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Assessing the thermal performance of upcycled shipping container as a sustainable building material in a Warm humid climate

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Abstract. The current trends in the construction sector are responsible for majority of the CO_2 emissions in India. The sustainable methods to reduce the CO_2 emissions should include not just recycling but also upcycling the materials, for instance – shipping containers. Despite the industry's best efforts to minimize waste generation, millions of shipping containers end up as scrap materials, every year. This phenomenon can be changed effectively by reusing the scrap materials as alternate building materials. The trend of reusing the shipping containers as building materials is at its peak in Western countries, while in India, it is still in a nascent stage. The aim of the current research paper is to evaluate and assess the thermal performance of upcycled shipping containers as a building material in warm humid climatic condition. This research includes a review of literature about the strengths and weaknesses of the shipping containers as a building material; it also compares and evaluates the thermal performance of uninsulated container buildings with base case conventional building and the insulated container building through Opaque simulation method. The results were obtained by comparing and assessing the thermal performance and cost of various insulating materials for a container building. The study outcomes greatly help the architects to reuse the shipping containers as a sustainable alternative building material in warm humid regions.

1. Introduction

The construction sector in India accounts for an approximate of 38% of the country's total yearly CO_2 emissions. The products or industrial processes of the four energy-intensive building materials such as cement, bricks, lime, glass, and others contribute to 80% of the CO_2 emissions from the construction sector. This can be lessened by reusing the construction materials. [1]

Cargotecture corresponds to the use of ISO-certified shipping containers, also known as cargo containers, for the construction of fully-operational buildings, commercial spaces and housing. Cargo containers have an active life of 8-10 years, when used for shipping purposes. However, it has a lengthy technical life and if properly maintained, it has the potential to last another 15-20 years [2] [3]. Refurbishing the existing containers reduces the need to extract and process new raw materials. Further, the used containers are also kept out of the waste stream, thus making the construction sector, a highly sustainable one. [4]

Based on their proportions, the shipping containers are categorized as either regular or high cube containers. The High Cube (HC) shipping containers are best suited for building construction since the space between the ceiling and the roof is sufficient for ductwork and a clear ceiling of 2.4m is provided. [5]

The shipping containers offer enormous potential as a habitable space including constructability, structural performance and building services. [6]. The current research paper examines the energy-efficient and cost-effective insulating materials for shipping container buildings in warm humid climate.

Table -1. SWOT analysis on shipping containers as a building material

Strength	• Container buildings can be pre-fabricated [7] • Can be easily transported by ship, truck and train [8] • Cargotecture building can be 30% cost-effective than a conventional building [4] • Repurposing the containers, instead of scrapping and melting, can save a lot of energy and reduce the emission of greenhouse gases. [9]
Weakness	• Containers are made of cor-ten steel due to which the internal temperature can be unbearable, if not insulated [3] [10] • Needs skilled labour for efficient construction [11] [10] • Container buildings have low acoustic and thermal performance [12] [10]
Opportunity	• An opportunity to reduce the carbon footprint through recycling [12] • Container buildings can be completed within 7 days and the time limit becomes lesser by about 40% to 60% compared to conventional construction methods [2] [13] • Addition of spaces can be easily made through stacking [10]
Threat	• Containers are not corrosion or rust-proof [14] • Old shipping containers might have lead-based paints and arsenic flooring, which is hazardous to human health. [15] [3]

Table 1 depicts an overview of the Strengths, Weaknesses, Opportunities and Threats of employing the shipping containers as building materials.

Shipping containers are relatively thin, uninsulated, and acoustically inferior boxes in which thermal comfort remains a primary concern. Heat is a key issue, when adopting the shipping containers as housing since steel has a high thermal conductivity. In such case, the shipping containers require thermal insulation and a ventilation system to maintain a suitable indoor environment in high temperature and high humidity climates. [16] [3]

2. Methodology

The study methodology contains the following steps; listing out the cost and thermal performance of various building and insulation materials used in the construction industry; a conventional 40 ft. (12.2m x 2.43m) brick building and a 40 ft. (12.2m x 2.43m) container building were designed as the base case and alternative case respectively, including various insulation materials to the setup; then, the thermal performance of the container steel along with insulation materials and conventional building materials was assessed and compared; a cost analysis was carried out to establish the cost-effectiveness of container building in comparison with the conventional brick building; the results were obtained by utilizing an opaque tool to evaluate the thermal performance and cost of the chosen insulating materials for a container building in a warm humid region.

