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Solar Reflectance and Energy Usage – Impact of Thermal Mass on Cool Walls

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ABSTRACT

Cool walls are designed to reduce energy consumption by having a high solar reflectance which minimizes the heat energy absorbed from solar radiation. This strategy is more effective for light-weight wall systems than for more thermally massive walls due to the ability of the mass to act as a buffer against heat transfer. In this study, three different wall systems were analyzed – fiber cement cladding, brick veneer cladding, and brick veneer over typical concrete masonry unit (CMU) – to cover a spectrum of thermal masses typical in residential and commercial buildings. Using a 2D finite element program, along with typical metrological year (TMY) climate data, these walls' performance was simulated. The influence of climate zone, wall orientation, and solar reflectance was studied. It was found that the thermal performance of the light-weight wall had the highest sensitivity to changes in solar reflectance due to its minimal capacity to store and buffer solar energy. Conversely, increasing the wall's thermal mass not only made the thermal performance less sensitive to solar reflectance, but also significantly reduced the energy usage of dark-colored walls. A brick veneer wall was found to have a 22% decrease in cooling energy and 44% decrease in peak cooling load as compared to a fiber cement wall in climate zone 1. A brick veneer wall over CMU was found to have a 28% decrease in cooling energy and a 66% reduction in peak cooling load as compared to a fiber cement wall in climate zone 1. If a wall has enough thermal mass and is in a favorable climate, there are conditions where a darker colored wall has a lower total energy usage. These results emphasize the need for holistic design of the building envelope when trying to optimize energy efficiency.

KEYWORDS

Thermal Mass, Solar Reflectance, Energy Modeling, Wall Envelope

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INTRODUCTION

Reducing energy usage in residential and commercial construction is important, as they consume roughly 28% of all U.S. energy consumption [1]. Traditional strategies like increasing insulation levels are reaching the point of diminishing returns, pushing the exploration into alternative methods for increasing energy efficiency [2]. One way to do this is by controlling the solar reflectance of the building envelope. Solar reflectance, which determines how much solar radiation is converted into heat on the exterior surface, is important for a building's overall energy usage since the sun is the largest heat load on a building.

One type of active management of the building's solar reflectance is already in practice—cool roofs. These are roofs where the solar reflectance is significantly higher than typical roofing materials which results in a cooler surface temperature under direct sun exposure. The minimum solar reflectance to qualify as a cool roof material is 70%. Cool roofs have been shown to significantly decrease building energy consumption under favorable climates. For example, a cool roof with a solar reflectance of 80% reduced cooling demand by 24.3% in Dubai [3]. In other regions, the impact varies: in the warm temperate climate of California, a cool roof decreases cooling load, but increases heating load [4]; in Spain, cool roofs can yield energy savings between 10-20% depending on location [5]; in Shanghai, a cool roof was found to have only a minor decrease in cooling load, but a significant increase in heating load, leading to higher energy demand [6]. In very cold climates, cool roofs were not found to decrease energy usage—the lowest energy usage building had a dark colored roof and a high R-value building envelope [7]. These studies show that cool roofs work best in warm to hot climates.

Moving beyond cool roofs, the impact of cool walls has also been studied for its potential in reducing building energy consumption. One of the potential issues when analyzing the impact of the wall on the performance of a building is the very different response of the building energy demand to windows vs. opaque walls. Most literature discusses whole-building results rather than a direct wall-to-wall comparison which this paper focus on. The impact of wall solar reflectance is small compared to window solar heat gain coefficient for residential buildings [8]. Cool walls were found to reduce energy consumption in buildings in climate zones 1-4 similarly to cool roofs [9, 10]. Savings were found to be greater on older buildings with lower R-values [9]. In addition to lowering total cooling load, the peak cooling load of a building was also significantly reduced by up to 20% under favorable building conditions and climate zone with the use of a cool wall [10]. Different climates showed different preferences for wall surface characteristics to minimize energy usage. In hot climates, low solar reflectance and high emissivity surfaces did the best. In temperate climates, moderate solar reflectance and low emissivity performed the best, and in cold climates, a low solar reflectance and low emissivity did the best [11, 12]. The finding of low solar reflectance and low emissivity being the most efficient is not obvious but makes sense as a lot of the building's heat loss at night can be attributed to long-wave thermal radiation to the sky and environment. A low reflectance helps during the summer, and a low emissivity helps during the cold winter.

