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Measured Differences of Ground and Space Temperatures for Side-by-Side Slab-on-Grade Residences With and Without Carpet

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ABSTRACT

A particularly suspect aspect for building simulations has been the ability to predict ground heat transfer. In Florida, slab-on-grade construction dominates. To better understand ground heat transfer, as well as the differences between uncovered slab and applying an insulation layer (carpeting) over a slab in a mild climate, the Florida Solar Energy Center built two identical residential laboratory buildings with 164 embedded slab and ground thermocouples. In July 2014, an experiment began comparing the thermal performance of carpet to uncovered slab flooring. The buildings were cooled to 77°F (25°C) in summer and heated to 73°F (22.8°C) in winter. The thermostats were set to either cooling or heating, as during Florida's winters interior temperatures sometimes drift above the cooling set point and occasionally when set to cooling they drift below the winter set point. Each laboratory home is unoccupied with automated internal sensible and moisture loads provided hourly to represent human, appliance, and lighting loads. The hypothesis is that in Central Florida, where year-round ground temperatures are between winter and summer set points, the non-carpeted slab should have an advantage.

The paper presents findings for a year's worth of data collection, differences in heating and cooling loads on each home, and images of temperature differences through the matrix of slab measurements. Net heat transfer in Central Florida was small during the cooling season. There was some benefit available during early spring time. Results are sensitive to geographic location and interior set points.

INTRODUCTION

In warm regions bordering the Mediterranean or the Gulf of Mexico, tiled or terrazzo slab-on-grade floors are a popular residential option. With tile on a slab floor there is more heat transfer than with carpet. Is this beneficial? Empirical data are somewhat limited in warm climates.

Past research has focused on the impact of slab-on-grade foundations and insulation schemes in predominantly heating-dominated climates. Bareither et al. (1948) at the University of Illinois compared the performance of seven types of slab floor insulation. Perhaps the most rigorous work has been that of Adjali et al. (2000), at Cardiff School of Engineering, comparing numerical simulations with measured slab performance of detailed measurements in Wales.

Simulation research is often used by researchers or practitioners to compare options. However, models using EnergyPlus and DOE2 engines indicate cooling savings of 4% to 7% for single-family homes with tile versus carpet. Are those results accurate?

EXPERIMENTAL DESIGN

Experiments in this research were performed over an entire year from 2014–2015 in Cocoa, Florida, at the Florida Solar Energy Center (FSEC) Flexible Residential Test Facility (FRTF) and intended to assess slab-on-grade influence in a cooling-dominated climate. This facility consists of two 1536 ft^2 (142.7 m^2) identical buildings that are extensively metered (Figure 1). The FRTF was completed in 2010 and is more thoroughly described elsewhere (Vieira and Sherwin 2012).

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Figure 1 *Side-by-side FRTF buildings at FSEC in Cocoa, Florida.*

Table 1. Locations of Sensors

Configuration	Quantity	0 ft (0 m)	1 ft (0.30 m)	2 ft (0.61 m)	5 ft (1.5 m)	10 ft (3.0 m)	20 ft (6.1 m)	Moisture at 1 and 5 ft (0.30 and 1.5 m)	Location
A	3	x	x	x	x	x	x	x	Center of homes and midway between homes
B	6	x	x	x	x	x	x		Footer midway on east and west sides and 2 ft (0.61 m) out from home
C	12	x	x	x	x	x			Corners of home and midway on north- and south-side footers
D	12	x	x	x					8 ft (2.44 m) in from each corner in both directions and 8 ft (2.44 m) in from midway edge points on north and south sides

Each building has a standard 4 in. (0.10 m) concrete monolithic slab with perimeter footers poured over sand fill at the time of construction. The east test building has a standard 3/8 in. (0.0095 m) rubber pad and 1/2 in. (0.15 m) synthetic carpet (which has compressed somewhat after installation) installed in late 2013 with an estimated combined R-value of approximately 2.4 $h \cdot ft^2 \cdot °F/Btu$ (0.423 $m^2 \cdot °C/W$). The west test building has an unmodified uncovered concrete slab floor. The envelope for each is meant to represent older building stock in Florida with R-19 $h \cdot ft^2 \cdot °F/Btu$ (3.35 $m^2 \cdot °C/W$) ceiling, uninsulated concrete block walls, and single-pane glass windows with blinds.

