14TH CANADIAN MASONRY SYMPOSIUM
MONTREAL, CANADA
MAY 16TH – MAY 20TH, 2021

ENERGY CONSERVATION METHODS FOR ENERGY CONSUMPTION OF BUILDINGS IN TROPICAL (HAWAIIAN) CLIMATE

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ABSTRACT

Both the demand and the cost of energy is increasing as the US population and economy continues to grow. This has prompted more energy efficient buildings to be designed and constructed. Although Energy Code provisions define alternative design methods that can be used to meet the energy efficiency requirements, due to ease of use, most buildings are designed using the prescriptive approach. The Hawaiian State Building Code recently adopted the 2015 IECC and now prescriptively requires continuous insulation for exterior masonry walls. Although the alternative provisions will allow non-insulated walls to be used, most designers use the IECC prescriptive provisions and thus will likely design exterior masonry walls with prescriptive continuous insulation. These increases in the prescriptive envelope provisions suggest that energy efficient designs must start with increases in the thermal resistance of the building envelope. However, studies have shown that increasing exterior envelope insulation may have only a minimal effect on the overall energy performance of the building, especially for exterior walls with a high thermal mass. A holistic energy study was conducted using a variety of energy conservation measures intended to improve the energy performance of buildings with exterior walls of uninsulated masonry in the Tropical (Hawaiian) climate. Payback analysis were also conducted to evaluate the economic performance of a variety of proposed energy saving strategies. These analyses suggest that, in general, high reflectance walls are recommended for all buildings in Hawaiian climate and produce buildings with good energy performance.

KEYWORDS: *energy analysis, uninsulated exterior masonry walls*

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INTRODUCTION

To reduce the energy consumption by buildings, the building code 2015 IECC [1] prescriptively requires continuous insulation for exterior masonry walls. Although the alternative provisions will allow non-insulated walls to be used, most designers use the IECC prescriptive provisions and thus will likely design exterior masonry walls with prescriptive continuous insulation. These increases in the prescriptive envelope thermal resistance provisions suggest that energy efficient designs must start with increases in the thermal resistance of the building envelope. However, the effectiveness of increasing exterior envelope insulation has been questioned and it has suggested that these changes may have only a minimal effect on the overall energy performance of the building, especially for exterior walls with a high thermal mass.

Generally, conventional energy saving strategies can be classified as either active or passive. Active strategies include refining the heating, ventilation, and air condition (HVAC), and lighting systems, while the passive approaches focus on the reduce energy losses through the building envelope [2]. Typical passive energy saving strategies include changing the reflectance of the exterior surface, using shading, reducing the U factor of envelope, and employing high efficiency lighting and HVAC systems.

The impact of the building envelope characteristics on building energy consumption can be complex. Analysis by Feng et.al. [3] of an office building in Shenyang (a cold region in China), showed that 60-70% of the envelope heat loss was through exterior wall, 10% through building roof, and 20~30% is through exterior doors and windows. In addition, Haie Huo et.al. evaluated the energy performance of an uninsulated room (16.2 m^2, 240 mm brick wall with 20 mm internal and external plaster and 200 mm reinforced concrete roof and floor with 20 mm internal and external plaster - R value of wall assembly of 0.37 m^2K/W and 0.18 m^2K/W, respectively) in four different climatic regions in China. They found that the heat loss of 30% through the roof (larger in hotter cities), about 5% through the floor (larger in hotter cities), and about 10% through the windows (smaller in hotter cities). The remainder (about 55% of total) was through the walls [4]. This suggests about 55% or more of the total energy loss or gain is through the exterior walls. However, some research has shown that there is only a minor impact on energy consumption with increasing wall thermal resistance (R) beyond a certain value [5, 6]. This optimum thermal resistance was also verified by Pengfei Jie et.al. that showed revealed that there was a critical value of insulation thickness for both walls and roofs [6]. It appears that the more insulation, the less energy consumption up to a critical R value, after which the impact is substantially less. Yang et al. [7] and Rodrigues et al. [8] also showed that there is an optimum thermal resistance for minimum energy consumption. These studies did note that this minimum energy use wall R value was not necessarily the most economical configuration in regard to energy used.