This study aims to provide missing data where different opaque wall assemblies are simulated without the contributing factor of the rest of the building allowing for a more direct comparison of a single variable. Although this data may not be sufficient to predict whole-building performance, it does allow for direct comparative performance metrics which are not affected by other variables. Here, three different wall systems are modeled: fiber cement cladding, brick veneer cladding, and brick veneer over concrete masonry units. These walls were selected to cover the typical range of thermal masses commonly found in residential and commercial construction. The impact of thermal mass, IECC climate zone, and wall orientation all impact the relationship between energy usage and solar reflectance.

METHODS

The 2D finite element software program MATSS (Masonry Assembly Thermal Simulation Software) was used to carry out heat transfer simulations utilizing typical metrological year climate data from 6 different cities in the United States. These cities were chosen to represent different IECC climate zones. This software simulates transient heat transfer of the opaque building envelope only under constant interior conditions. Modeling conditions are given in Table 1. Additional modeling details and software specifications are listed in reference 13. MATSS handles radiative boundary conditions implicitly, and the default interior convection coefficient was chosen so that a wall with a thermal emissivity of 0.9 would have an overall interior convection coefficient matching ASHRAE Handbook of Fundamentals values [14]. The performance of each wall was quantified by evaluating the heat flux and total energy on the interior surface of the wall.

Table 1 – Model inputs

IECC Climate Zone	City	Indoor Air Temp	Indoor Convection Coefficient	Exterior Air Temperature	Exterior Convection Coefficient
1	Miami, FL	22 °C	3.7 W/m2K	Climate Dependent	Climate Dependent
2	Houston, TX				
3	Atlanta, GA				
4	New York, NY				
5	Buffalo, NY				
6	Minneapolis, MN				

The details of each of the three wall systems chosen for this study are given in Table 2. The fiber cement wall and brick veneer are typical of residential construction, while the brick veneer over CMU is typical of commercial construction in the US. A cross-section view of each of these systems is shown in Figure 1.

Table 2 – Wall configuration

Cladding	Air Space	Backup Wall
Fiber Cement Board	None	2x4 Wood Stud Wall with R-13 Batt Insulation
C216 Modular Brick Veneer	1-inch Air Space	2x4 Wood Stud Wall with R-13 Batt Insulation
C216 Modular Brick Veneer	1-inch Air Space + 2-inch XPS Insulation	3-Web Uninsulated, 115-pcf CMU

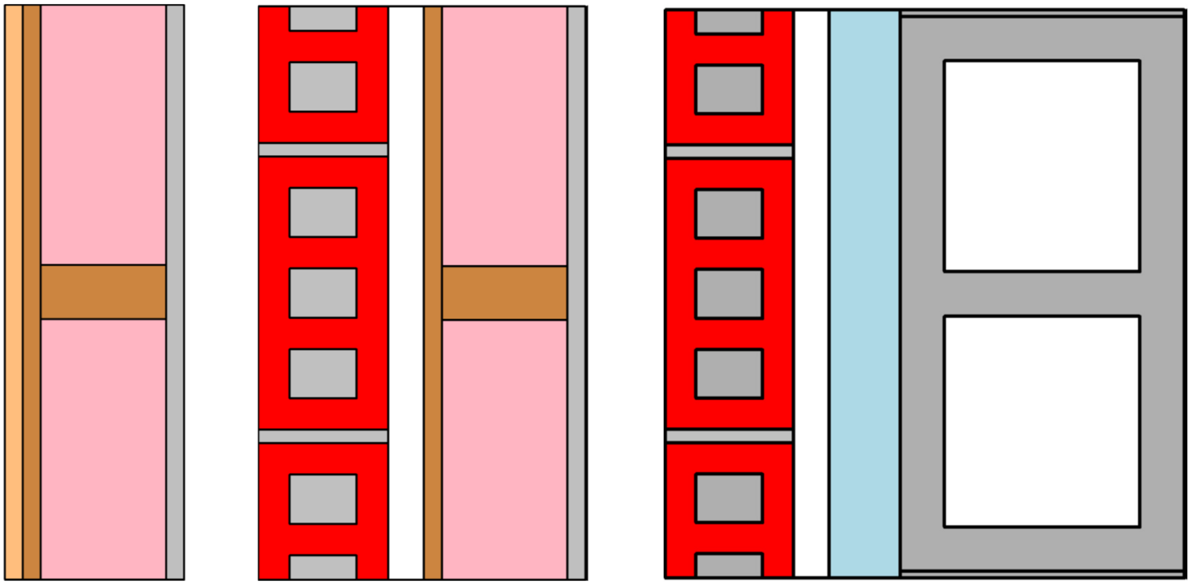

Figure 1 – Cross-sectional view of fiber cement (left), brick veneer (center), and brick veneer over CMU (right).