In this study, 21 building models were considered. The models 1-5 correspond to base case buildings with conventional building materials, Model 6 is an un-insulated 40 ft. shipping container and the models 7-21 are insulated shipping container buildings.

Table 2. Cost and thermal conductivity of various insulation materials

Insulation materials [17]	**Cost (₹) (per square meter)** [18]	**Thickness (mm)**	**K-value (W/m.k)** [19]	**Types of insulation**
Spray insulation	200	100	0.036	Open-cell spray polyurethane foam (OCSPF)
	800	50	0.026	Closed-cell spray polyurethane foam (CCSPF)
	480	100	0.040	Damp-spray cellulose insulation
	595	75	0.380 [20]	Cementitious spray foam insulation
Blanket insulation	250	25,50	0.043	Fiberglass
	470	25-75	0.035	Mineral wool
	110	25-100	0.045 [20]	Rock wool
Expandable rigid foam insulation	200	75	0.036	Open-cell polyurethane foam insulation (OCPU foam)
	300	25	0.026	Closed-cell polyurethane foam insulation (CCPU foam)
	190	25-50	0.032	Expanded polystyrene foam insulation (EPS)
	300	20-50	0.034	Extruded polystyrene foam insulation (XPS)
	520	25-100	0.022	Polyisocyanurate (polyiso)
Strawbale	100	100	0.052	-
Cork insulation	150	10-60	0.038 [20]	-
Rooftop garden	200	60-250	0.060	Extensive, Semi-intensive, Intensive
Sandwich PU panel	800	60	0.038	-

Table 2 displays various types of insulation materials and its cost (per square meter), thickness (mm) and thermal conductivity (W/m.k) values.

Table 3. Cost and thermal conductivity of the conventional building materials

Building materials	**Cost (₹) (per piece)** [18]	**No. of pieces required**	**Cost (₹) (per square meter)**	**K-value (W/m.k)** [19]
Brick	8	40-45	360	0.98
Fly-ask brick	7	40-45	315	0.85
Autoclaved aerated concrete (AAC)	44	8-9	400	0.18
Concrete block	10	40-45	450	1.3
Cellular lightweight concrete (CLC)	50	40-45	2250	0.188
Shipping container	85,000 – 1,25,000	-	1630	43

Table 3 shows different types of conventional building materials along with its cost (per square piece), number of pieces required (per square meter) and its thermal conductivity (W/m.k) value.

3. Comparative analysis

3.1. Material specification

Table 4. Detailed material specifications for base case and the alternative case

	Wall	**Roof**
1. Base case	12.5mm external plaster + 230mm brick + 12.5mm internal plaster	10mm Tiles + 100mm RCC Slab + 12.5mm plaster
2. Alternative case 1	12.5mm external plaster + 200mm AAC block + 12.5mm internal plaster	
3. Alternative case 2	12.5mm external plaster + 230mm fly-ash brick + 12.5mm internal plaster	
4. Alternative case 3	12.5mm external plaster + 200mm concrete block + 12.5mm internal plaster	

