CASTLE ROCK MONITORING

July 30, 2021

prepared by Emu Systems

for Colorado Earth

COE001

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BUILDING SCIENCE BACKGROUND

Dependable Buildings

The North American construction market is undergoing a transformation about the way buildings are designed and built.

On one side, the more affordable availability of renewable energy systems is allowing for more and more buildings to reach a net zero energy balance. On the other, the more frequent extreme weather events are pushing the conversation to focus on future-proofing buildings and on allowing for higher resilience of the built environment.

This scenario challenges traditional American design and construction methods. The simplified prescriptive approach of Building Codes is often unable to fully address the complex dynamics occurring between people, building, and climate.

This report covers the performance of compressed earth block wall assemblies (CEB), as an alternative to conventional American timber frame construction.

The first part of the report addresses the underlying science this research is based upon.

The second part covers the monitoring of an occupied building using CEB walls, and the results in terms of Sinter and Summer performance.

Thermal Mass And Building Performance

For decades, scientists have investigated the use of thermal mass to improve thermal performance of buildings.

In the recent years, the international Passive House Institute has conducted detailed research on the use of thermal mass in vert high performance buildings. The research covered non-residential buildings [14], as well as in warm climates [12].

The results indicate that there is a close connection between the impact of thermal mass on the energy efficiency of a building, and the gains the building experiences over a typical day.

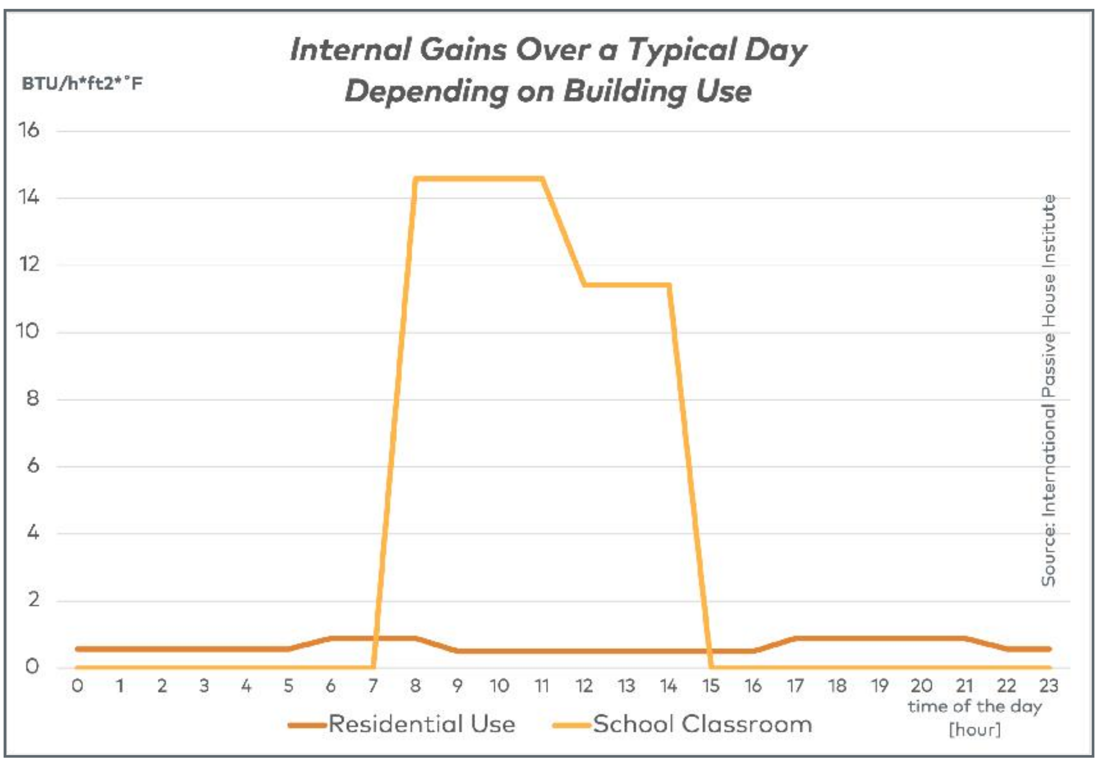

Image 01: Variability of interior heat gains over a typical day depending on building use [12].

Specifically, the research conducted on Passive House school building showed the great benefit of using thermal mass in these types of buildings, due to the high variability of the interior gains due to intermittent high occupancy density.

These results indicate the greater impact of the use of thermal mass in non-residential buildings than in residential ones.

CEB Wall Assemblies vs Standard Framed Walls

We investigated three CEB wall assemblies:

A - 10" CEB wall with 2" exterior mineral wool insulation
B - 2x 6" CEB wall with 3" perlite insulation between the two wythes
C - 2x 6" CEB wall with 4" perlite insulation between the two wythes

The following paragraphs cover the performance of these CEB assemblies in terms of heat losses (U-values), and in terms of compliance with the 2021 IECC [6].

The CEB assemblies are also compared to a standard 2x6 framed wall in terms of dynamic performance. This is particularly significant in terms of performance in Summer, or in case of extreme weather events.

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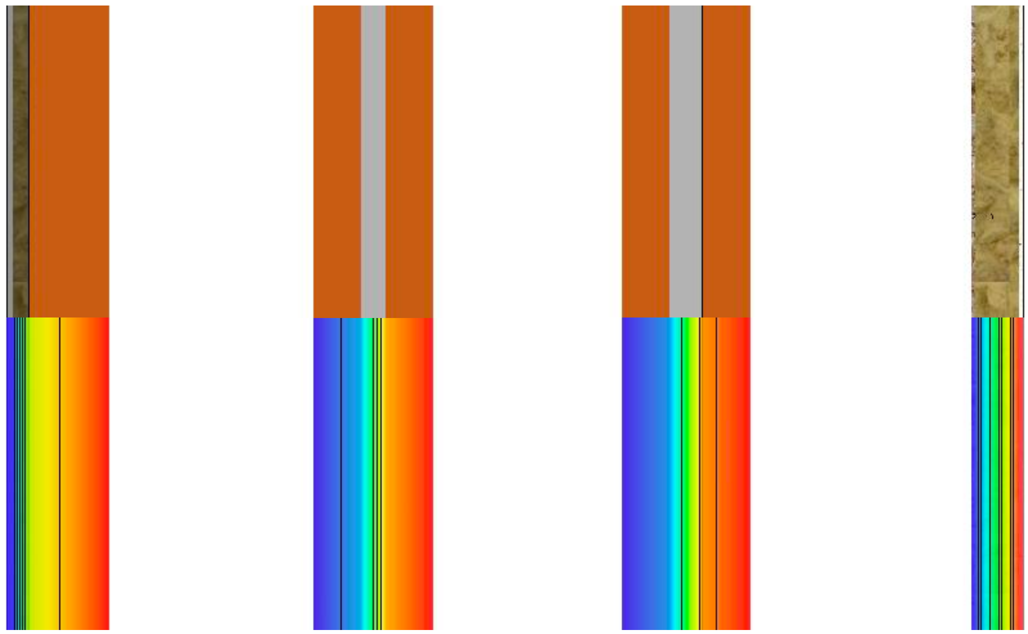

Image 02: The CEB wall assemblies modeled (from left to right: A, B, C), and the standard 2x6 framed wall (far right). For each wall assembly, the top image shows the section view, while the bottom shows the steady state temperature distribution (isotherm view).

CEB Walls U-values

The steady state performance of the CEB wall assemblies was modeled in PHPP [11] in compliance with ISO 6946 [7]. The results are shown in Table 01 below.

It was preferred to use the U-values of the assemblies, as these values describe the actual heat losses occurring through the assembly (unlike the R-values).

For details on how the U-values were calculated, see Appendix A.

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U-vale Calculation Of CEB Wall Types - ISO 6946							
Description		Thickness	U-value	Thickness	U-value	Notes
		[m]	[W/m2K]	[in]	[BTU/h*ft2*°F]	
A	10" CEB Wall + Exterior Mineral Wool	0.324	0.426	12.75	0.075	U-value calculation accounts for thermal bridging due to e.g. metal fasteners and other repetitive thermal bridging through the insulation
B	2x 6" CEB Wall + 3" Perlite	0.381	0.384	15.00	0.068	
C	2x 6" CEB Wall + 4" Perlite	0.406	0.320	16.00	0.056	

Table 01: Results from the U-value calculations of the CEB assemblies considered, modeled in PHPP in compliance with ISO 6946. For more details, see Appendix A.