Each of these wall systems can conceptually be formulated in a 1D model as a two-part wall consisting of a cladding and a backup wall. Drawing an equivalent circuit diagram for these walls yields the diagram in Figure 2. Note the thermal mass is represented as a capacitor in parallel with the thermal resistance of each layer. Also, the solar absorbance from sunlight is a constant-current source directly applied to the exterior surface. This model will only be used to help explain some of the results from the more exact 2D finite element results, specifically the heat balance at the exterior surface for different ambient conditions. Symbol definitions for the diagram in Figure 2 are given in Table 3.

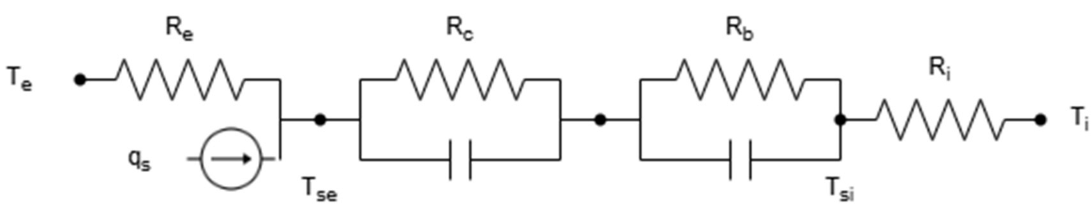

Figure 2 – Equivalent electrical circuit for a 1D heat flow model including a heat source

Table 3 – Variables for 1D heat flow model including a heat source

Temperatures	Resistance	Capacitance	Heat Flux
T_e – Exterior air temperature	R_e – Exterior air film resistance	C_c – Cladding capacitance	q_s – Exterior surface applied heat flux
T_{se} – Exterior surface temperature	R_c – Cladding resistance	C_b – Backup wall capacitance	
T_{si} – Interior surface temperature	R_b – Backup wall resistance		
T_i – Interior air temperature	R_i – Interior air film resistance		

RESULTS AND DISCUSSION

1D equivalent electrical circuit model

The equivalent circuit model was analyzed under steady-state conditions in order to explore the heat balance on the exterior surface of the wall and how an applied heat flux changes the interior heating and cooling load. We specifically aimed to assess how the solar load impacted the heating and cooling demand in summer and winter conditions. For a wall with a total R-value (cladding resistance + backup wall resistance) of approximately R-13 $ft^2hr°F/BTU$, an exterior air film resistance of 0.17 $ft^2hr°F/BTU$, and an interior air film resistance of 0.68 $ft^2hr°F/BTU$, any significant heat load was quickly dissipated to the exterior environment through convection and radiation due to the low exterior air film resistance compared to the walls total R-value. For instance, under direct sunlight with a dark colored wall (800 W/m^2) in the summer, 787 W/m^2 was re-emitted to the environment, with only 13 W/m^2 transferring to the interior. The low exterior film resistance and higher wall R-value is critical for this balance. Figure 3 illustrates the interior heat flux for three different interior air temperatures (30, 15, and 5 °C), representing summer, spring/fall, and winter conditions. The interior temperature was 22 °C. Even in winter, if sufficient heat flux is applied to the wall, the net heat flux can become positive, indicating that cooling would be required.