5. Alternative case 4	12.5mm external plaster + 200mm CLC block + 12.5mm internal plaster	
6. Alternative case 5	1.6 mm corrugated corten steel sheet	2 mm corrugated corten steel sheet
7. Alternative case 6	1.6 mm corrugated corten steel sheet + 100mm OCSPF + 5mm Gypsum board	1.6 mm corrugated corten steel sheet + 100mm OCSPF + 5mm Gypsum board
8. Alternative case 7	1.6 mm corrugated corten steel sheet + 50mm CCSPF + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm CCSPF + 5mm Gypsum board
9. Alternative case 8	1.6 mm corrugated corten steel sheet + 100mm Damp-spray cellulose insulation + 5mm Gypsum board	2 mm corrugated corten steel sheet + 100mm Damp-spray cellulose insulation + 5mm Gypsum board
10. Alternative case 9	1.6 mm corrugated corten steel sheet + 75mm Cementitious foam insulation + 5mm Gypsum board	2 mm corrugated corten steel sheet + 75mm Cementitious foam insulation + 5mm Gypsum board
11. Alternative case 10	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm Fiberglass + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm Fiberglass + 5mm Gypsum board
12. Alternative case 11	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 75mm Mineral wool + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 75mm Mineral wool + 5mm Gypsum board
13. Alternative case 12	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 100mm Rock wool + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 100mm Rock wool + 5mm Gypsum board
14. Alternative case 13	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 75mm OCPU foam + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 75mm OCPU foam + 5mm Gypsum board
15. Alternative case 14	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 25mm CCPU foam + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 25mm CCPU foam + 5mm Gypsum board
16. Alternative case 15	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm EPS + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm EPS + 5mm Gypsum board
17. Alternative case 16	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm XPS + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 50mm XPS + 5mm Gypsum board
18. Alternative case 17	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 100mm Polyisocyanurate + 5mm Gypsum board	2 mm corrugated corten steel sheet + 50mm wooden stud framing + 100mm Polyisocyanurate + 5mm Gypsum board
19. Alternative case 18	1.6 mm corrugated corten steel sheet + 100mm Straw bale + 30mm cement mortar	2 mm corrugated corten steel sheet + 100mm Straw bale + 30mm cement mortar
20. Alternative case 19	1.6 mm corrugated corten steel sheet + 60mm Cork Insulation + 5mm Gypsum board	2 mm corrugated corten steel sheet + 60mm Cork Insulation + 5mm Gypsum board
21. Alternative case 20	1.6 mm corrugated corten steel sheet + 50mm wooden stud framing + 100mm polyurethane sandwich panel + 5mm Gypsum board	10mm Plants + 100mm Growing medium + 50mm Filtration + 8mm Drainage + 3mm Waterproof layer + 2 mm corrugated corten steel sheet + 5mm Gypsum board

Table 4 illustrates different material layers of the selected walls and roofs for the 21 models that are inclusive of the base model and the alternate cases.

3.2. Base case – Sample conventional building

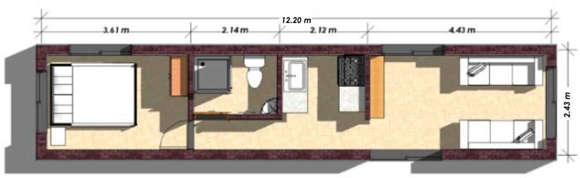


Figure 1. Floor plan – Conventional building

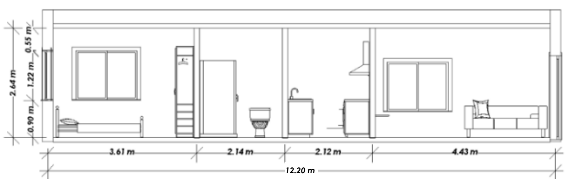


Figure 2. Section – Conventional building

Floor area = 27.45 m^2, Wall area = 83 m^2

Figures 1 and 2 depict the floor plan and section of a 40-foot-long base case brick building (12.2m x 2.43m) resepctively, which includes a bedroom, a living space, a kitchen and a bathroom.

3.3. *Alternate case – Sample container building*

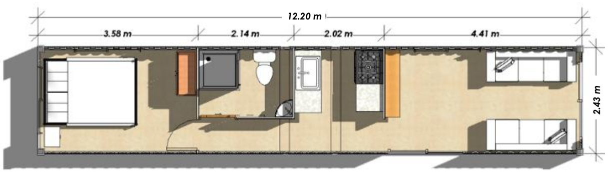


Figure 3. Floor plan – Container building

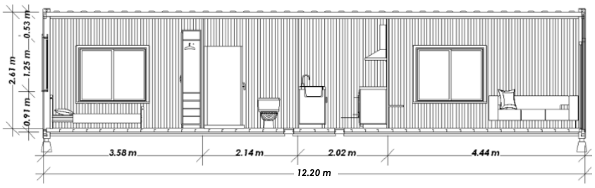


Figure 4. Section – Container building

Floor area = 27.36 m^2, Wall area = 84 m^2

Figures 3 and 4 depict the floor plan and section of a 40-foot container building (12.2m x 2.43m) respectively, which includes a bedroom, a living space, a kitchen and a bathroom.