Compliance With Energy Code

The results shown in Table 01 allow to verify compliance with the prescriptive requirements of Energy Code.

The U-value requirements for the 2021 International Energy Conservation Code (2021 IECC, [6]) are listed in Table 02.

Table 03 provides feedback for the CEB wall assemblies considered here in terms of meeting the U-value requirements of the 2021 IECC.

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TABLE R402.1.2 MAXIMUM ASSEMBLY *U*-FACTORS[a] AND FENESTRATION REQUIREMENTS

CLIMATE ZONE	FENESTRATION *U*-FACTOR[f]	SKYLIGHT *U*-FACTOR	GLAZED FENESTRATION SHGC[d, e]	CEILING *U*-FACTOR	WOOD FRAME WALL *U*-FACTOR	MASS WALL *U*-FACTOR[b]	FLOOR *U*-FACTOR	BASEMENT WALL *U*-FACTOR	CRAWL SPACE WALL *U*-FACTOR
0	0.50	0.75	0.25	0.035	0.084	0.197	0.064	0.360	0.477
1	0.50	0.75	0.25	0.035	0.084	0.197	0.064	0.360	0.477
2	0.40	0.65	0.25	0.026	0.084	0.165	0.064	0.360	0.477
3	0.30	0.55	0.25	0.026	0.060	0.098	0.047	0.091[c]	0.136
4 except Marine	0.30	0.55	0.40	0.024	0.045	0.098	0.047	0.059	0.065
5 and Marine 4	0.30	0.55	NR	0.024	0.045	0.082	0.033	0.050	0.055
6	0.30	0.55	NR	0.024	0.045	0.060	0.033	0.050	0.055
7 and 8	0.30	0.55	NR	0.024	0.045	0.057	0.028	0.050	0.055

For SI: 1 foot = 304.8 mm.

a. Nonfenestration *U*-factors shall be obtained from measurement, calculation or an approved source.

b. Mass walls shall be in accordance with Section R402.2.5. Where more than half the insulation is on the interior, the mass wall *U*-factors shall not exceed 0.17 in Climate Zones 0 and 1, 0.14 in Climate Zone 2, 0.12 in Climate Zone 3, 0.087 in Climate Zone 4 except Marine, 0.065 in Climate Zone 5 and Marine 4, and 0.057 in Climate Zones 6 through 8.

c. In warm humid locations as defined by Figure R301.1 and Table R301.1, the basement wall *U*-factor shall not exceed 0.360.

d. The SHGC column applies to all glazed fenestration.

Exception: In Climate Zones 0 through 3, skylights shall be permitted to be excluded from glazed fenestration SHGC requirements provided that the SHGC for such skylights does not exceed 0.30.

e. There are no SHGC requirements in the Marine Zone.

f. A maximum *U*-factor of 0.32 shall apply in Marine Climate Zone 4 and Climate Zones 5 through 8 to vertical fenestration products installed in buildings located either:

1. Above 4,000 feet in elevation above sea level, or
2. In windborne debris regions where protection of openings is required by Section R301.2.1.2 of the *International Residential Code*.

Table 02: Maximum allowed assembly U-values (U-factors) for the 2021 IECC.

Compliance of CEB Wall Assemblies With The 2021 IECC, Maximum Assembly U-values										
Ref. Table R402.1.2 'Maximum Assembly U-factors And Fenestration Requirements'. Note B) Mass walls with more than half of the insulation on the inside of the wall.										
Climate Zone		0	1	2	3	4 except Marine	5 and Marine 4	6	7	8
Max U-value By 2021 Code [BTU/h*ft2*°F]		0.17	0.17	0.14	0.12	0.087	0.065	0.057	0.057	0.057
A	10" CEB Wall + Exterior Mineral Wool	Pass	Pass	Pass	Pass	Pass	Not Pass	Not Pass	Not Pass	Not Pass
B	2x 6" CEB Wall + 3" Perlite	Pass	Pass	Pass	Pass	Pass	Not Pass	Not Pass	Not Pass	Not Pass
C	2x 6" CEB Wall + 4" Perlite	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Table 03: Compliance of the CEB assemblies considered here with the maximum allowed assembly U-values of the 2021 IECC.

Dynamic Performance Of Wall Assemblies

The steady state performance of an assembly (i.e. R-value, U-value) is representative of how the assembly performs in Winter, when the direction of the heat flow is predominant from the inside to the outside.

For assemblies with low R-values (i.e. R40 or less), it is helpful to also consider the periodic thermal transmittance of the assembly. This describes the performance of the assembly under dynamic conditions e.g. in the Summer, when the direction of the heat flow changes from day time to night time. Note that this behavior becomes secondary to other factors in buildings with high R-value assemblies.

The dynamic performance of the CEB assemblies was modeled in compliance with ISO 13786 [9], using Mold Simulator v5 [5]. The results are listed in Table 04, and illustrated in Image 03. For further details of the results, see Appendix A.

Dynamic Performance Of Wall Assembly - ISO 13786						
		Periodic Thermal Transmittance, Y_mn		Decrement Factor Delay (thermal lag)	Decrement Factor 'f' (attenuation)	Reduction of incoming heat wave through wall
		W/m2K	[BTU/h*ft2*°F]	[h]	[%]	[%]
Standard 2x6 Wall w/ Mineral Wool Batt Insulation, R23		0.2244	0.0039	6.49	96.4%	3.6%
A	10" CEB Wall + Exterior Mineral Wool	0.0506	0.0009	13.42	11.9%	88.1%
B	2x 6" CEB Wall + 3" Perlite	0.0471	0.0008	15.51	12.3%	87.8%
C	2x 6" CEB Wall + 4" Perlite	0.0360	0.0006	15.95	11.3%	88.7%

Table 04: Results from the dynamic performance modeling of the CEB assemblies considered, modeled in Mold Simulator in compliance with ISO 13786. For more details, see Appendix A.

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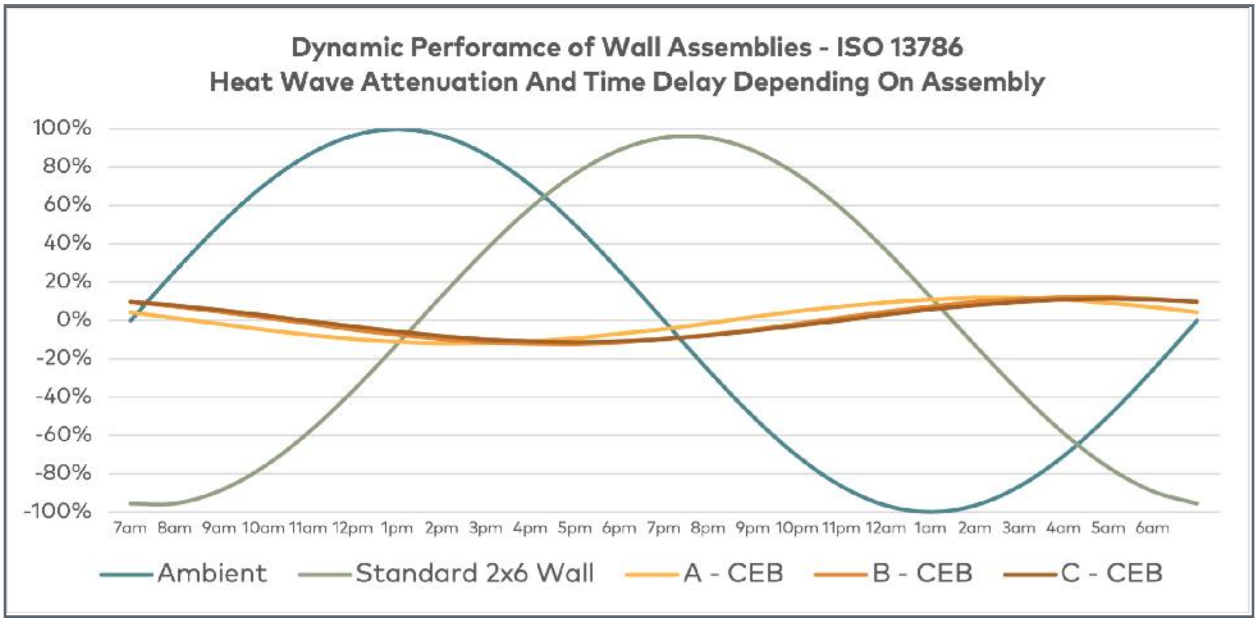

Image 03: Results of thermal attenuation and delay of the assemblies considered, as modeled per ISO 13786 with Mold Simulator. For further details, see Appendix A.