Identical datalogger systems and associated instrumentation were installed in each building. Data were processed and archived using a pair of networked Campbell Scientific dataloggers (CR3000 and CR1000) along with associated peripherals. The data set included pertinent building materials' surface temperatures, interior space conditions (temperature and relative humidity), attic space conditions (*T*/RH), HVAC energy use, and infiltration rate via carbon dioxide injection and monitoring. An on-site meteorological weather station monitored irradiance, wind speed, ambient temperature, humidity, and carbon dioxide concentrations. Measurements were taken every 10 s and stored at 15 min intervals (Vieira and Sherwin 2012). Heating and cooling set points in each building were set to 73°F and 77°F (22.8°C and 25°C), respectively, by a pair of identical digital thermostats. A schedule of internal sensible and latent heat gains was introduced to both buildings to simulate occupied loads.

A grid of 156 temperature measurements (see Table 1) were taken using copper-constantan (type T) thermocouples with a read resolution of 0.1°F (0.56°C) and an uncertainty of +0.9°F (0.5°C). Temperatures were affixed to the slab surface using thermocouple epoxy and buried at depths of 0 (i.e., ground surface under concrete slab polyethylene vapor barrier), 1, 2, 5, 10 and 20 ft (0, 0.3, 0.61, 1.5, 3 and 6.1 m). A schematic diagram of the measurement locations at the two FRTF buildings, starting at the surface and descending down

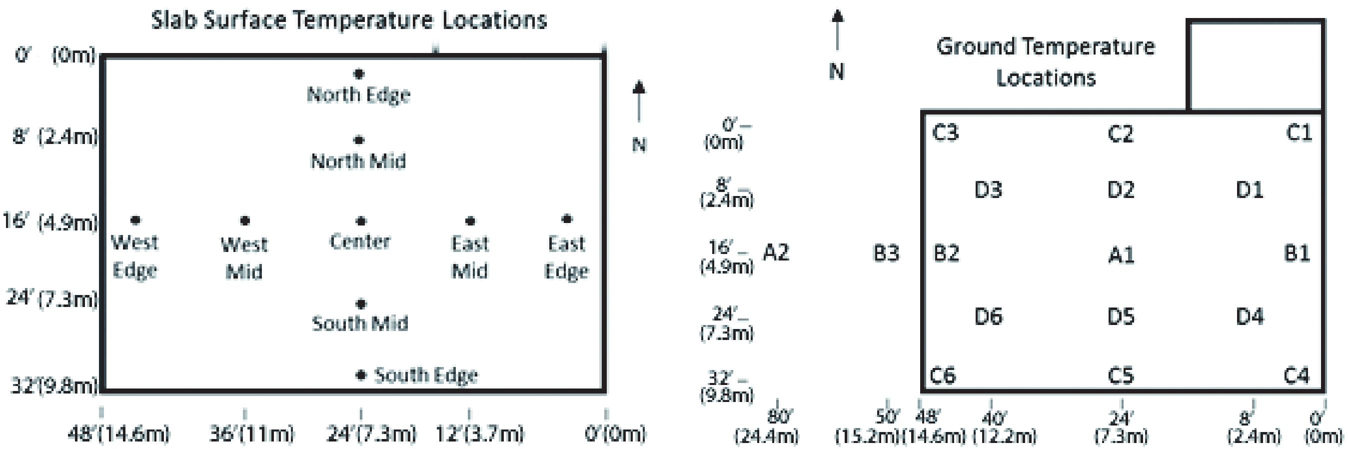

Figure 2 *Schematic diagram of slab temperature measurement points at FRTF.*

through the ground, is shown in Figure 2. Point A2 is taken 32.5 ft (9.9 m) from the west and east walls, respectively, of the two buildings. Point B3 is taken 2 ft (0.61 m) from the outside edge of the slab.