3.4. *Analyses of the thermal performance and cost of wall and roof materials using OPAQUE tool* [21]

Opaque tool was used in this research to evaluate the thermal performance of the chosen base and the alternative cases. The thermal properties of the material such as k-value, density, specific heat capacity, thickness and the location of the building were fed into the tool for analysis and comparison.

Based on the chosen climate, this tool assumes the rest of the parameters such as the surface temperature, absorptivity and reflectance to determine the U-value, Time Lag, and Decrement Factor by generating the details of a wall or roof section and plotting the temperature drop using a Heat Flow graph.

Table 5. Performance specification of different wall materials [21]

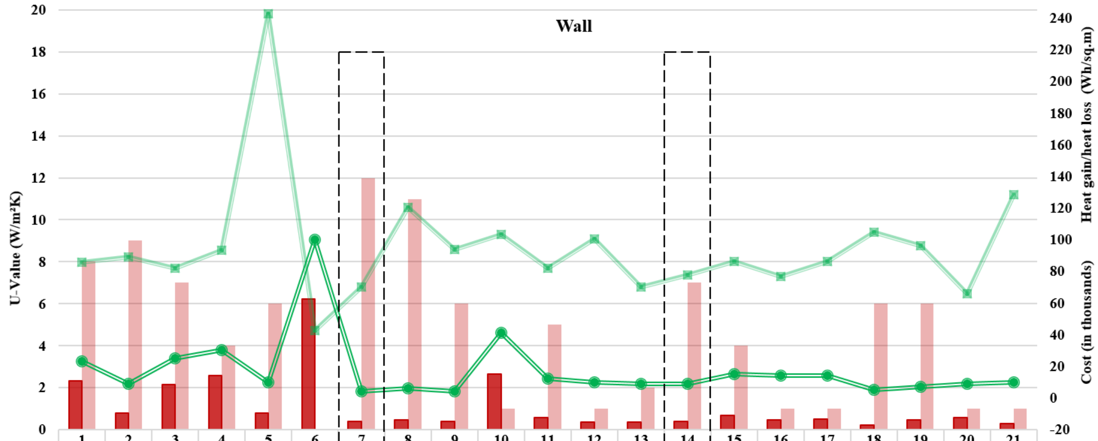
Sl. no	Wall material	U-Value	Heat gain/ loss	Time lag	Cost (in thousand)	Roof material	U-Value	Heat gain/ loss	Time lag	Cost (in thousand)
01	Conventional Brick wall	2.33	23	**8**	85.8	Conventional RCC roof	2.83	35	6	36.6
02	AAC block	0.781	**9**	**9**	89.1	Conventional RCC roof	2.83	35	6	36.6
03	Fly-ash brick	2.16	25	**7**	**82**	Conventional RCC roof	2.83	35	6	36.6
04	Concrete block	2.59	30	4	93.2	Conventional RCC roof	2.83	35	6	36.6
05	Cellular lightweight concrete block	0.8	10	6	242.6	Conventional RCC roof	2.83	35	6	36.6
06	Unmodified 40′HC Shipping container	6.24	100	0	**42.5**	Unmodified 40′HC Shipping container	5	103	0	**21.25**
07	40′HC Shipping container with Open-cell spray polyurethane foam	**0.384**	**4.2**	**12**	**70.14**	40′HC Shipping container with Open-cell spray polyurethane foam	**0.334**	**4.1**	**12**	**30.28**
08	40′HC Shipping container with Closed-cell spray polyurethane foam	0.475	**6**	**11**	120.5	40′HC Shipping container with Closed-cell spray polyurethane foam	0.467	**6**	**11**	46.7
09	40′HC Shipping container with Damp-spray cellulose	**0.373**	**4.2**	6	93.6	40′HC Shipping container with Damp-spray cellulose	**0.367**	**3.6**	6	37.94
10	40′HC Shipping container with Cementitious foam	2.63	41	1	103.3	40′HC Shipping container with Cementitious foam	2.38	48	1	41.09
11	40′HC Shipping container with Fiberglass	0.58	12	5	81.9	40′HC Shipping container with Fiberglass	0.56	**8**	1	34.11