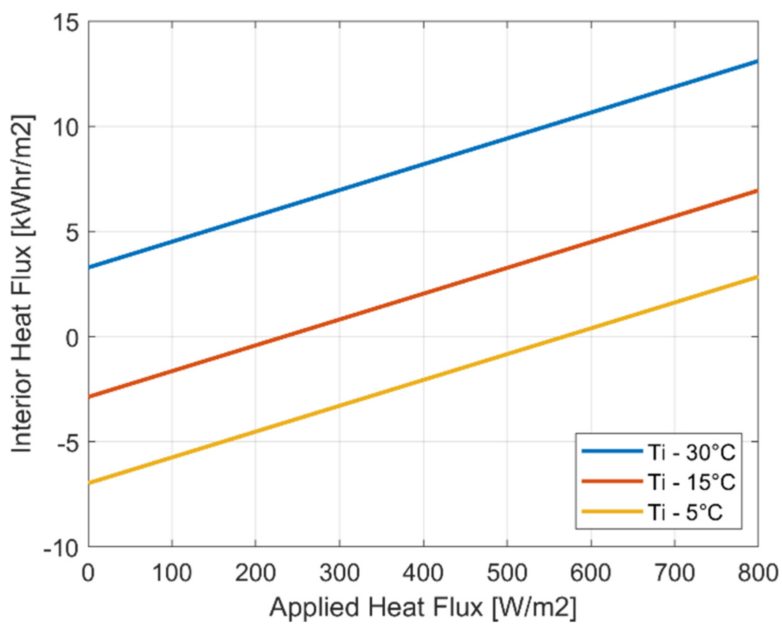

Figure 3 – Interior heat flux vs. applied heat flux for 1D circuit in steady-state.

Impact of Wall Orientation

Wall orientation had a significant impact on the heating and cooling loads of the wall systems. This was driven primarily due to orientation between the wall surface and the sun. North facing walls had significantly lower cooling loads and higher heating loads due to differences in sun exposure. The energy saved could be as high as 70% depending on climate zone, and wall orientation for all three wall systems. The cooling energy usage was found to be less dependent on wall orientation as thermal mass increased. These results are shown graphically in Figure 4 for climate zone 3. Similar results were obtained for other climate zones.

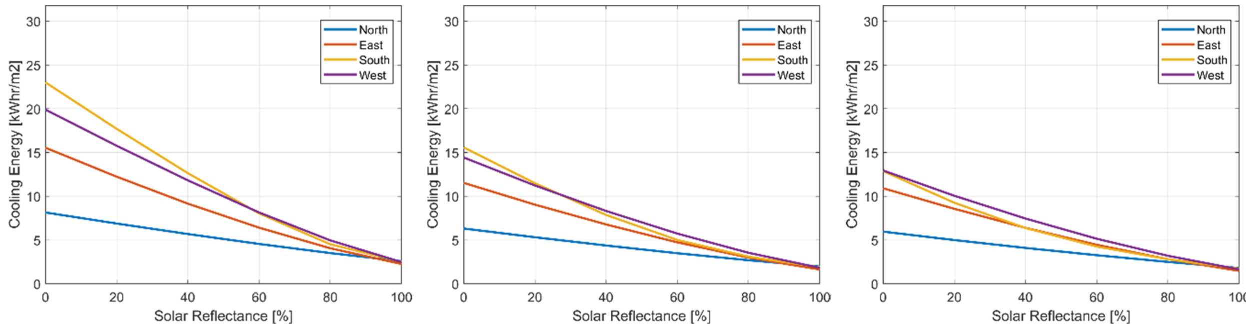

Figure 4 – Total cooling energy for a fiber cement (left), brick veneer (center), and a brick veneer over CMU (right) wall in climate zone 3.

The heating energy load for climate zone 3 for each wall system is shown in Figure 5. Unlike the cooling load where the difference between different wall directions becomes less significant with more thermal mass, the difference between the different directions seems to become greater with increasing thermal mass. This is mostly driven by the significantly lower heating loads for dark colored walls due to the wall's better ability to manage heat in the winter. The increase in heating load with increasing solar reflectance can be up to 45%, 81%, and 94 % higher for a fiber cement wall, brick veneer wall, and brick veneer over CMU wall respectively depending on climate zone and orientation.