CASTLE ROCK MONITORING

Description Of Monitoring Plan

Scope And Goals

Emu was engaged by Colorado Earth to monitor the performance of the CEB walls used in the project.

The goal was to determine the performance of the blocks in a real occupied building, and to investigate the behavior of the blocks as exposed to different heat gains (i.e. direct and indirect passive solar gains, interior gains).

Project Description

Image 04: View of the West elevation of the building.

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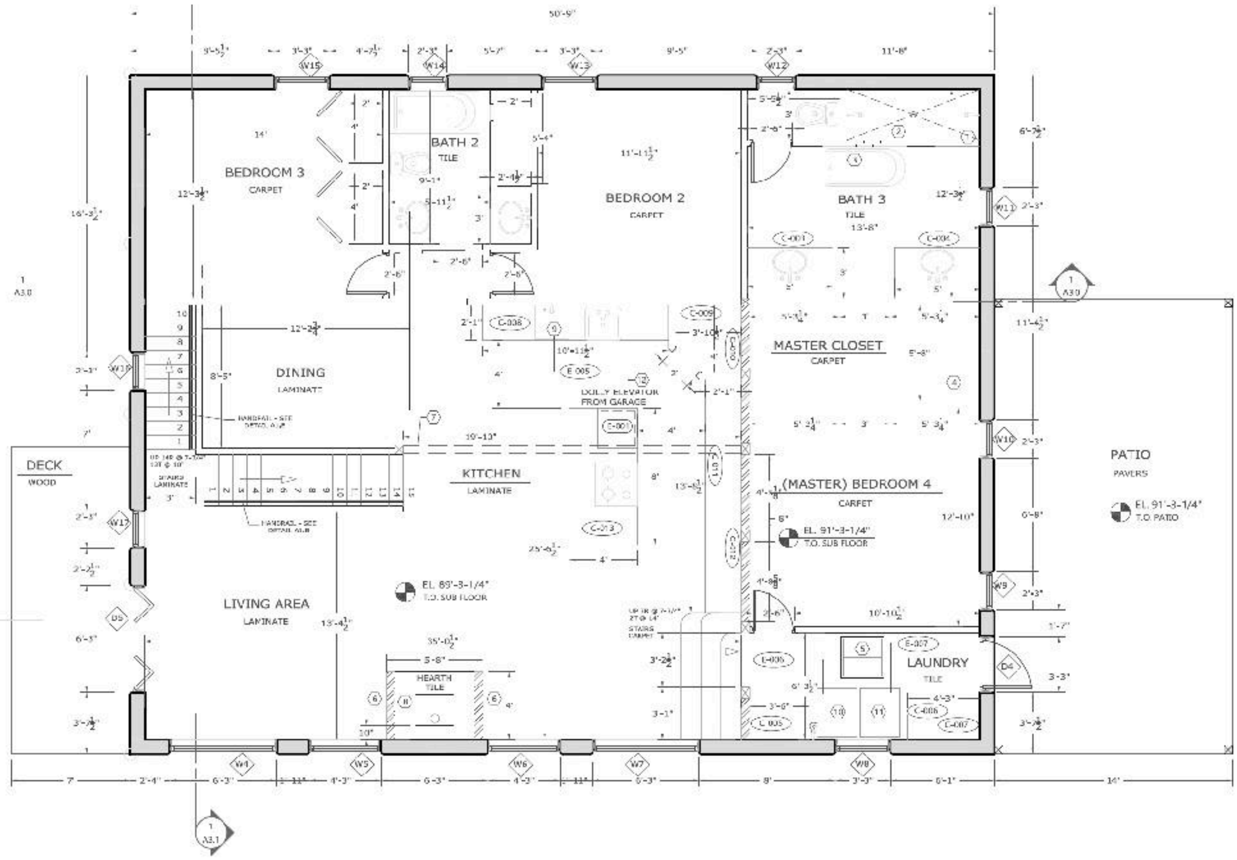
The monitored building is a single family house built in Castle Rock, Colorado. The building constitutes of two stories plus a loft space, with the main living space located at the second floor.



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A1.1
MAIN LEVEL FLOOR PLAN
SCALE: 1/4" = 1'-0"

Image 05: Floor plan of the main level of the building (second floor).

In the floor plan, the area described as 'Living Area' corresponds to what is described later as 'Great Room'.

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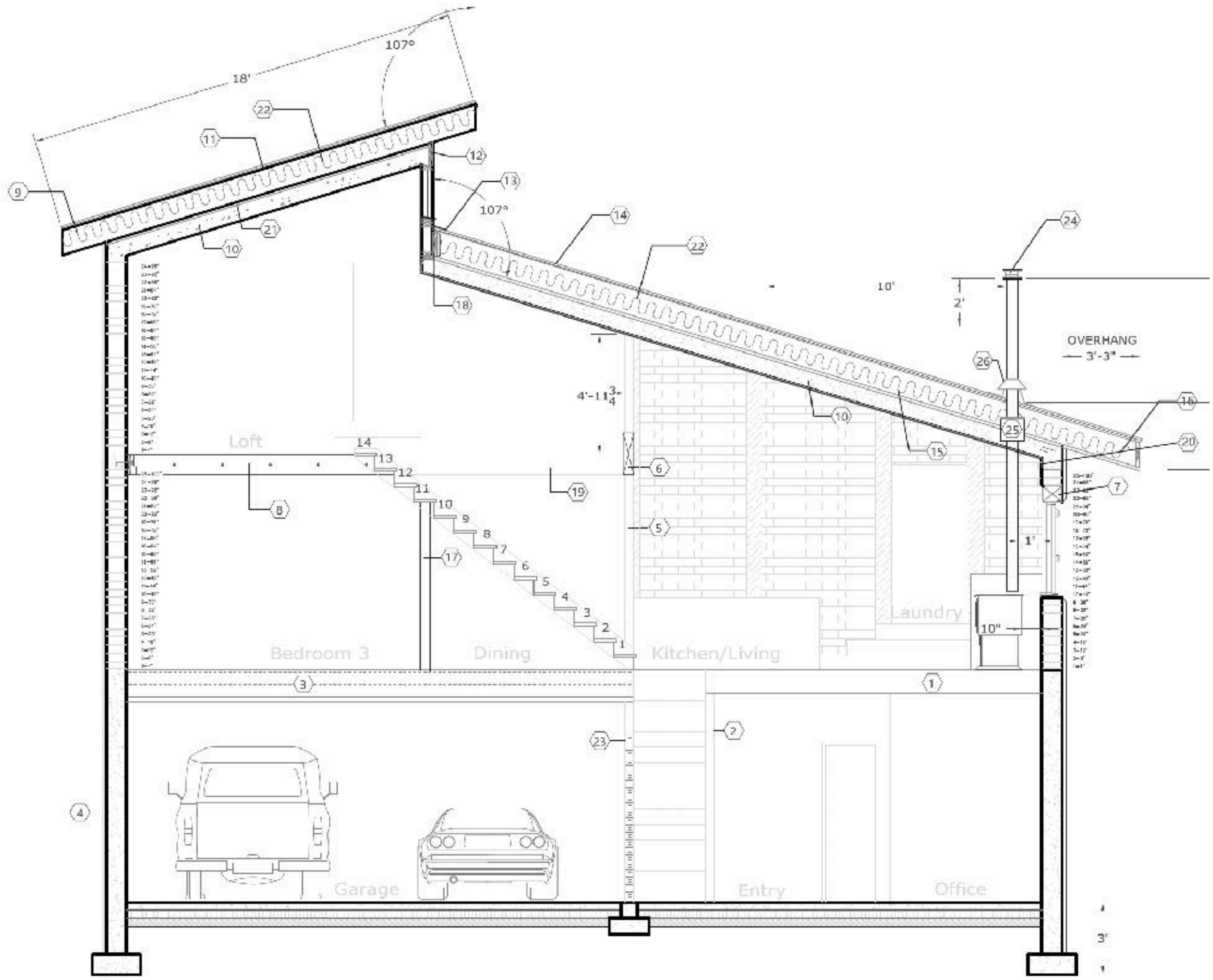

Image 06: Cross section of the building.