EXPERIMENTAL RESULTS

Floor Slab Thermal Performance

Various center-of-building slab temperatures were examined at both surface and depth, located at A1 in Figure 2. Examples for the center slab profiles are shown in Figure 3 and show strong thermal heat flow from the interior building to the ground during the uncooled spring period, which is quite apparent to a depth of 5 ft (1.52 m). Figure 3 also shows widely varying shallow temperatures between October 31, 2014, and April 2015, during Florida's heating season when the cooling system is not available and the temperature inside the building floats upward above 73°F (22.8°C) but not below. However, this period of time with higher floating interior temperatures creates prominent heat flows, evident down through the slab and into the ground layers as shown by the data. In particular, the data show that the uncovered slab floor in the west building is creating surface temperatures approximately 1°F (0.56°C) lower than those shown for the east carpeted building. The trend remains the same down to 5 ft (1.5 m) below the surface.

Estimated Surrogate Heat Fluxes

To address the lack of physical measurement of heat fluxes, surrogate heat fluxes were estimated from the available temperature data. This involved subtracting the measured slab surface temperature from the measured interior air temperature. While they are not true heat fluxes, these temperature differences give an indication of heat flow direction and order of magnitude.[1] The measured values on the east carpeted section reflect the measured temperature under the carpet and pad and have been divided by the R-value of that assembly, 2.4 h·ft^2·°F/Btu (0.423 m^2·°C/W), to yield a comparative value shown for the west house, which is exposed slab.

Table 2 shows the surrogate heat fluxes for the carpeted East building and the uncarpeted West building with the exposed slab. Positive numbers indicated heat gain to the space; negative values indicate heat losses from the slab. Note some missing data for January for the north slab data due to sensor/communication issues.

Evaluating the surrogate heat flux data reveals the following:

- *Heating:* Winter heat losses are seen at all measurement points; greatest at edges. Heat gains and losses are lowest slab floor center at the midpoints between the center and edges.
- *Heating:* Carpet attenuates winter heat losses seen relative to the unsurfaced slab.
- *Cooling:* Heat gains, adding to cooling load, are seen across the slab in summer and are also greatest at the edges—particularly the north edge by the unconditioned garage (which becomes very hot in summer).
- *Cooling:* Heat gains to the interior in summer are reduced by the carpet.
- *Floating Conditions:* Heat fluxes change (including flow direction) over the seasons, particularly at the slab center and midpoints.

Heating Results

For heating, we examined 14 days (Table 3) over the year where the outdoor temperature was less than 55°F (12.8°C), which have been shown to clearly be heating periods in Florida

1. As an approximation, it can be considered that the horizontal heat transfer surface conductance for still air from the 2009 *ASHRAE Handbook—Fundamentals* (Table 1, p. 26.1) (ASHRAE 2009) are 1.63 Btu/h·ft^2·°F (9.25 W/m^2·°C) for heat transfer upwards and 1.08 Btu/h·ft^2·°F (6.13 W/m^2·°C) for heat transfer downwards.

(a) **(b)**

Figure 3 *Ground temperatures for the carpeted east building and uncarpeted west building: (a) °F and (b) °C.*

homes (Parker et al. 2015). The carpeted east building showed lower energy consumption by approximately 0.65±0.15 kWh/day (4.3%). Resistance heat consumption was 15.16 kWh/day in the carpeted east building and 15.81 kWh/day in the west exposed slab building. While this difference was measurable and statistically significant, the energy quantity is very small. Relative humidity in the two buildings was virtually identical. Similar differences in energy use (4.1%) were found limiting the data to the four days of temperature less than 50°F (10°C).

Contour plots presented in this and following sections were generated using the average measured data for the period indicated with the points shown (small black dots). Thermal contours were generated using the Plotly.js software package (https://plot.ly/feed/), which interpolates contours using a rectangular mesh. The contours of heating period data (Figure 4) show heat loss to the ground, with particularly striking changes seen from the slab edge. Note that these changes at slab edge are not an artifact of sensor space, as the temperature measured at the slab edge are 1 ft (0.3 m) inside the interior of the wall and the estimate outside the slab edge is only 2 ft (0.61 m) from the wall.[2] This finding is in agreement with experimental measurements of slab floors stretching back to work done post-World War II by the University of Illinois (Bareither et al. 1948). The plots show solar heating of the soil surface outside the building profile as well as the profile across the building interior the ground temperatures down to 10 ft (3 m). Note the very different thermal domains under and outside the building in winter.