In addition, thermal mass was also a factor to consider in optimizing the energy performance of building envelopes. Thermal performance of buildings with similar assembly U factors and climate conditions can vary with the thermal mass of walls. Sadineni et.al. [9] indicated that building thermal mass (including phase change material) is more effective in places where the outside ambient air temperature differences between the days and nights are high. They also determined that air tightness and building envelope infiltration are also very important in energy savings [9]. In a 2017 study, Fadejev et al. [10] compared the heating and cooling load of two buildings with the same U value (0.15 W/m^2K) but different thermal mass (wood vs. concrete). They found that, due to higher thermal mass, the cooling demand reduced by 16% (short term) and 11% (long term) [10]. Rodrigues, et al.[8], found that the impact of the thermal mass of buildings varied with climate conditions, control strategies and occupant use. This variation has confirmed by research of a building in Milan, Italy, with the same U value of 0.34 W/m^2K. Here, higher thermal mass reduced heating demand by 10% and cooling demand by 20%. In general, increased thermal mass increased the cooling energy demand and reduced the heating energy demand for warmer climates but may increase the heating energy demand for colder climates. However, this is only an inference.

Exterior walls also include fenestrations that can dominate the energy loss through the envelope. Improving the R value of window systems or changing the solar heat gain coefficient (SHGC) can significantly reduce envelope heat losses and gains. Allen et al. [11] suggest that significant energy savings is possible using switchable glazing and showed reduction of energy movements of 33%. In study by Sun et al. [2], window glass coatings and insulation reduces solar heat gain and heat flux through the windows.

In addition to the impact of the thermal resistance of the building envelope, the lighting and heating ventilating and air conditioning systems (HVAC) can also significantly impact energy use. More efficient lightning and air conditioning systems, have been shown to be a very effective energy saving strategy, as was better lighting and HVAC controls [2]]. Building ventilation systems and their impact on energy use was also investigated and found to have a significant impact on energy use [12]. In fact, the general conclusion of these investigations was that more efficient lighting and HVAC systems were much more cost-effective energy saving strategies than envelop improvements.

To assess the effectiveness of recent code mandated increases in envelope thermal resistance, a holistic energy study was conducted using a variety of energy conservation measures intended to improve the energy performance of buildings with exterior masonry walls in the Tropical but with moderate temperature and humidity (Hawaiian) climate. Payback analysis were then conducted to evaluate the economic performance of a variety of proposed energy saving strategies.

MODEL DESCRIPTION

To investigate the impact of a number of energy saving strategies on buildings in the Hawaiian climate, four of the prototype buildings published by U.S. Department of Energy (DOE) that are commonly constructed with concrete masonry walls were selected. These included a stand-alone retail building, a secondary school, a midrise apartment building and low-rise apartment building. Weather file used in analysis is historical weather data in Honolulu available on EnergyPlus website. Figure 1 shows the OpenStudio (EnergyPlus) [13] model developed for each prototype. U factors of wall and roof of models were modified to meet 2015 International Energy

Conservation Code [1] for all but the low-rise apartment building. The low-rise building fell under the residential code [1] and was configured to meet the prescriptive requirements in this code. Each of these baseline configurations were designated as Baseline. For each simulation, total site energy, electric and gas consumption, electric and gas peak demand was recorded.

