmest zones were now found in the indoor air and slab surface. The 0.2 m thick GAF insulation demonstrated the best performance out of all test cases and showed a significant decrease in heat lost compared to the control test. However, only a slight gain in performance was seen between 0.05 m and 0.2 m thick geofoam tests which suggests 0.05 m thick geofoam in GAF configuration is a more economical choice.
- Since GAF test results outperformed GBF by a significant margin, it can be concluded that the controlling mechanism of heat transfer in case of slab-on-grade footings is the heat lost from the indoor warm air to the atmosphere through the top, shallow soil layer.

This study demonstrates the efficacy of foundation insulation using geofoam and an efficient configuration of insulation placement to significantly reduce thermal losses from a residential home. The observations, along with the knowledge that a considerable amount of energy is consumed by residential homes in order to sustain a pleasant indoor temperature, highlight the critical role that geofoam insulation in foundations can play in curbing energy losses and attaining the goal of zero-energy homes.

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