Performance During Floating Conditions

The performance of the two buildings was evaluated during the fall and spring for a period of 55 days when the HVAC system was inactive. During this 55-day spring and fall period, the carpeted east building ran 0.72°F ± 0.5°F (0.40°C ± 0.28°C) warmer than the uncarpeted west building (77.89°F versus 77.17°F [25.5°C versus 25.1°C]). Interior relative humidity was slightly higher in the carpeted east building

[2] The contour plots shown should be considered approximate. While spacing of 2 ft (0.61 m) or less would provide much more precise indication of thermal anomalies and intervals, it was decided that such a representation as that made in the report must be used to help the reader visually understand the relationship of the eight odd measurement points being represented for each slab floor.

Table 2. Monthly Surrogate Heat Flux Data Δ*T* for Measured Locations

Month	NE °F	NE °C	SE °F	SE °C	WE °F	WE °C	EE °F	EE °C	CNT °F	CNT °C	NM °F	NM °C	SM °F	SM °C	WM °F	WM °C	EM °F	EM °C
West—Exposed Slab (Uncarpeted)																		
Jan	—	—	–2.38	–1.32	–3.83	–2.13	–4.06	–2.26	–1.04	–0.58	—	—	–0.94	–0.52	–0.79	–0.44	–0.62	–0.34
Feb	–2.84	–1.58	–3.64	–2.02	–4.63	–2.57	–4.21	–2.34	–1.37	–0.76	–1.69	–0.94	–1.22	–0.68	–1.10	–0.61	–0.79	–0.44
Mar	–1.56	–0.87	–2.82	–1.57	–3.18	–1.77	–2.44	–1.36	–0.97	–0.54	–1.11	–0.62	–0.95	–0.53	–0.79	–0.44	–0.50	–0.28
Apr	–1.14	–0.63	–2.31	–1.28	–1.61	–0.89	–0.65	–0.36	–0.71	–0.39	–0.44	–0.24	–0.85	–0.47	–0.76	–0.42	–0.44	–0.24
May	2.99	1.66	0.39	0.22	1.41	0.78	1.61	0.89	–0.35	–0.19	0.21	0.12	–0.45	–0.25	–0.39	–0.22	–0.43	–0.24
June	4.46	2.48	1.62	0.90	3.05	1.69	3.34	1.86	0.33	0.18	1.03	0.57	0.29	0.16	0.30	0.17	0.13	0.07
July	5.22	2.90	2.33	1.29	3.77	2.09	4.10	2.28	0.26	0.14	1.06	0.59	0.26	0.14	0.25	0.14	0.00	0.00
Aug	5.52	3.07	3.19	1.77	3.73	2.07	6.09	3.38	0.17	0.09	1.47	0.82	0.88	0.49	0.75	0.42	0.47	0.26
Sept	3.06	1.70	1.46	0.81	0.87	0.48	1.12	0.62	0.71	0.39	1.02	0.57	0.92	0.51	0.61	0.34	0.51	0.28
Oct	–0.51	–0.28	–0.89	–0.49	–2.42	–1.34	–1.65	–0.92	–0.45	–0.25	–0.60	–0.33	–0.35	–0.19	–0.44	–0.24	–0.25	–0.14
Nov	–2.61	–1.45	–1.72	–0.96	–4.62	–2.57	–2.94	–1.63	–0.83	–0.46	–1.23	–0.68	–0.66	–0.37	–0.82	–0.46	–0.45	–0.25
Dec	–3.12	–1.73	–2.28	–1.27	–4.46	–2.48	–4.06	–2.26	–1.01	–0.56	–1.50	–0.83	–0.82	–0.46	–0.92	–0.51	–0.61	–0.34
East—Carpeted																		
Jan	—	—	–1.05	–0.58	–1.78	–0.99	–2.41	–1.34	–0.23	–0.13	—	—	–0.22	–0.12	–0.16	–0.09	–0.26	–0.14
Feb	–1.06	–0.59	–1.63	–0.91	–2.30	–1.28	–2.40	–1.33	0.25	0.14	–0.13	–0.07	–0.51	–0.28	–0.46	–0.26	–0.25	–0.14
Mar	–0.61	–0.34	–1.37	–0.76	–1.68	–0.93	–1.47	–0.82	0.08	0.04	–0.14	–0.08	–0.34	–0.19	–0.33	–0.18	–0.24	–0.13
Apr	0.72	0.40	–1.36	–0.76	–0.87	–0.48	–0.38	–0.21	0.64	0.36	–0.14	–0.08	–0.44	–0.24	–0.45	–0.25	–0.29	–0.16
May	1.68	0.93	–0.13	–0.07	0.54	0.30	0.68	0.38	0.93	0.52	–0.10	–0.06	–0.53	–0.29	–0.51	–0.28	–0.44	–0.24
June	3.05	1.69	0.99	0.55	2.03	1.13	2.00	1.11	1.22	0.68	0.96	0.53	0.38	0.21	0.45	0.25	0.40	0.22
July	3.28	1.82	1.19	0.66	2.27	1.26	2.24	1.24	0.52	0.29	0.77	0.43	0.17	0.09	0.29	0.16	0.17	0.09
Aug	3.73	2.07	1.78	0.99	2.54	1.41	2.55	1.42	1.17	0.65	1.29	0.72	0.66	0.37	0.76	0.42	0.61	0.34
Sept	2.80	1.56	1.27	0.71	1.54	0.86	1.50	0.83	1.23	0.68	1.77	0.98	1.23	0.68	1.33	0.74	1.17	0.65
Oct	0.23	0.13	–0.48	–0.27	–0.95	–0.53	–0.81	–0.45	0.25	0.14	0.39	0.22	0.01	0.01	0.15	0.08	0.08	0.04
Nov	–0.66	–0.37	–0.71	–0.39	–2.03	–1.13	–1.54	–0.86	–0.76	–0.42	0.24	0.13	–0.04	–0.02	0.03	0.02	0.02	0.01
Dec	–1.17	–0.65	–1.03	–0.57	–2.31	–1.28	–2.26	–1.26	–0.28	–0.16	–0.01	–0.01	–0.20	–0.11	–0.16	–0.09	–0.14	–0.08