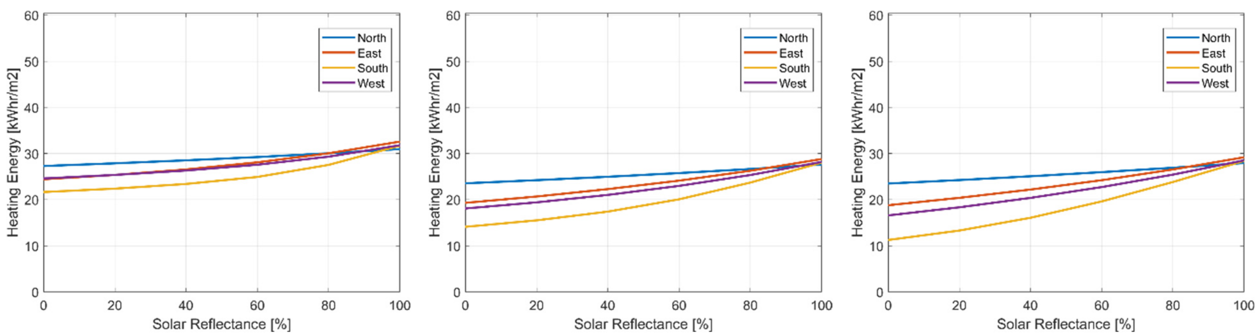

Figure 5 – Total heating energy for a fiber cement (left), brick veneer (center), and brick veneer over CMU (right) wall in climate zone 3.

The total energy usage from climate zone 3 for each wall system is shown in Figure 6. The balance between the tradeoff in thermal energy usage leads to some interesting results which are presented in the next section. The total energy usage appears to have the most variation with respect to wall orientation for the fiber cement wall and becomes almost inconsequential (except for south-facing) for the brick veneer and CMU walls. The south-facing wall has the lowest total energy usage. For most climate zones, there was observed to be a local minimum in the total energy usage curve vs. solar reflectance for south-facing walls. The more thermal mass in the wall, the lower the reflectance at which the minimum occurred. For the south-facing wall in climate zone 3, the minimum energy usage occurred at a solar reflectance of 80%, 60%, and 40% for the fiber cement, brick veneer, and brick veneer over CMU wall respectively. The brick veneer wall had a total energy usage 21.8% lower than the fiber cement and the brick veneer over CMU wall was 29.7% lower for a south-facing wall at the optimum reflectance in climate zone 3.

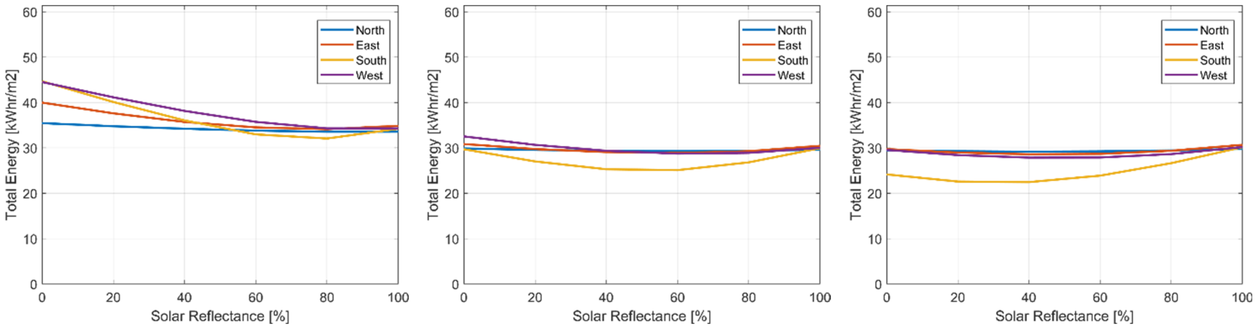

Figure 6 – Total energy requirement for a fiber cement (left), brick veneer (center), and brick veneer over CMU (right) wall in climate zone 3.

The wall orientation that has the largest change in energy usage with respect to solar reflectance is a south-facing wall. Due to this, the remainder of the paper will focus on this wall direction to simplify the analysis and figures. All scenarios were modeled, and if necessary, others will be mentioned.

Impact on Cooling Energy Requirements

The solar reflectance has a dramatic impact on both the peak cooling load and the total cooling energy usage of the south-facing wall. Interestingly, the peak cooling load was found to be largely climate zone independent, while the total cooling load decreased significantly with increasing climate zone. Increasing climate zones equate to colder climates, more dominated by heating loads, while lower climate zones are warmer and cooling loads dominate. The impact of climate zone and solar reflectance on peak cooling load is shown in Figure 7. One striking result was how effective the thermal mass was in reducing the peak cooling load of the wall. This impact was more pronounced for walls with lower solar reflectance. For a brick veneer wall with a solar reflectance of 0%, the peak cooling load was equivalent to that of a fiber cement wall with a solar reflectance of 40%. For a brick veneer wall over CMU with a solar reflectance of 0%, the peak cooling load was equivalent to that of a fiber cement wall with a solar reflectance of nearly 60%. Numerical data for a solar reflectance of 20% and 80% is given in Table 4.