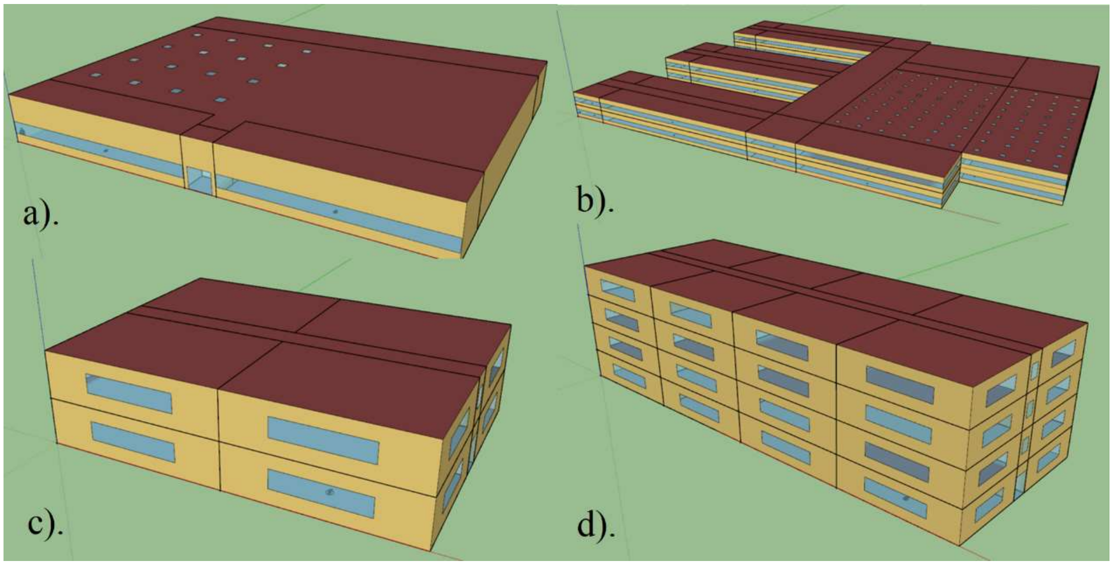


Figure 1: Four Prototypes OpenStudio Models: a). Standalone Retail, b). Secondary School, c). Low-rise Apartment, d). Midrise Apartment

To evaluate the impact of thermal mass on building energy consumption in the Hawaiian climate, the exterior walls of the protypes were assumed to have five different configurations, including fully grouted 105 pcf (1682 kg/m^3), 8" (203.2 mm) concrete masonry (CMU) walls ("105FM"), partially grouted 105 pcf (1682 kg/m^3), 8" (203.2 mm) CMU walls partially grouted with vertical rebar at 24 in. (609.6 mm) OC, with the other cells filled with insulation foam ("105PM"), 120 pcf (1922 kg/m^3), poured concrete walls ("120PC"), 130 pcf (2082 kg/m^3), poured concrete walls ("130PC"), 150 pcf (2403 kg/m^3), poured concrete walls ("150PC"). The properties (U factors, R values and thickness, etc.) [14-16] used in the analysis are summarized in Table 1. Note that the U-factors include impacts of air films.

For each wall configuration, eight different energy saving strategies were simulated along with the baseline configuration. These strategies were identified with a letter A though G. The baseline exterior wall configuration used whichever wall was under considerations and added insulation and wall board to the interior face sufficient to meet the maximum prescriptive U-factor limit in the Energy code.

Table 1: Thermal Properties of Exterior Wall Materials (Baseline)

Wall Configurations	Descriptions	Conductivity W/mK (Btu·in/hrft^2·R)	Specific Heat J/gK (Btu/lb·R)	U Factor Including Air Film W/m2K (Btu/ft^{2}hR)
Fully Grouted 8" CMU (105FM)	Solid Grouted	1.212 (8.400)	874 (0.209)	2.996 (0.528)
Partially Grouted 8" CMU (105PM)	Cells Insulated	0.486 (3.248)	678 (0.162)	1.668 (0.294)
Poured Concrete 120 pcf (120PC)	Limestone Concrete	1.139 (7.900)	879 (0.210)	3.047 (0.537)
Poured Concrete 130 pcf (130PC)	Sand and Gravel or Stone Aggregate Concrete	1.356 (9.400)	879 (0.210)	3.337 (0.588)
Poured Concrete 150 pcf (150PC)	Sand and Gravel or Stone Aggregate Concrete	2.149 (14.900)	879 (0.210)	4.091 (0.721)