Codes are CNT/Center, NE/North Edge, NM North Mid, and so on

(0.51% ± 0.22%), and the dew point in the carpeted east building was 0.48°F ± 0.07°F (0.27°C ± 0.039°C) higher.[3]

The interior temperature profile for a springtime floating period, March 13–24, 2015, shows a clear rise in interior temperature in the carpeted building, as shown in Figure 5. The temperature of the carpeted home averaged over 86°F (30.0°C) in the afternoon, whereas the exposed-slab home kept the peak average around 84°F (28.9°C). During such periods in spring while the ground is near its coolest temperatures the exposed slab would provide an advantage.

3. Uncertainties estimated considering stated sensor accuracy. For multiple measurement points, such as dew point, the estimate assumes stated accuracies of temperature and relative humidity measurement with errors propagated considering the root mean square error (RMSE) of the resulting error stream.

Thermal contours shown in Figure 6 for the March 13–24, 2015, period reveal that most of the free cooling during spring is actually coming from the slab edge at a depth down to approximately 2 ft (0.61 m). Of particular note, the deep ground temperature is now actually higher than that at shallow depths (as seen in the undisturbed ground temperature profiles). Also, the magnitude of the temperature differences seen from the slab surface down to the ground at a 10 ft (3.05 m) depth are modest—just over 6°F (3.3°C). This is quite different from the larger differences seen during the heating periods. Homes with carpeted slab floors in central Florida will tend to run slightly warmer during the floating unconditioned season than those with strongly earth-coupled floors.