CEB Wall Assembly Description

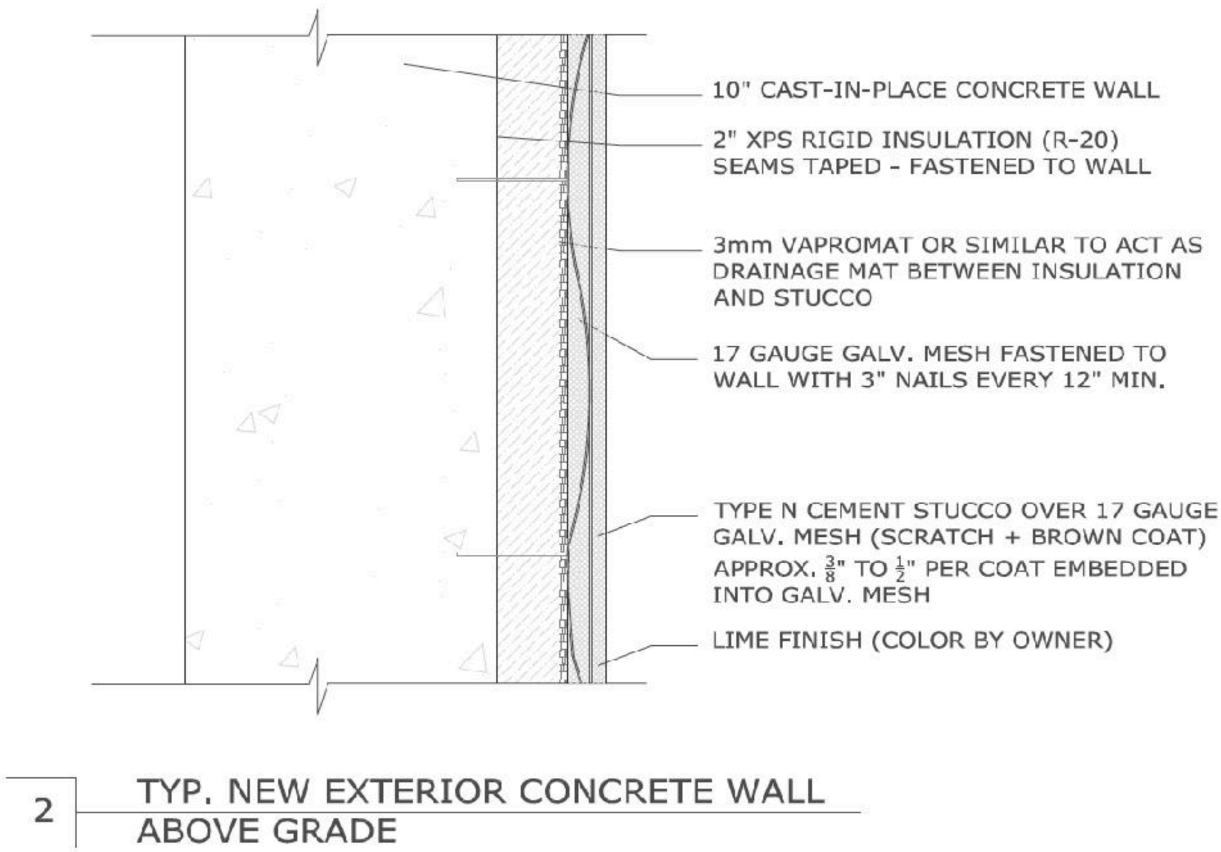

Image 07: Typical CEB wall assembly used in the Castle Rock project, corresponding to assembly 'A' modeled above.

The typical CEB wall assembly used for walls above grade in the Castle Rock project is shown in Image 07. This corresponds to the CEB wall assembly 'A' modeled above in this report.

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Sensor Package

Two main types of sensors were selected for the monitoring of the Castle Rock project:

1. Sensors embedded in the CEB blocks, used to record variations in temperature inside the block. A total of four sensors was used for this purpose, grouped into two couples i.e. two sensors embedded in one block, one closer to the inside of the building, the other closer to the outside.

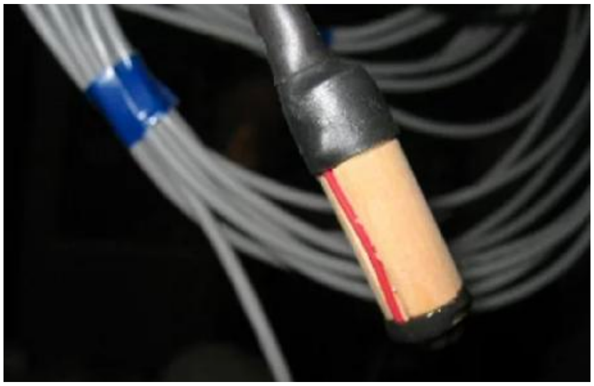

Image 08: Embedded sensor (EMS, by SMT), embedded in the CEB blocks at two locations of the building.

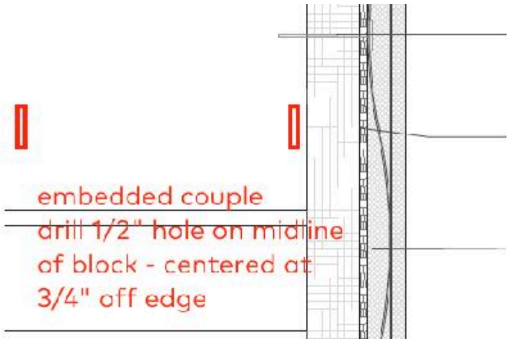

Image 09: Location of the EMS sensor couple within one block. The sensor package included two couples of embedded sensors: one in the South wall, and the other in the West wall.

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2. Data loggers used to record conditions in the Great Room, as well as ambient conditions outside the building.

Image 10: Extech RHT10 data loggers used to record conditions in the Great Room as well as ambient conditions outside the building.