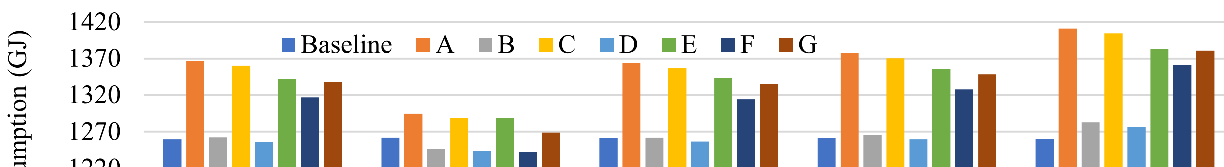
Configuration A was the baseline code prescriptive configuration with no added wall insulation, Configuration B was the baseline configuration with no exterior insulation but with the exterior surface reflectance of the walls increased to 0.64. Configuration C was the baseline configuration with no exterior insulation but with overhangs with a projection factor (PF) of 0.3 on all fenestrations. Configuration D was Configuration C with the exterior surface reflectance of the walls increased to 0.64. Configuration E was Configuration A with approximately twice the roof insulation (Roof U-factor decreased to 0.146 W/m^{2}K (0.026 Btu/ft^{2}hR). Configuration F was Configuration A with 10% more efficient light luminaires being used (the minimum expected with LED lighting [14]). Configuration G was Configuration A with 8% more efficient HVAC systems (typical of higher efficiency units). Note that in baseline models the exterior wall assembly U factor was 0.863 W/m^{2}K for the low-rise apartment and 1.116 W/m^{2}K for the rest.

Table 2: Case Descriptions

Case Suffix	U Factor			Reflectance of Wall (Roof)	Projection Factor (PF)	Lighting Demand	HVAC Efficiency
	Wall	Roof	Floor				
Baseline	0.863(1.116)	0.273	1.894	0.3(0.55)	-	-	-
A	Varies with Properties of Wall Configuration See Table 1	0.273	1.894	0.3(0.55)	-	-	-
B		0.273	1.894	0.64(0.55)	-	-	-
C		0.273	1.894	0.3(0.55)	0.3	-	-
D		0.273	1.894	0.64(0.55)	0.3	-	-
E		0.146	1.894	0.3(0.55)	-	-	-
F		0.273	1.894	0.3(0.55)	-	-10%	-
G		0.273	1.894	0.3(0.55)	-	-	+8%

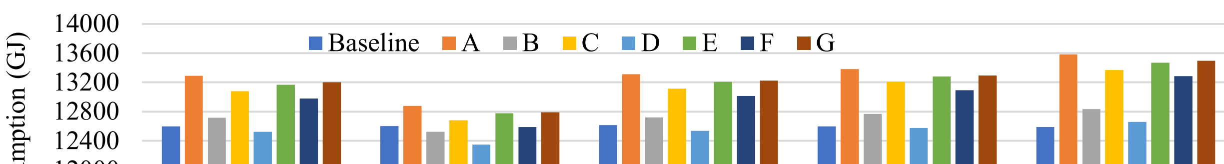
RESULTS

A holistic energy analysis of four prototypes was conducted using the OpenStudio (Energy Plus) software. These analyses showed typical yearly energy consumption for the stand-alone retail protype was roughly 10% to 32% for lighting, 30% to 55% for HVAC, while other systems made up 27% to 55% of the total yearly energy use. Similar results were obtained for each of the three prototypes in the Hawaiian climate, as represented by Honolulu weather data. The yearly energy use for each of the four prototypes for the eight different system configurations are shown in Figures 2 to 5. For each of the four prototypes, baselines with the different exterior wall configurations showed similar energy consumption. The minor differences between baseline energy consumption with different wall configurations was due to variation in specific heats, since the U factors of these baseline walls were the same and equal to the maximum code allowed values [1].



	105FM	105PM	120PC	130PC	150PC
Baseline	1259.23	1261.75	1261.19	1261.03	1259.72
A	1366.69	1294.54	1364.05	1377.62	1411.13
B	1261.89	1246.22	1261.75	1265.15	1282.55
C	1360.36	1288.99	1356.81	1370.35	1404.55
D	1255.9	1243.52	1256.47	1259.54	1276.18
E	1341.91	1288.7	1343.5	1355.32	1383.12
F	1316.84	1242.29	1314.16	1327.62	1361.49
G	1337.91	1268.62	1335.35	1348.39	1380.66

Figure 2: Energy Used for the Stand-alone Retail with Variable Energy Savings Strategies