Light Cooling Period Results

Periods of light cooling were defined as the 132 days where the average daily dew-point temperature was less than 70°F (21.1°C) but the building still required the air conditioning system

Table 3. Interior Conditions and Space Heating Energy Use for the 14 Days of Heating Below 55°F (12.8°C)

	East (Carpeted)	West (Exposed Slab)	Difference	% Difference	Standard Deviation	Standard Error	T-Stat (df = 313)	P-Value
Interior temperature, °F (°C)	74.99 (23.9)	74.49 (23.6)	0.50 (0.3)		1.27	0.07	6.95	<0.001
Interior relative humidity, %	39.16	39.20	–0.04		7.64	0.43	–0.09	0.927
Interior dew point, °F (°C)	47.86 (8.81)	47.45 (8.58)	0.42 (0.23)		2.55	0.14	2.89	0.004
Air-handling unit energy use, kWh/day	15.16	15.81	–0.65	–4.3%	2.65	0.15	–4.35	<0.001

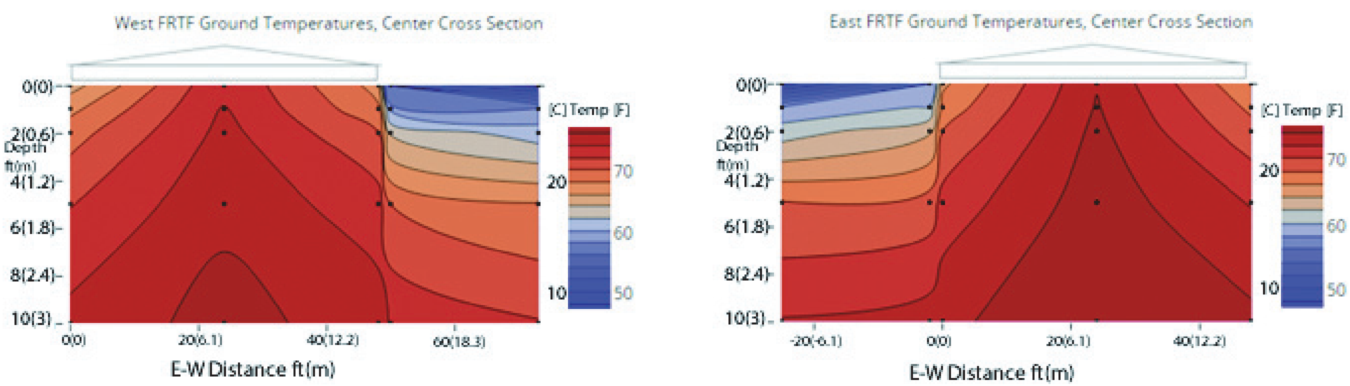

Figure 4 Thermal performance contours of slab and ground thermal performance during peak winter day, February 20, 2015. Note that the distance between houses has been shortened from 65 to 50 ft (19.8 to 15.2 m) to simplify display.

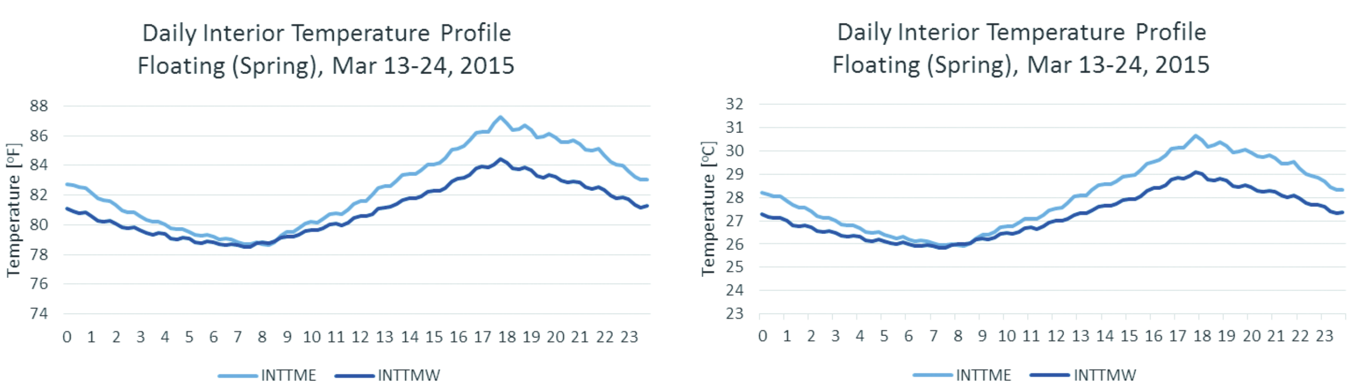

Figure 5 Interior temperatures while floating during a period of warm spring weather, March 13–24, 2015.