12	20′HC Shipping container with Mineral wool	**0.37**	10	1	100.38	20′HC Shipping container with Mineral wool	**0.36**	10	1	40.13
13	40′HC Shipping container with Rock wool	**0.36**	**9**	2	**70.14**	40′HC Shipping container with Rock wool	**0.35**	**9**	2	**30.28**
14	40′HC Shipping container with Open-cell polyurethane foam insulation	**0.38**	**9**	**7**	**77.7**	40′HC Shipping container with Open-cell polyurethane foam insulation	**0.37**	**8**	**8**	**32.74**
15	40′HC Shipping container with Closed- cell polyurethane foam insulation	0.66	15	4	86.1	40′HC Shipping container with Closed- cell polyurethane foam insulation	0.64	15	5	35.48
16	40′HC Shipping container with Expanded polystyrene foam	0.47	14	1	**76.86**	40′HC Shipping container with Expanded polystyrene foam	0.46	14	1	**32.47**
17	40′HC Shipping container with Extruded polystyrene foam	0.49	14	1	86.1	40′HC Shipping container with Extruded polystyrene foam	0.48	14	1	35.48
18	40′HC Shipping container with Polyisocyanurate	**0.2**	**5**	6	104.5	40′HC Shipping container with Polyisocyanurate	**0.19**	**2.9**	4	41.5
19	40′HC Shipping container with Strawbale	0.47	**7**	6	96.09	40′HC Shipping container with Strawbale	0.46	**8**	6	**27.54**
20	40′HC Shipping container with Cork Insulation	0.57	**9**	1	65.94	40′HC Shipping container with Cork Insulation	0.55	11	1	**28.91**
21	40′HC Shipping container with PU sandwich panels	**0.3**	10	1	128.6	40′HC Shipping container with Rooftop Garden	**0.28**	**2.8**	6	41.61

Table 5 illustrates the U-value, heat gain/loss, time lag and the cost of 21 cases in which the high-performing materials are highlighted for each parameter.

4. Result and Discussion

4.1. Comparison of efficiency of the wall material



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
U-Value	2.33	0.781	2.16	2.59	0.8	6.24	0.384	0.475	0.373	2.63	0.58	0.37	0.36	0.38	0.66	0.47	0.49	0.2	0.47	0.57	0.3
Time lag (hrs)	8	9	7	4	6	0	12	11	6	1	5	1	2	7	4	1	1	6	6	1	1
Heat gain/heat loss	23	9	25	30	10	100	4.2	6	4.2	41	12	10	9	9	15	14	14	5	7	9	10
Cost (in thousands)	85.8	89.1	82	93.2	242.6	42.5	70.14	120.5	93.6	103.3	81.9	100.38	70.14	77.7	86.1	76.86	86.1	104.5	96.09	65.94	128.6

1 2 3

Figure 5. Comparison of the performance between base case and the alternate case wall materials

1.	Conventional brick wall	8.	Closed cell spray foam wall	15.	Closed cell polyurethane foam wall
2.	AAC block wall	9.	Damp-spray cellulose wall	16.	Extruded polystyrene foam wall
3.	Fly-ash brick wall	10.	Cement spray wall	17.	Expanded polystyrene foam wall
4.	Concrete block wall	11.	Fiberglass wool wall	18.	Polyisocyanurate wall
5.	CLC block wall	12.	Mineral wool wall	19.	Straw bale wall
6.	Unmodified steel wall	13.	Rock wool wall	20.	Cork insulation wall
7.	Open cell spray foam wall	14.	Open cell polyurethane foam wall	21.	Polyurethane sandwich panel wall

4.1.1. Discussion. The shipping container building case, with polyisocyanurate (Polyiso) insulation, achieved the least U-value for a wall – 0.2 W/m²K, followed by polyurethane (PU) sandwich panels with a U-value of 0.3 W/m²K, Open-cell spray polyurethane foam and Open-cell polyurethane foam with its U-values being 0.38 W/m²K. However, neither polyiso nor PU sandwich panel was found to be cost-effective.