	105FM	105PM	120PC	130PC	150PC
Baseline	12594.8	12602.25	12614	12598.7	12589.97
A	13287.92	12874.97	13309.13	13382.27	13583.2
B	12714.9	12521.71	12720.03	12766.73	12832.44
C	13078.43	12680.99	13114.99	13203.47	13367.3
D	12524.39	12349.08	12533.45	12575.88	12657.47
E	13166.46	12777.85	13204.59	13281.72	13466.78
F	12976.34	12586.29	13010.88	13089.79	13283.06
G	13200.52	12790.5	13221.68	13294.29	13493.92

Figure 3: Energy Used for Secondary School with Variable Energy Savings Strategies

Examination of Figure 2 shows that for the stand-alone retail protype, regardless of what type of exterior wall configuration was used, the total yearly energy consumption of the uninsulated wall configuration (Configuration A) was reduced roughly 8% when the exterior surface reflectance value changed from 0.3 to 0.64. Improving HVAC efficiency (8% higher) resulted in a reduction of total energy consumption of around 2.1%. Note that the results also showed that a 10 % reduction in lighting demand reduced the total yearly energy consumption only by around 50 GJ/year. This reduction was significant when the overall energy use was low (such as with the partially grouted wall system) but much less significant when energy use was high (such as with bare concrete walls). The energy saving effect of shading was not very significant unless combined with higher surface reflectance. Total energy consumption of the 105 fully grouted 8" CMU cases were similar with 120 pcf poured concrete cases. However, a comparison of the relative performance of the three configurations of bare concrete walls suggest that the impact of high thermal mass is not beneficial in all cases and there appears to be an optimum value for best performance. This behavior was similar for all four prototypes.

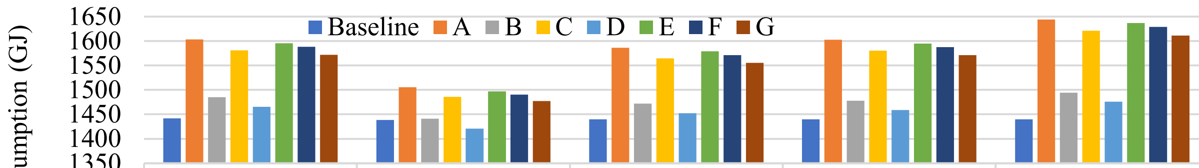
For the stand-alone retail prototype, partially grouted exterior masonry walls with cell insulation had lower overall energy usage than the base line configuration in all configurations except E (roof insulation) and G (Efficient HVAC) and thus were energy code compliant using the energy budget method. Configuration D (reflective surface and shading) used less yearly energy than the baseline configuration for all wall types except the 150 pcf concrete walls and were thus code compliant without exterior insulation.

For the secondary school prototype shown in Figure 3, the total yearly energy consumption reduced by 4% to 5% when the reflectance value changed from 0.3 to 0.64. However, improving HVAC efficiency (8% higher) only reduced the total energy consumption by around 0.7%. The reduction in lighting demand (10 %) only reduced the total energy consumption by around 300 GJ. With the total energy use in the school being much larger, the reduction in lighting energy had much less of an impact. The impacts of energy saving strategies were similar to that described for the stand-alone retail prototype and had the same code compliant configurations.

Figure 4 shows that, for midrise apartment prototype, total energy consumption was reduced by about 7% when the reflectance value changed from 0.3 to 0.64. However, HVAC efficiency improvements (8% higher) only reduced total energy consumption by around 2%. The reduction in lighting demand (10 %) resulted in a reduction in total energy consumption by around 15 GJ. Lighting is only a small percentage of overall demand for apartments. Configuration D was code compliant for the partially grouted and cell insulated masonry wall configuration only.

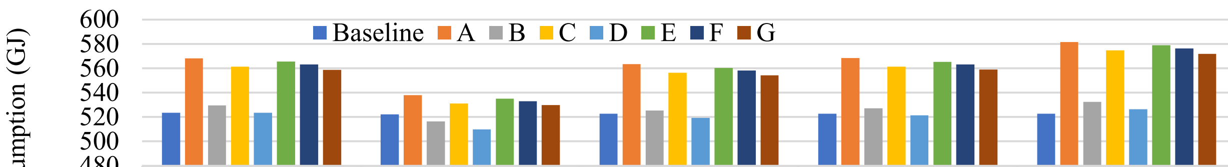
For the low-rise apartment prototype, similar behavior to the midrise apartment prototype was observed (see Figure 5). It should be noted that the low-rise apartment building has a larger surface to volume ratio than the midrise apartment. This provides better heat dissipation capacity so that Case D was code compliant for low-rise apartment with 105FM, 120PC and 130PC walls.