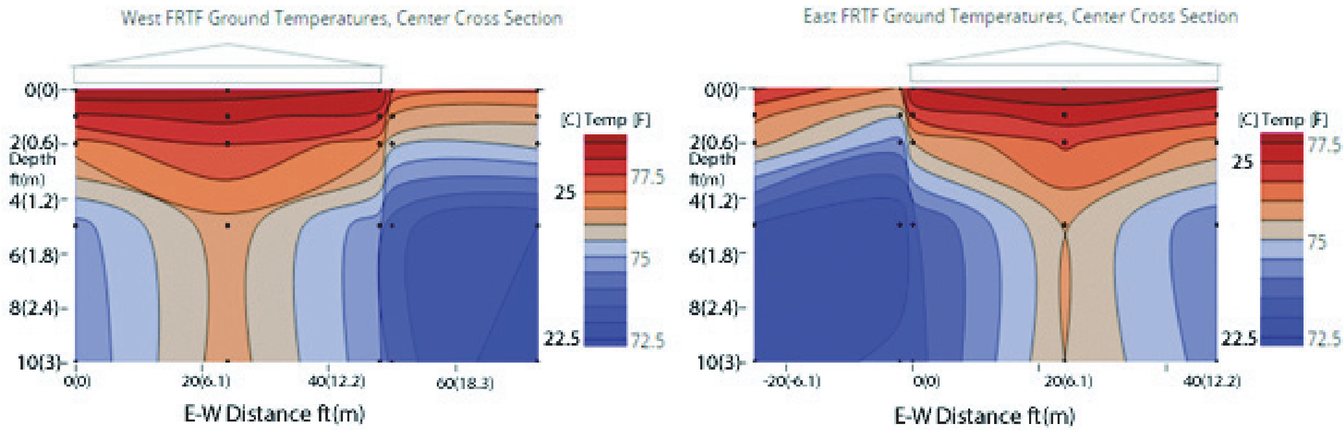

Figure 6 *Thermal performance contours during spring floating condition: March 13–24, 2015. Note the distance between houses has been shortened from 65 to 50 ft (19.8 to 15.2 m) to simplify display.*

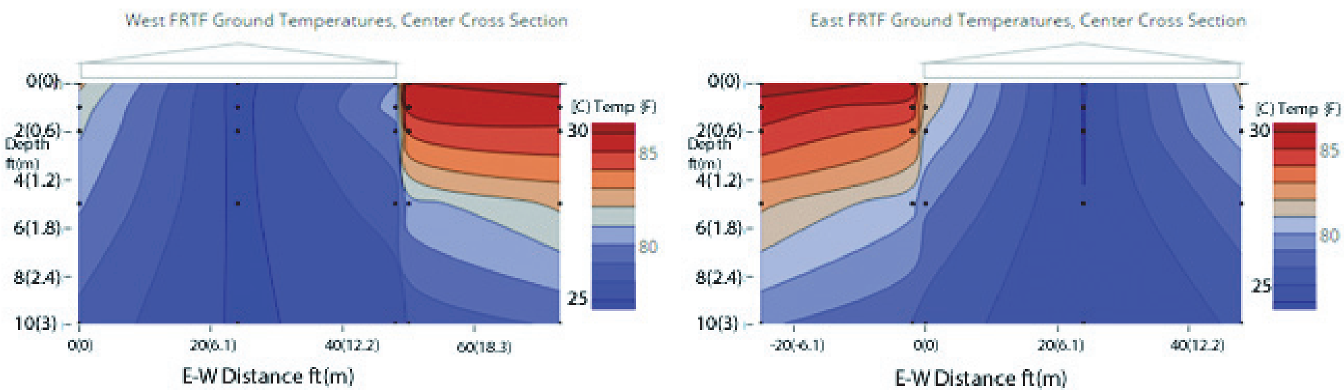

Figure 7 *Thermal performance contours during an extended period of heavy cooling: June 13–28, 2015. Note that the distance between houses has been shortened from 65 to 50 ft (19.8 to 15.2 m) to simplify display.*

to maintain the interior set point of 76°F (24.4°C). These cooling energy needs were typically low; however, the uncarpeted west building showed an average measured daily space cooling of 16.94 kWh against 16.64 kWh in the carpeted east building. This results in a small but statistically significant increase in energy use for the carpeted home (0.29±0.03 kWh, 1.7%).