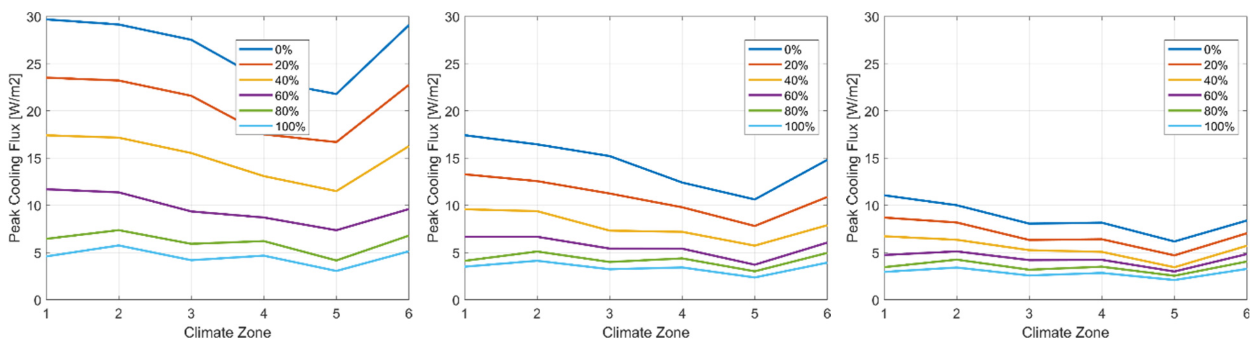

Figure 7 – Peak cooling load for a fiber cement (left), brick veneer (center), and brick veneer over CMU (right) wall versus climate zone.

The total cooling load results were not quite as dramatic as the peak reduction, but the brick veneer and brick veneer over CMU wall with a reflectance of 0% performed similarly to a fiber cement wall with a solar reflectance of 20%. The thermal mass was equivalent to an effective 40-60% increase in solar reflectance in terms of the peak cooling load, and an effective 20% increase in the solar reflectance in terms of the net cooling load. The impact on net cooling load is shown in Figure 8. Numerical data for a solar reflectance of 20% and 80% is given in Table 5.

Table 4 – Peak cooling load [W/m^2] for a south-faccing fiber cement (left), brick veneer (center), and a brick veneer over CMU (right)

Climate Zone	Fiber Cement		Brick Veneer		Brick Veneer over CMU	
Solar Reflectance	*20%*	*80%*	*20%*	*80%*	*20%*	*80%*
1	23.5	6.5	13.3	4.1	8.7	3.4
2	23.2	7.4	12.6	5.1	8.2	4.3
3	21.6	5.9	11.3	4.0	6.3	3.2
4	17.5	6.2	9.8	4.4	6.4	3.5
5	16.7	4.2	7.8	3.0	4.7	2.5
6	22.8	6.8	10.9	5.0	7.0	4.1

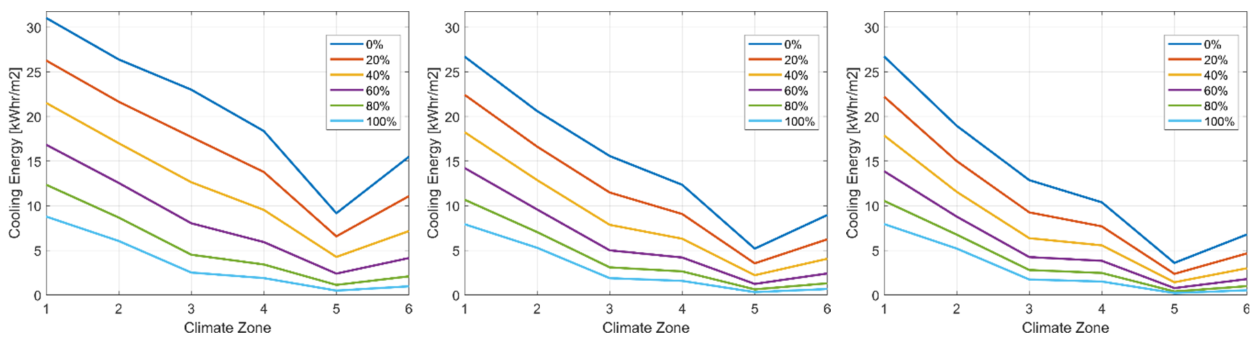

Figure 8 – Total cooling energy for a fiber cement (left), brick veneer (center), and a brick veneer over CMU (right) wall versus climate zone.