Meanwhile, the midrise apartment with same wall configuration and energy saving strategy consumes more energy than baselines.



	105FM	105PM	120PC	130PC	150PC
Baseline	1441.47	1438.64	1439.97	1440.02	1439.91
A	1603.11	1505.56	1586.28	1602.41	1644.06
B	1485.1	1440.81	1471.65	1477.98	1494.58
C	1580.89	1485.51	1564.57	1580.25	1620.92
D	1465.54	1420.76	1452.14	1458.88	1475.83
E	1595.51	1496.94	1578.79	1595.01	1636.81
F	1588.09	1490.54	1571.22	1587.4	1629.13
G	1571.61	1477.24	1555.36	1570.94	1611.3

Figure 4: Energy Used for Midrise Apartment with Variable Energy Savings Strategies



	105FM	105PM	120PC	130PC	150PC
Baseline	523.48	522.08	522.74	522.74	522.79
A	568.1	538.02	563.29	568.3	581.45
B	529.54	516.3	525.3	527.25	532.31
C	561.33	531.22	556.29	561.28	574.67
D	523.55	509.91	519.38	521.32	526.44
E	565.41	535.09	560.32	565.38	578.89
F	563.04	532.93	558.22	563.22	576.22
G	558.77	529.68	554.12	558.96	571.72

Figure 5: Energy Consumption of Low-rise Apartment with Variable Energy Strategies Applied

PAYBACK ANALYSIS

In the payback analysis, a differential cost analysis was conducted. In this analysis, the capital cost of system changes were determined using Building Construction Costs with RSMeans data, 2018 [17]. Yearly energy savings costs were determined using electricity and natural gas consumption from the energy simulations and the average price of electricity" published on Hawaiian Electric website, and the cost of natural gas from the "Oahu Rate Schedules/Riders" published on HAWAII GAS website.

HVAC and lighting equipment varied significantly and were not included in the payback analysis. The results of the payback analysis for the four prototypes were listed in Table 3. Relative to the baseline models, Configurations A, B, C, D, E, F all had lower initial costs than the baseline configuration. If more total yearly energy was used (compared with baseline), then the value in energy saved column was taken as a negative. If the configuration used more energy than the baseline but cost less to construct, then the payback period would be the number of years needed for the additional energy costs to equal the additional capital cost of the baseline configuration. If there is a positive value in the energy column then this configuration used less energy than the baseline and was cheaper to build. Those configurations were marked a "-" in the payback period column, since that strategies are definitely recommended. For cases with negative "energy saved", a longer payback period is better, as there is a large reduction in initial cost but this configuration consumes slightly more energy than baseline.