Heavy Cooling Period Results

During days where the average dew-point temperature was greater than 70°F (21.1°C) (115 heavy cooling days), we found that the uncarpeted west building tended to run about 0.35°F (0.194°C) cooler than the carpeted east building, with a 0.43°F (0.239°C) lower dew-point temperature as well. Cooling energy use in the two homes was nearly identical (28.18 and 28.27 kWh for east and west, respectively) and showed no statistically significant difference. This tends to reinforce the idea that for summer conditions in Central Florida, the slab floor has only very minor influence on cooling and the center of the slab is largely adiabatic with the deep ground temperature condition and across the rest of the slab floor the temperature differences remain very modest.

During an extended maximum cooling period, June 13–28, 2015, where the ambient temperature averaged 81.7°F (27.6°C) compared to the overall heavy cooling period ambient temperature of 80.2°F (26.8°C), the carpeted building showed a significant decrease in daily cooling energy, 0.73±0.15 kWh (2.1%). This supports the idea that carpet helps to control slab edge heat gains under very hot weather conditions and was reinforced by time-lapse thermography taken of the interior of the uncarpeted west building over a series of cooling days that showed heat gain from the slab edge.

Thermal performance contours during the June 13–28, 2015, period (Figure 7) showed greatest thermal gains from the slab edge.

Comparison to Simulation Models

The FRTF measurements contradict the National Renewable Energy Laboratory (NREL) BEopt foundation model (https://beopt.nrel.gov/) using the Winkelmann (2002) approximations within EnergyPlus (DOE 2015). The measured heating savings of carpeted floors on heating does not show up in the simulation even though we would expect envelope differences that have the savings shown in the experiment to be represented in a building simulation result. Furthermore, the simulation predicts cooling savings for uncarpeted floors, and that was not observed. This same limitation existed with other software often used for residential analysis. For instance, EGUSA (http://www.energygauge.com/) shows the same behavior as BEopt, which not surprising since it also uses the Winkelmann foundation model as linked with DOE-2.1E (http://doe2.com/doe2).

Sensitivity to Soil Temperature Assumptions in BEopt

To explore whether the soil temperatures assumed were to blame for the poor correspondence between measurements and the BEopt results, we took the EnergyPlus files for the FRTF and edited the monthly ground temperature input file of the software. The conclusion of this exercise is that altering the ground temperatures in BEopt will not necessarily solve the heat transfer phenomenon observed. A more sophisticated analytical simulation method appears to be needed.

CONCLUSIONS

In experiments from 2014 to 2015, the impact of slab floors on space heating and cooling in the Central Florida climate of two extensively instrumented residential buildings was examined in detail. One building (east) had standard carpet and pad over the monolithic slab, while the other building (west) had unsurfaced concrete exposed. Both buildings were carefully configured to be otherwise nominally identical. A cooling set point of 77°F (25°C) and a heating set point of 73°F (22.8°C) were used in both buildings.

A fundamental finding is that uncarpeted floors have relatively minor thermal influence on building heating and cooling loads in Central Florida's climate under the temperatures examined. In particular, they show low influence on space cooling, with the center slab floor being nearly adiabatic with the deep ground temperature over the summer season. Carpeted floors were shown to have small (4.3%) energy-savings advantages over uncarpeted slab floors for space heating.

The most important caveat is that we would expect results to differ considerably for different interior temperature conditions, as the ground temperature and interior set points in Central Florida are very close. For instance, a household maintaining 80°F (26.7°C) inside during the cooling season would likely see an air-conditioning advantage from the uncovered slab floor. Similarly, occupants maintaining a cooling set point of 73°F (22.8°C) would likely find the carpeted floor to yield significant performance advantages during the cooling season. Because the floor is largely adiabatic in summer in Central Florida at a set point of 77°F (25°C), uncarpeted slabs may prove beneficial in summer for houses located in Georgia or other locations with lower ground temperatures.

Another finding is that the results are not readily replicable in typical software used for modeling residential building energy use. More empirical data in other climates should be collected and models should be refined to match the data.

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