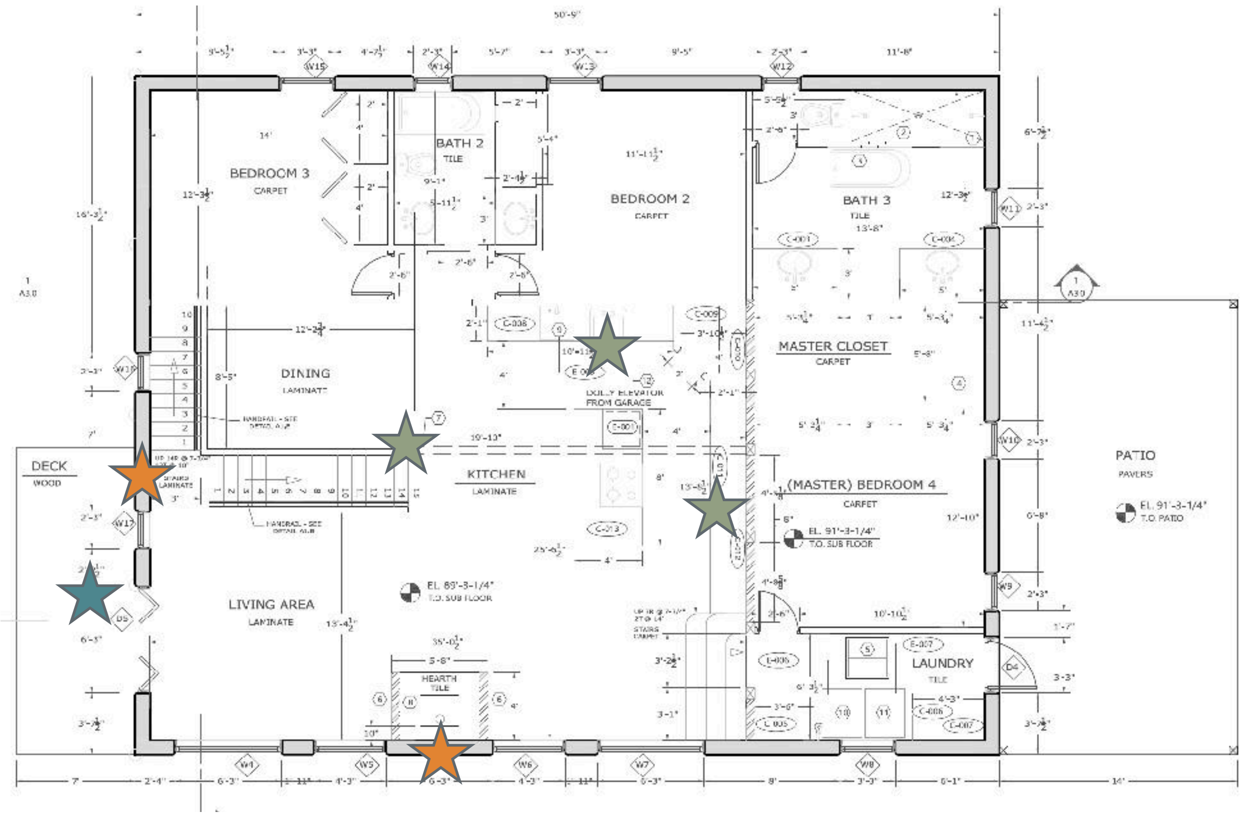

Image 11: Location of the sensors in the Castle Rock Project. Orange: embedded sensors in the South wall (bottom) and West wall (left), two sensors each (inner, outer). Green: data loggers recording the conditions in the Great Room. Blue: data logger recording conditions of the outside ambient (under the balcony deck).

The embedded sensor couple installed in the South wall was intentionally located right behind the wood fire stove. The intention was to record the temperature increase inside the CEB blocks, as a way to show the ability of the blocks to store heat from peak internal heat gains.

Image 12: View of the South and West walls of the building (respectively: right and left). The stars indicate the approximate locations of the embedded sensors (orange), and the ambient data logger under the deck (blue).

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Image 13: View of the Great Room while the building was about to be completed. The two stars show the approximate location of the sensors embedded in the South wall (left), and in the West wall (right).

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Image 14: Panoramic view of the Great Room looking North towards the kitchen, approximately from the location of the wood fire stove. The green stars indicate the approximate locations of the data loggers used to record the conditions inside the Great Room.

Image 15: A CEB block being prepared with the two embedded sensors.

Image16: A CEB block equipped with the embedded sensors, as installed in a CEB wall in the Castle Rock project.

Image17: One of the data loggers installed in the Great Room.

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Monitoring Results

The purpose of the monitoring project was to record the behavior of the CEB assembly over different conditions of interior gains as well as passive solar gains.

The data below is divided by type of conditions the building was exposed to, in order to allow for an easier interpretation of the results.

Summer Performance

Images 18-20 show the temperature variations occurring over typical Summer conditions, with significant temperature changes in the outside ambient.

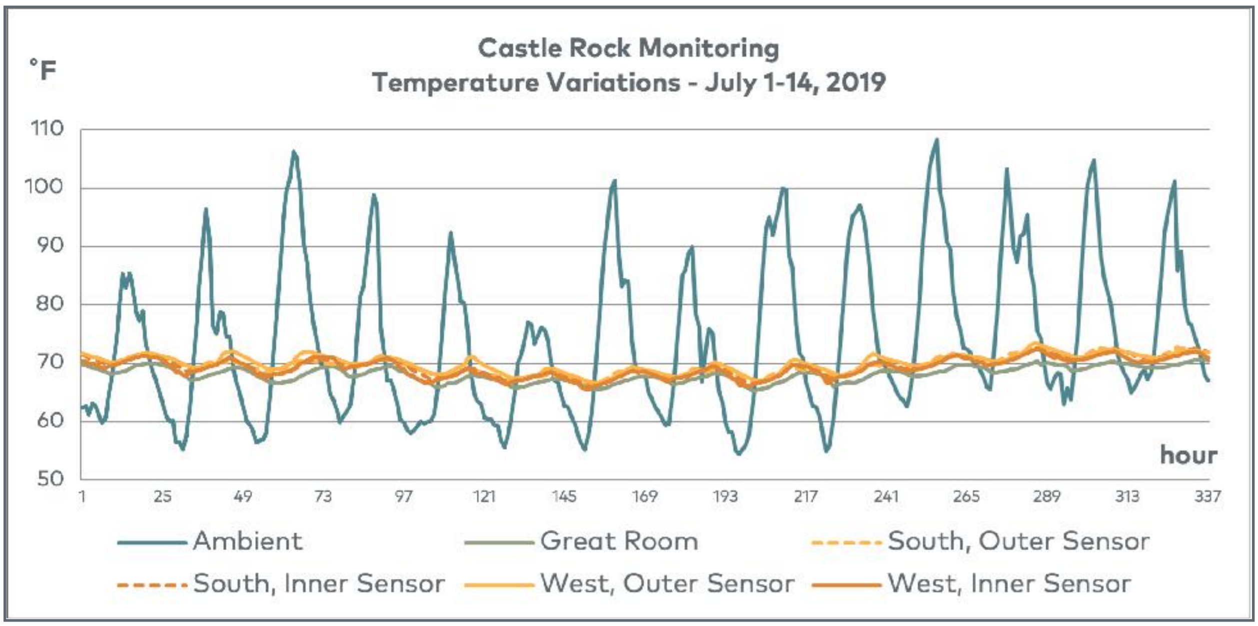

Image 18: Temperature variations recorded over two weeks in July 2019.

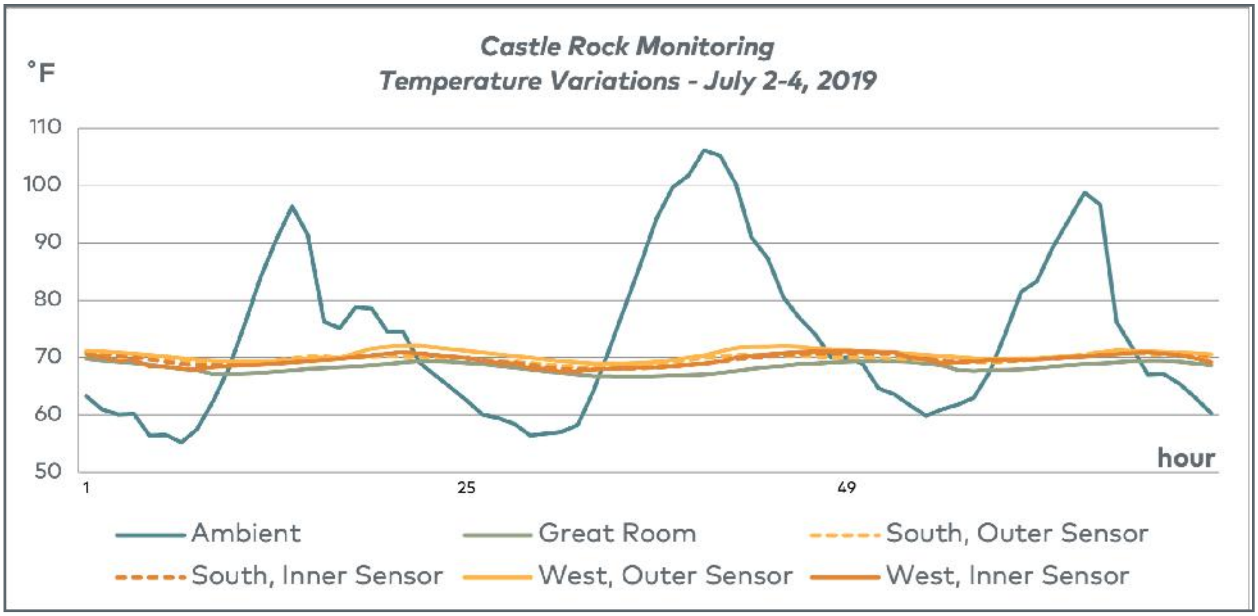

Image 19: Enlarged graph showing the variation over a 3-day period. The data recorded from the Castle Rock building shows very close resemblance with the results from the dynamic performance modeling shown in Image 03.