Table 5 – Total cooling load [kWhr/m^2] for a south-faccing fiber cement (left), brick veneer (center), and a brick veneer over CMU (right)

Climate Zone	Fiber Cement		Brick Veneer		Brick Veneer over CMU	
Solar Reflectance	*20%*	*80%*	*20%*	*80%*	*20%*	*80%*
1	26.3	12.4	22.4	10.7	22.2	10.5
2	21.7	8.7	16.6	7.1	15.0	6.8
3	17.7	4.5	11.5	3.1	9.3	2.8
4	13.8	3.4	9.1	2.6	7.7	2.5
5	6.6	1.1	3.5	0.6	2.4	0.4
6	11.1	2.1	6.2	1.3	4.7	1.0

Impact on Heating Energy Requirements

The peak heating load was found to be independent of the solar reflectance and only depended on the climate zone and thermal mass. The total heating load, however, was found to be linearly dependent on the solar reflectance but had a much stronger dependence on climate zone than solar reflectance. The relative impact of the solar reflectance on the heating load was greater for walls with more thermal mass. Darker walls with more thermal mass had a better relative performance than light-colored walls. This is shown in Figure 9.

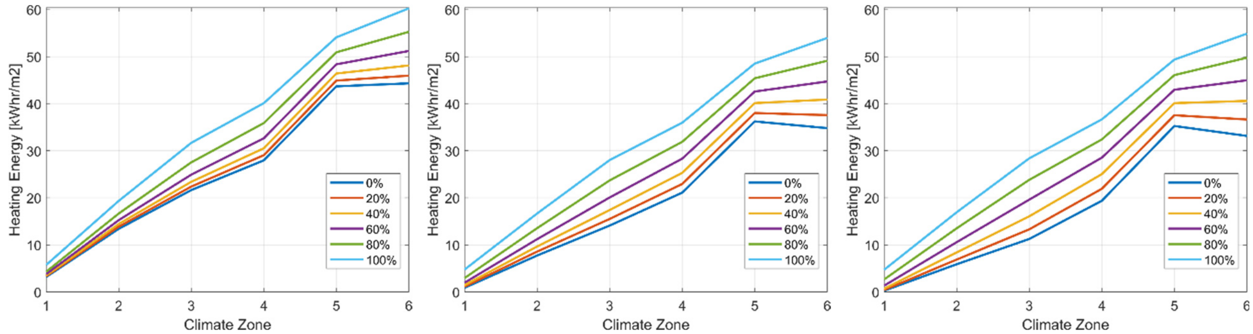

Figure 9 – Total heating energy for a fiber cement (left), brick veneer (center), and a brick veneer over CMU (right) wall versus climate zone.

Impact on Total Energy Requirements

Total energy usage showed a minimum energy usage with respect to solar reflectance for most climate zones (except climate zone 1). The solar reflectance with the minimum total energy usage decreases as climate zone increases. Darker colored walls are more favorable in higher climate zones. This is directly due to the balance between heating and cooling energy over a year. The impact of thermal mass was found to be to shift the minimum towards a lower solar reflectance (similar to the impact on cooling load). These results are shown in Figure 10. Numerical data for a solar reflectance of 20% and 80% is given in Table 6.