The open-cell spray polyurethane foam and the closed-cell spray polyurethane foam had a maximum time lag of 12 hrs and 11 hrs respectively.

The open-cell spray polyurethane foam and the damp-spray cellulose insulation achieved a low heat gain/loss of 4.2 Wh/sq.m. However, the damp-spray cellulose insulation was expensive than the open-cell spray polyurethane foam insulation.

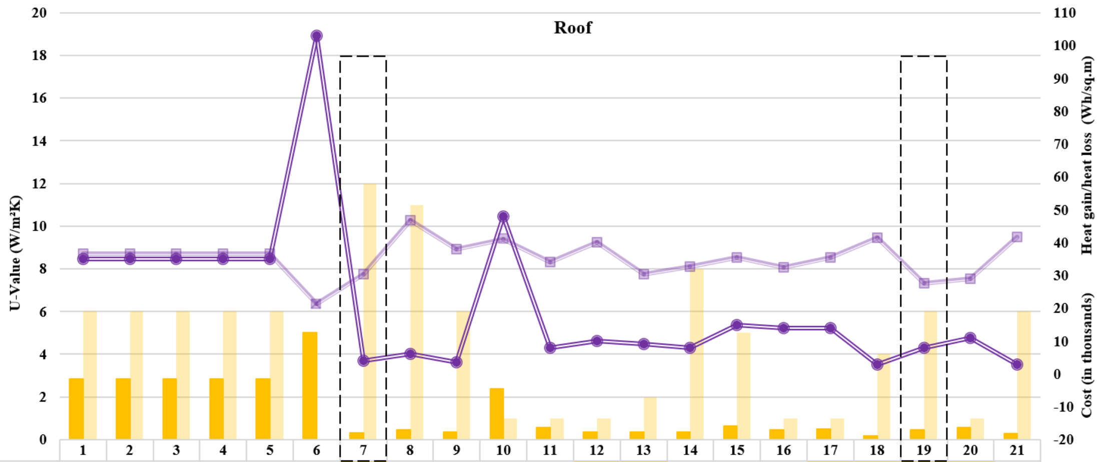
Table 6. Best performing cost-effective wall insulation materials

	Wall material	U-Value	Time lag	Heat loss/ gain	Cost
1.	**7. Open-cell spray polyurethane foam**	**0.384 W/m²K**	**12 hrs**	**4.2 Wh/sq.m**	**₹ 70,146**
2.	14. Open-cell polyurethane foam	0.38 W/m²K	7 hrs	9 Wh/sq.m	₹ 77,706

Table 6 compares the thermal performance of open-cell spray polyurethane foam with open-cell polyurethane foam.

4.1.2. Inference. Figure 7 shows that the open-cell spray polyurethane foam had the least heat gain/loss (4.2 Wh/sq.m) and was found to be the most cost-effective one (₹ 70,146) of all the insulating materials evaluated, with a U-value of 0.384 W/m²K and a maximum time lag of 12 hours.

4.2. *Comparison of the efficiency of roof materials*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
U-Value	2.83	2.83	2.83	2.83	2.83	5	0.334	0.467	0.367	2.38	0.56	0.36	0.35	0.37	0.64	0.46	0.48	0.19	0.46	0.55	0.28
Time lag (hrs)	6	6	6	6	6	0	12	11	6	1	1	1	2	8	5	1	1	4	6	1	6
Heat gain/heat loss	35	35	35	35	35	103	4.1	6	3.6	48	8	10	9	8	15	14	14	2.9	8	11	2.8
Cost (in thousands)	36.6	36.6	36.6	36.6	36.6	21.25	30.28	46.7	37.94	41.09	34.11	40.13	30.28	32.74	35.48	32.47	35.48	41.5	27.54	28.91	41.61
							1						3						2		

Figure 6. Comparison of the performance between base case and the alternate case roof materials