The data collected in July 2019 shows a behavior of the CEB walls very close to the dynamic performance (i.e. thermal attenuation and time delay) modeled according to ISO 13786. Ref. Image 03 above.

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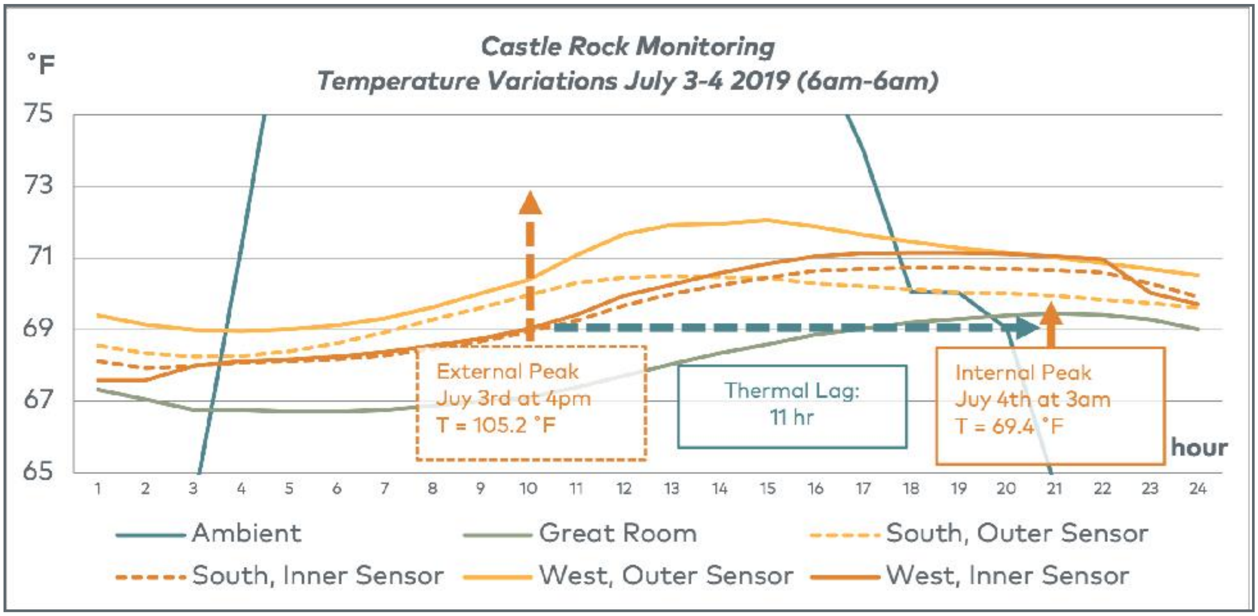

Image 20: Enlarged graph showing the temperature variation over a 24-hour period. The delay and attenuation of the heat wave are highlighted in the graph.

Winter Performance - Indirect Passive Solar Gains

Images 21 and 22 below show the temperature variations recorded in November 2019.

The temperatures recorded in the Great Room show increases due to passive solar gains coming into the space from the South-facing windows.

These temperature increases cause the interior side of the CEB walls to absorb heat from the interior air.

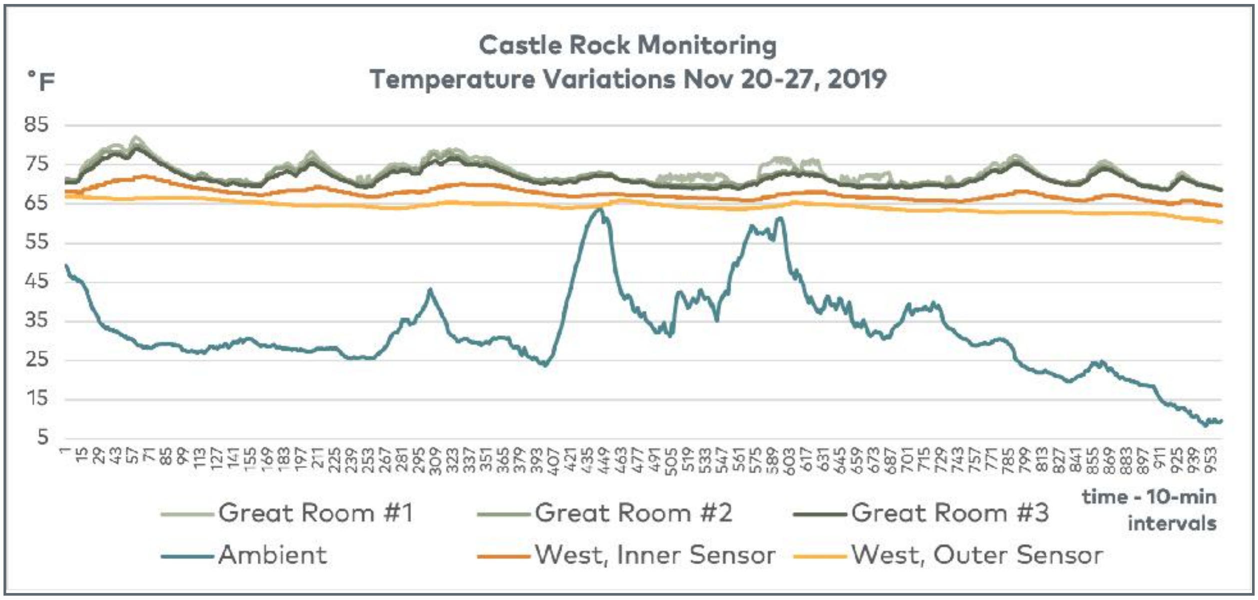

Image 21: Temperature variations recorded on November 20-27, 2019.

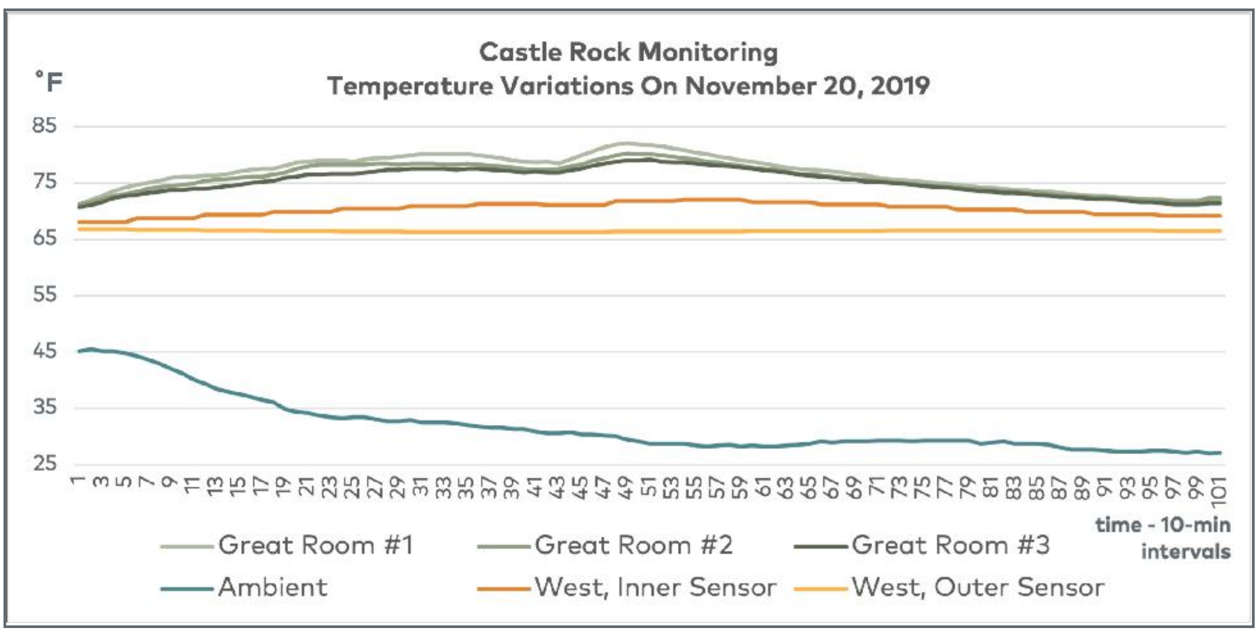

Image 22: Enlargement showing the Temperature variations recorded on November 20, 2019.