Table 3: Payback Analysis

Wall Configuration	Case	Stand-alone Retail		Secondary School		Midrise Apartment		Low Rise Apartment	
		Energy Saved ($/yr.)	Payback Period (yr.)	Energy Saved ($/yr.)	Payback Period (yr.)	Energy Saved ($/yr.)	Payback Period (yr.)	Energy Saved ($/yr.)	Payback Period (yr.)
105FM	A	-7460	31.4	-47038	25.3	-11224	27.4	-3098	31.4
	B	-195	944.1	-8351	111.5	-3029	79.4	-421	181.3
	C	-7022	33	-34110	33.1	-9681	30.8	-2628	36
	D	219	-	3591	-	-1671	138.8	-5	14579.3
	E	-5740	29.5	-39280	21.7	-10697	26.6	-2911	25.8
105PM	A	-2275	101.3	-19245	60.8	-4647	65	-1107	86.5
	B	1067	-	4895	-	-151	1560.2	401	-
	C	-1890	120.8	-7025	158	-3255	90.1	-635	146.4
	D	1255	-	15866	-	1242	-	845	-
	E	-1864	88.9	-13085	63.6	-4048	69.1	-903	81.5
120PC	A	-7141	32.8	-47479	25	-10159	30.2	-2815	34.6
	B	-47	3917.6	-7605	122.5	-2199	109.4	-178	428.6
	C	-6638	34.9	-35551	31.8	-8651	34.5	-2329	40.6
	D	320	-	4108	-	-844	274.7	234	-
	E	-5713	29.7	-40891	20.8	-9639	29.6	-2609	28.8
130PC	A	-8093	29	-53301	22.3	-11276	27.2	-3163	30.8
	B	-294	624.3	-11723	79.5	-2636	91.3	-313	243.7
	C	-7588	30.6	-42463	26.6	-9737	30.6	-2676	35.3
	D	95	-	276	-	-1309	177.2	99	-
	E	-6543	25.9	-46967	18.1	-10762	26.5	-2960	25.4
150PC	A	-10513	22.3	-66843	17.8	-14176	21.7	-4073	23.9
	B	-1596	115.1	-16367	56.9	-3796	63.4	-660	115.5
	C	-10056	23.1	-53701	21	-12569	23.7	-3602	26.2
	D	-1153	157.3	-5589	156.1	-2494	93	-253	290.4
	E	-8564	19.8	-59523	14.3	-13672	20.8	-3894	19.3

Examination of Table 3 shows that uninsulated masonry walls and uninsulated concrete walls can be used in the Hawaiian climate very successfully when the high reflectance surface coatings are used. Although these walls result in the prototypes that use more energy than code prescriptive code configurations and are thus not code compliant, the additional energy cost for these configurations would take in excess of 60 years, and in many cases well over a hundred years, to payback the difference in capital expenditures for the code compliant configurations. Simply increasing wall reflectance in warm climates reduced the total energy consumption by a significant amount with limited investment in all the four prototypes analyzed in Hawaiian climate. Wall surface reflectance can be changed easily through painting or adding architectural surface treatments.

CONCLUSION

Wall surface reflectance can be changed easily through painting or other surface treatments but this simple change can produce significant energy savings in warm climates. This investigation analyzed the energy consumption of the four prototype buildings in the Hawaiian climate. The DOE developed stand-alone retail, secondary school, midrise apartment, low-rise apartment prototypes were used to investigate various energy saving strategies for use in buildings that often use exterior masonry or concrete wall systems. It was shown that increasing the reflectance of exterior walls will significantly reduce the yearly energy use, even without code mandated insulation. In many cases this coating combined with shading of fenestrations was sufficient to provide energy code compliance for uninsulated masonry and concrete wall based on the energy budget method. However, the effect of reflectance changes differed with exterior wall configuration. For the five wall configurations evaluated, the higher U factor of the exterior wall, the higher the total energy consumed, and greater percentage of energy saved with high reflectance surfaces. This change had the single greatest impact of the behavior of the building protypes and configurations studied.

In a number of the building configurations analyzed, applying high reflectance surface coatings and fenestration shading produced Code compliance based on the energy budget method. However, where the building configurations used more energy than the code mandated base line, applying high reflectance surface coatings and fenestration shading to configurations that had uninsulated masonry or concrete exterior walls decreased the energy used sufficiently to make the slight increase in yearly energy use take in excess of 60 years to compensate for the additional capital costs of the prescriptive code baseline configurations. In many cases, these payback periods were well in excess of 100 years.

The effect of exterior wall thermal mass on yearly energy use, for the tropical climate and building types investigated, was shown to be variable. Increasing thermal mass did not improve energy use behavior. this suggest that once a minimum amount of thermal mass, additional thermal mass may not improve behavior. The investigation showed that within the range of thermal mass studied, thermal mass does not have much impact on energy consumption in Hawaiian weather condition.

Improved roof insulation proved to be the least economical method of decreasing energy used in the Hawaiian weather conditions. Increases in roof insulation reduces energy consumption, but not significantly.

Under the condition of buildings studied, improvement in lighting and HVAC did not reduce energy consumption much.

ACKNOWLEGMENTS
This investigation was funded under a grant from the Masonry Institute of Hawaii.

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