1. RCC roof
2. RCC roof
3. RCC roof
4. RCC roof
5. RCC roof
6. Unmodified steel roof
7. Open cell spray foam roof
8. Closed cell spray foam roof
9. Damp-spray cellulose roof
10. Cement spray roof
11. Fiberglass wool roof
12. Mineral wool roof
13. Rock wool roof
14. Open cell polyurethane foam roof
15. Closed cell polyurethane foam roof
16. Extruded polystyrene foam roof
17. Expanded polystyrene foam roof
18. Polyisocyanurate roof
19. Straw bale roof
20. Cork insulation roof
21. Green roof

4.2.1. Discussion. The shipping container building, with polyisocyanurate (Polyiso) insulation, achieved the least U-value – 0.19 W/m²K for its roof, followed by the green roof with a U-value of 0.2 W/m²K. However, neither polyiso nor green roof was found to be cost-effective.

While, Strawbale (₹ 27,548), cork insulation (₹ 28,916) and open-cell spray polyurethane foam (₹ 30,284) were found to be less expensive. But, the cork insulation yielded the least time lag of 1 hour followed by Strawbale insulation time lag being 6 hours.

Table 7. Best performing and cost-effective roof insulation materials

	Roof material	U-Value	Time lag	Heat loss/ gain	Cost
1.	**7. Open-cell spray polyurethane foam**	**0.334 W/m²K**	**12 hrs**	**4.1 Wh/sq.m**	**₹ 30,284**
2.	19. Strawbale	0.46 W/m²K	6 hrs	8 Wh/sq.m	₹ 27,548

Table 7 compares the thermal performance of open-cell spray polyurethane foam with Strawbale insulation.

4.2.2. Inference. Figure 8 depicts that the open-cell spray polyurethane foam achieved the least U-value – 0.334 W/m²K, maximum time lag – 12 hours, minimum heat gain/loss – 4.1 Wh/sq.m, and better cost-efficiency (₹ 30,284), of all the insulating materials evaluated.

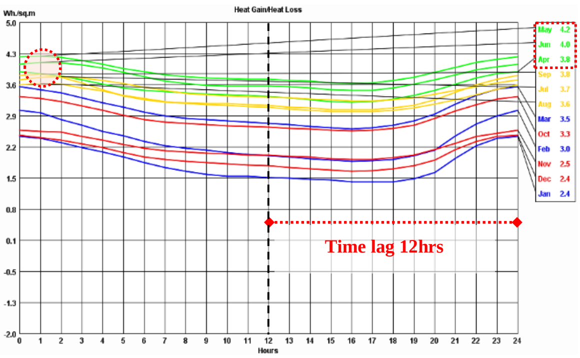


Figure 7. Heat drop graph for OCSPF wall [21]

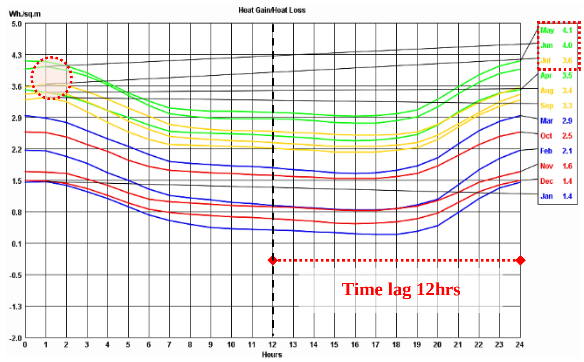


Figure 8. Heat drop graph for OCSPF roof [21]

5. Conclusion

Shipping containers have been recommended as potential building materials to address various housing issues in temperate and cold regions. However, due to lack of awareness and social acceptance among people, the use of cargo containers as buildings is limited in warm and humid climate conditions.

In this study, the authors found that the open-cell spray polyurethane foam wall outperformed the traditional brick wall by 83% in U-Value, 81% in heat gain/loss and 18.2% in cost. Further, the open-cell spray polyurethane foam roof outperformed the traditional RCC roof by 88% in U-Value, 88.3% in heat gain/loss and 20.7% in cost.

The study outcomes infer that if adequate insulating materials are incorporated in a shipping container building in a warm humid climate, it may be both thermally comfortable as well as cost-effective. So, it is important to create an awareness among the public that low-cost container buildings are not inferior to conventional brick and concrete structures. In the future, further research should be conducted on the structural stability and life cycle evaluation of the shipping container buildings.

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