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The data from November 2019 shows the ability of the CEB blocks to absorb heat from the inside of the room, and to buffer temperature increases over time.

Note that the West CEB wall itself was not directly exposed to passive solar gains from the South-facing windows. The increase in temperature recorded by the sensor 'West, Inner Sensor' are to be associated with heat absorbed from the wall from the room air.

Winter Performance - Fire Stove (intermittent high interior gains)

Images 23-25 show data recorded in April 2019, with the intention to focus on intermittent interior heat gains as in the case of the wood fire stove being used.

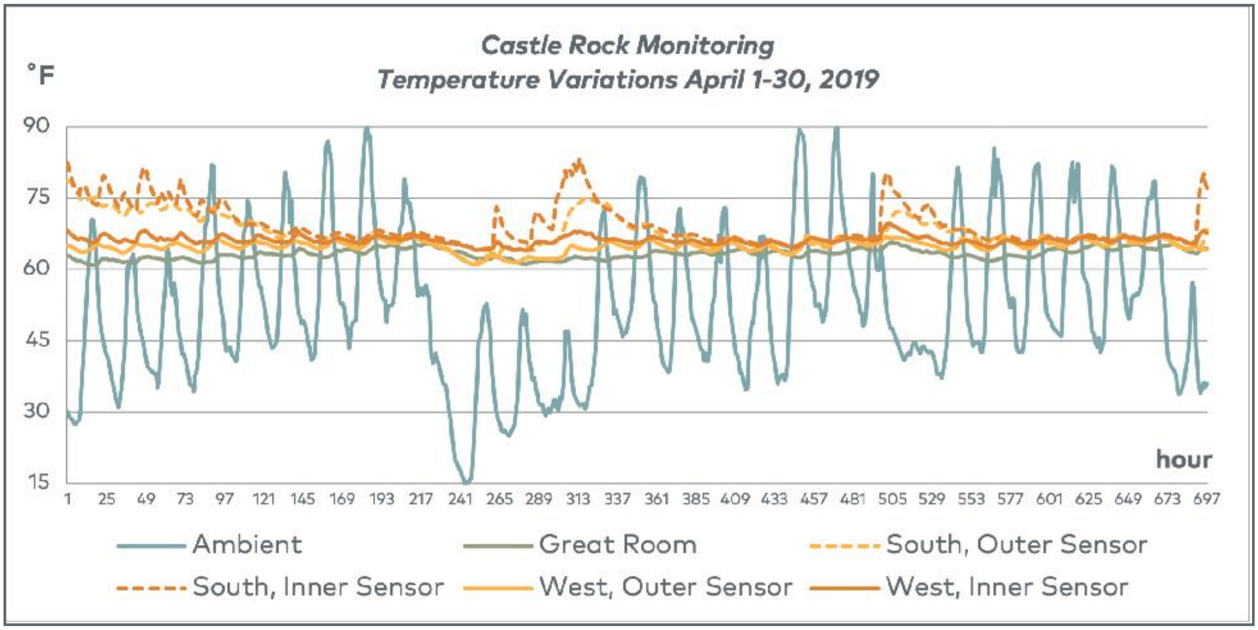

Image 23: Data collected in April 2019.

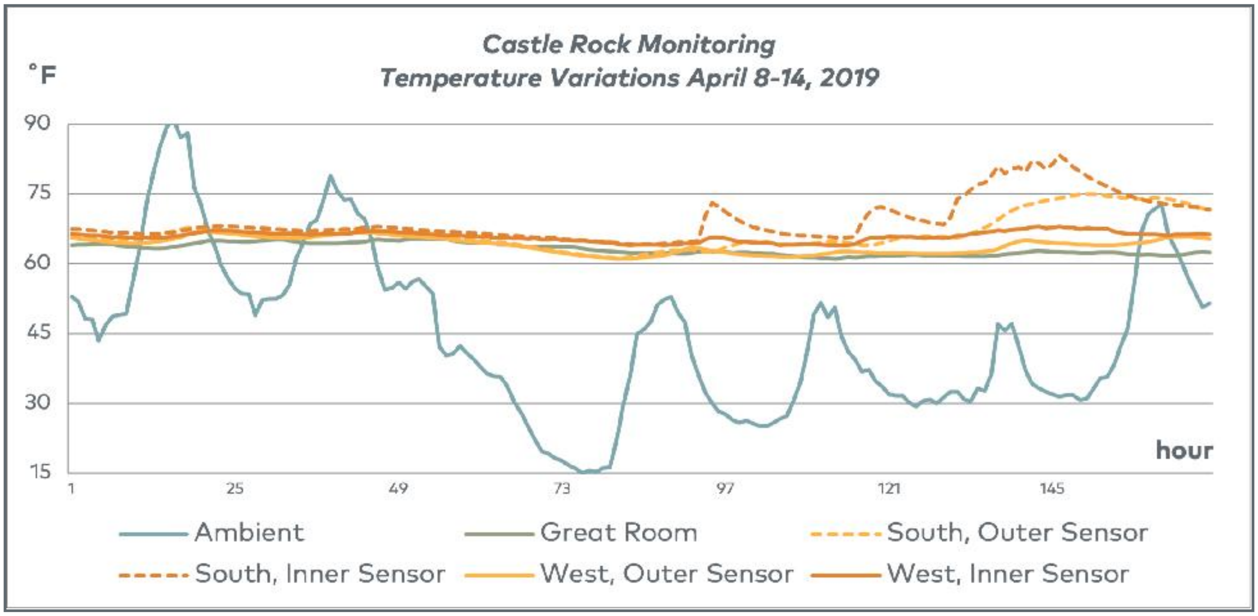

Image 24: Enlarged graph showing data from April 8-14, 2019. The dashed orange l

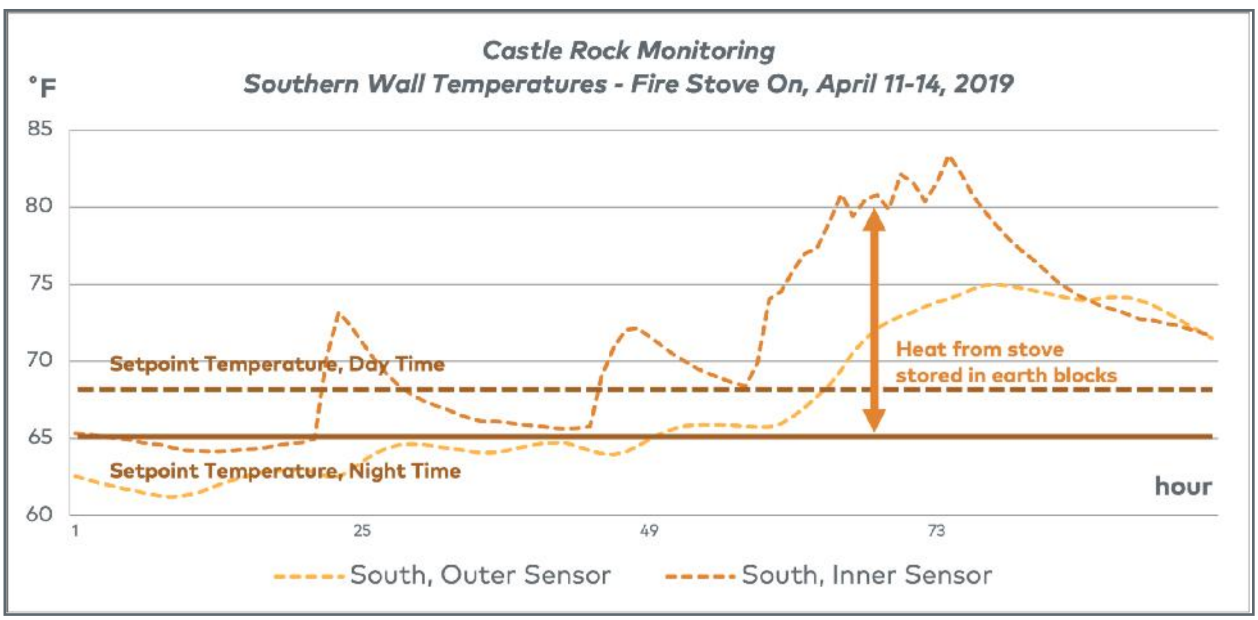

Image 25: Enlarged graph.