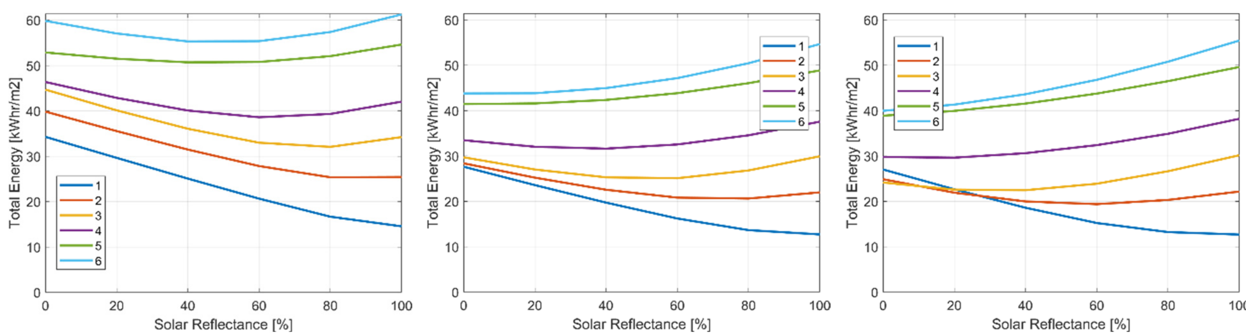

Figure 10 – Total energy requirement for a fiber cement (left), brick veneer (center), and brick veneer over CMU (right) wall versus solar reflectance.

Table 6 – Total energy requirement [kWhr/m^2] for a south-facing fiber cement (left), brick veneer (center), and a brick veneer over CMU (right).

Climate Zone	**Fiber Cement**		**Brick Veneer**		**Brick Veneer over CMU**	
Solar Reflectance	*20%*	*80%*	*20%*	*80%*	*20%*	*80%*
1	29.6	16.7	23.6	13.6	22.6	13.2
2	35.5	25.3	25.2	20.6	21.9	20.3
3	40.1	32.1	27.0	26.8	22.6	26.6
4	42.8	39.3	32.0	34.5	29.6	34.9
5	51.5	52.0	41.6	46.0	39.9	46.5
6	57.0	57.4	43.8	50.4	41.3	50.8

One potential outcome from this shift towards lower solar reflectance is that walls with more thermal mass show less potential for savings (and could potentially incur penalties) by switching to a high solar reflectance material or color. Thermal mass works best when there are significant temperature swings on the exterior of the wall and darker colors facilitate this temperature swing. The slope of the total energy curve was evaluated at two points (10% and 70% solar reflectance) and is given in Table 7. The slope gives energy savings in kWhr/m^2 per 1% change in solar reflectance. This is the sensitivity of the wall's total energy savins to the solar reflectance. From the table, it's clear that a dark colored brick veneer and brick veneer over CMU wall is much less sensitive to solar reflectance than a fiber cement wall. The brick veneer wall has 11.2%, 26.5%, 41.2%, and 58.9% smaller slope than the fiber cement wall for climate zones 1, 2, 3, and 4 respectively. The brick veneer over CMU has a 5.6%, 31.2%, 65.8%, and 96.0% smaller slope than the fiber cement wall for climate zone 1, 2, 3, and 4 respectively.

Table 7 – Calculated sensitivity [kWhr/m^2 per 1% change in solar reflectance] of total energy requirement on solar reflectance.

Climate Zone	Fiber Cement		Brick Veneer		Brick Veneer over CMU	
Solar Reflectance	*10%*	*70%*	*10%*	*70%*	*10%*	*70%*
1	-0.231	-0.199	-0.205	-0.128	-0.218	-0.100
2	-0.215	-0.124	-0.158	-0.010	-0.148	0.047
3	-0.228	-0.046	-0.134	0.086	-0.078	0.138
4	-0.175	0.036	-0.072	0.101	-0.007	0.125
5	-0.069	0.064	0.007	0.110	0.053	0.137
6	-0.139	0.100	0.002	0.164	0.069	0.200

CONCLUSION

Similar to previous work on cool roofs and cool walls, we find that in general, increasing the solar reflectance of a wall decreases the peak cooling load, and total cooling energy usage. Also, the total heating load increased with increasing solar reflectance. Unlike prior work, we quantitatively demonstrate that the thermal mass of the wall system has a large impact on the sensitivity of the wall system to the solar reflectance. A cost-effective change in solar reflectance for a light-weight wall system may not be cost-effective on a wall with significant amounts of thermal mass due the decreased sensitivity. The largest impact of the thermal mass was in the huge reduction in peak cooling load for dark colored walls with thermal mass.

Future work needs to be done to take this research beyond a wall-to-wall comparison and evaluate building-level sensitivity on the opaque wall solar reflectance to determine if cool walls are cost beneficial for thermally massive walls with insulation, as current building codes require.

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