CONCLUSIONS

The data collected from the Castle Rock monitoring confirms the close relationship between temperature changes inside the building, and the energy absorbed and released by the thermal mass that is exposed to those changes.

Overall, the response of the sensors installed closer to the interior of the building show more rapid engagement to the changes in interior conditions. This is clearly depicted in images 22 and 25. In other words, the more exposed the thermal mass is to the interior conditions, the more it is engaged by those changes. This is significant in the case of exposed CEB block walls, compared to other mass walls where the thermal mass is decoupled from the interior environment (e.g. ICF walls).

The dynamic performance of CEB wall assemblies compared to a regular 2x6 wall is supported by the data collected. The ISO 13786 modeling results in terms of attenuation and time delay are comparable to the data collected from the Castle Rock project (images 03 and 19 respectively).

With regards to the performance of the CEB wall assemblies in Winter, the data collected allows to review the behavior of the thermal mass in case of different types of heat gains.

The degree of thermal engagement of the mass is proportional to the increase of the air temperature inside the building. Images 22 and 25 show significant increases in temperature inside the CEB blocks following significant intermittent gains - indirect solar gains and wood fire stove respectively. This confirms the findings from the Passive House Institute about the use of thermal mass in non-residential buildings [14].

The main benefit for the building as a whole from this behavior of thermal mass seems to be the reduction of peak loads, as the exposed thermal mass allows to buffer sudden changes in interior temperature.

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In case of passive solar gains, the temperature profiles shown in Image 22 seem to indicate that the CEB blocks absorb heat from the higher temperature of the internal air, to then release it back to the inside of the building. The rather constant temperature recorder by the outer sensor seem to indicate that the heat from the indirect solar gains does not penetrate to the full 10" depth of the CEB block of the Castle Rock project.

Instead, in case of the high interior gains from the wood fire stove, the data shown in image 25 show that the whole block is engaged in storing heat. The stored heat is then gradually released back to the inside of the room over time.

Note that the higher temperature of the wall shown in Image 25 leads to higher heat losses to the outside. The rate of losses is proportional to the thermal transmittance (U-value) of the wall assembly: BTU/h*ft2*°F (°F: temperature difference between inside and outside).

In other words, to maximize the benefit of thermal mass inside the building, it is recommended to reduce the heat losses to the outside by means of thermal insulation (i.e. to reduce the wall U-value).

The combination of high thermal capacity via thermal mass, and low heat losses (i.e. low U-values, thanks to thermal insulation), leads building to having a higher time constant. This translates in higher thermal resilience, i.e. the ability of a building to remain inhabitable in case of extreme events e.g. long lasting power outages.

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13. Passive House Institute (PHI): 'Passive House Planning Package' (PHPP)
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APPENDIX A - CALCULATION DETAILS

Assembly no.: 01ud
Building assembly description: A — 10" CEB Wall + Exterior Mineral Wool
Interior insulation?

Heat transmission resistance [m²K/W]
Orientation of building element: 2-Wall — interior R_{si}: 0.13
Adjacent to: 1-Outdoor air — exterior R_{se}: 0.04

Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
		R/in		thickness [in]		
CEB Wall	0.345	0.42		10		254
Mineral Wool Board	0.035	4.10		2		51
Stucco	0.90	0.16		0.75		19

Percentage of sec. 1: 100% — Percentage of sec. 2: — Percentage of sec. 3: — Total: 32.4 cm

U-value supplement: 0.005 W/(m²K) — U-value: 0.426 W/(m²K)

Image A01: ISO 6946 U-value calculation for CEB Assembly 'A'.

Assembly no.: 02ud
Building assembly description: B — 2x 6" CEB Wall + 3" Perlite
Interior insulation?

Heat transmission resistance [m²K/W]
Orientation of building element: 2-Wall — interior R_{si}: 0.13
Adjacent to: 1-Outdoor air — exterior R_{se}: 0.04

Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
		R/in		thickness [in]		
CEB Wall	0.345	0.42		6		152
Perlite	0.048	3.00		3		76
CEB Wall	0.345	0.42		6		152

Percentage of sec. 1: 100% — Percentage of sec. 2: — Percentage of sec. 3: — Total: 38.1 cm

U-value supplement: 0.005 W/(m²K) — U-value: 0.384 W/(m²K)

Image A02: ISO 6946 U-value calculation for CEB Assembly 'B'.

Assembly no.: 03ud — C — 2x 6" CEB Wall + 4" Perlite

Interior insulation?

Heat transmission resistance [m²K/W]

Orientation of building element: 2-Wall — interior R_{si}: 0.13

Adjacent to: 1-Outdoor air — exterior R_{se}: 0.04

Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
		R/in		thickness [in]		
CEB Wall	0.345	0.42		6		152
Perlite	0.048	3.00		4		102
CEB Wall	0.345	0.42		6		152

Percentage of sec. 1: 100%

Percentage of sec. 2:

Percentage of sec. 3:

Total: 40.6 cm

U-value supplement: 0.005 W/(m²K)

U-value: 0.320 W/(m²K)

Image A03: ISO 6946 U-value calculation for CEB Assembly 'C'.

Z11	-65.255 - i25.488660	
|Z11|	70.0566	W/m²K
arg(Z11)	13.4224	h
Z12	19.723 - i1.035372	
|Z12|	19.7502	W/m²K
arg(Z12)	-0.2003	h
Z21	11.849 + i104.635705	
|Z21|	105.3045	W/m²K
arg(Z21)	5.5693	h
Z22	-15.132 - i25.383522	
|Z22|	29.5519	W/m²K
arg(Z22)	-8.0534	h

Image A04: ISO 13786 Periodic performance calculation for CEB Assembly 'A'.

Z11	-51.722 - i67.619473	
|Z11|	85.1327	W/m²K
arg(Z11)	15.5058	h
Z12	18.470 + i10.428043	
|Z12|	21.2103	W/m²K
arg(Z12)	1.9633	h
Z21	-1.095 + i417.610795	
|Z21|	417.6122	W/m²K
arg(Z21)	6.0100	h
Z22	-40.584 - i95.664173	
|Z22|	103.9168	W/m²K
arg(Z22)	-7.5326	h

Image A05: ISO 13786 Periodic performance calculation for CEB Assembly 'B'.

Z11	-57.162 - i95.885727	
|Z11|	111.6316	W/m²K
arg(Z11)	15.9466	h
Z12	22.448 + i16.345198	
|Z12|	27.7680	W/m²K
arg(Z12)	2.4040	h
Z21	-58.806 + i544.837433	
|Z21|	548.0018	W/m²K
arg(Z21)	6.4107	h
Z22	-39.775 - i130.275858	
|Z22|	136.2126	W/m²K
arg(Z22)	-7.1319	h

Image A06: ISO 13786 Periodic performance calculation for CEB Assembly 'C'.

Z11	-0.550 + i4.256063	
|Z11|	4.2914	W/m²K
arg(Z11)	6.4908	h
Z12	-3.845 - i2.251596	
|Z12|	4.4560	W/m²K
arg(Z12)	14.0234	h
Z21	4.607 - i0.930469	
|Z21|	4.6997	W/m²K
arg(Z21)	-0.7613	h
Z22	-0.982 + i4.552806	
|Z22|	4.6575	W/m²K
arg(Z22)	6.8114	h

Image A07: ISO 13786 Periodic performance calculation for a standard R23 2x6 wall assembly.

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